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Linking land use-land cover change with annual and perennial plant growth models for the spatio-temporal explicit simulation of ecosystem services

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A case study in a savanna region of Ghana

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FOR

MY SISTER AND PARENTS!

whose vitality and unconditional support are always with me

ABSTRACT

Many West African economies have been experiencing fast growth over recent decades. At the same time, their landscapes are also experiencing one of the fastest changes in the world, and the pace has accelerated over recent decades. These changes are driven both by local demands and the historical export of renewable resources. The need to satisfy the growing internal food demand has driven widespread and uncontrolled cropland expansion, whereas global concerns regarding the need to transition towards a new techno-economic paradigm based on the substitution of fossil fuels with biomass products, put additional pressures on local land use systems derived from the global competition for land. In this context, there are clear signs that many West African landscapes are experiencing a degradation of their capacities to reproduce biomass. Therefore, regional land use planning is of foremost importance to improve the satisfaction of human nutritional requirements and energy demand in the medium-term and ensure it in the long term. Land use planning processes involve an exercise of anticipating the impact that a chosen strategy may have on the achievement of certain goals. Because the future is uncertain, robust land use planning processes must explore different development pathways and rely on new simulated data.

The purpose of this study is to explore how available data and one-dimensional plant growth models can be used in a spatially-explicit modeling environment to represent medium-/long-term temporal dynamics of the match between ecosystem services supply (using biomass provision as an example), and demand on a district scale. Benefits derived from the consumption of biomass have been quantified in terms of nutritional, feed and fuel yields. The prospective trends of these indicators have been simulated in a spatio-temporally explicit way under three alternative land use change pathways, in combination with different paces of technology adoption change and three projections of population growth. The methodology has been applied over a land use-land cover (LULC) map of high grain and thematic resolution covering the districts of Bolgatanga Municipal and Bongo in the interior savanna zone of Ghana. Land use transitions have been simulated within the GISCAME platform, which allows simulation of future LULC scenarios using data for which no temporal series is available. Agricultural biomass production data has been simulated on the plot-scale with the process-based crop modeling platform APSIM to analyze the production trade-offs among different cropping choices, involving groundnut, millet, sorghum, maize, rice. Additionally, woody biomass growth data has been simulated at the stand-level by fitting a logistic curve to data selected after an extensive literature review.

The results show that the availability of micronutrients (iron and zinc) provided by regional agriculture shall be sufficient to satisfy the dietary requirements of the whole population, but the provision of calories is insufficient. Croplands are the land use types that provide the largest amounts of food and also fuel biomass. Therefore, scenarios with more widespread cropland expansion perform better in all of the indicators assessed. The main shortcoming of the methodology applied to inform real land use planning processes is that the spatio-temporal simulation of regulating ecosystems services was not considered. Therefore, the contribution of non-cultivated land use classes to the renewability of biomass production was not fully accounted for. Model and simulation of a wider range of land use and biomass types in spatially-explicit models would also contribute to significantly increasing the value of these studies to support land use decisions and inform better policies. Improvements across the whole chain are required to increase the efficiency in which biomass production and harvesting satisfies human demands. Integration of spatially-explicit biomass production assessments with models relevant to value chain development, such as transportation costs, could contribute to reducing the socio-ecological risks associated with socio-economic transitions.

Verknüpfung von Landnutzungs- und Landbedeckungsänderungen mit ein- und mehrjährigen Pflanzenwachstumsmodellen für die räumlich-zeitlich explizite Simulation von Ökosystemleistungen: eine Fallstudie in einer Savannenregion in Ghana

KURZFASSUNG

Viele westafrikanische Volkswirtschaften haben in den letzten Jahrzehnten ein schnelles Wachstum erlebt. Gleichzeitig erleben ihre Landschaften eine der schnellsten Veränderungen der Welt, und das Tempo hat sich in den letzten Jahrzehnten noch beschleunigt. Diese Veränderungen werden sowohl durch den lalsookalen Bedarf als auch durch den historischen Export erneuerbarer Ressourcen angetrieben. Die Notwendigkeit, den wachsenden internen Nahrungsmittelbedarf zu befriedigen, hat zu einer weit verbreiteten und unkontrollierten Ausdehnung der Anbauflächen geführt, während die globale Besorgnis über die Notwendigkeit eines Übergangs zu einem neuen technisch-wirtschaftlichen Paradigma, das auf der Substitution fossiler Brennstoffe durch Biomasseprodukte beruht, zusätzlichen Druck auf die lokalen Landnutzungssysteme ausübt, der sich aus dem globalen Wettbewerb um Land ergibt. In diesem Zusammenhang gibt es deutliche Anzeichen dafür, dass viele westafrikanische Landschaften eine Verschlechterung ihrer Kapazitäten zur Reproduktion von Biomasse erfahren. Daher ist eine regionale Landnutzungsplanung von größter Bedeutung, um die Deckung des menschlichen Ernährungs- und Energiebedarfs mittelfristig zu verbessern und langfristig zu sichern. Bei der Flächennutzungsplanung geht es darum, die Zukunft zu antizipieren und die Auswirkungen einer gewählten Strategie auf die Erreichung bestimmter Ziele zu berücksichtigen. Da die Zukunft unsicher ist, müssen robuste Landnutzungsplanungsprozesse verschiedene Entwicklungspfade untersuchen und sich auf simulierte Daten stützen.

In dieser Studie soll untersucht werden, wie verfügbare Daten und eindimensionale Pflanzenwachstumsmodelle in einer räumlich expliziten Modellierungsumgebung verwendet werden können, um die mittel- und langfristige Dynamik des Zusammenspiels zwischen dem Angebot an Ökosystemleistungen (am Beispiel der Bereitstellung von Biomasse) und der Nachfrage auf Kreisebene darzustellen. Der Nutzen aus dem Verbrauch von Biomasse wurde in Form von Ernährungs-, Futter- und Brennstofferträgen quantifiziert. Die voraussichtlichen Trends dieser Indikatoren wurden auf räumlich-zeitlich explizite Weise unter drei alternativen Wegen der Landnutzungsänderung in Kombination mit unterschiedlichen Geschwindigkeiten der Technologieübernahme und drei Projektionen des Bevölkerungswachstums simuliert. Die Methode wurde auf einer Landnutzungs- und Landbedeckungskarte (LULC) mit hoher Auflösung angewandt, die die Bezirke Bolgatanga Municipal und Bongo in der inneren Savannenzone Ghanas abdeckt. Landnutzungsänderungen wurden mit der GISCAME-Plattform simuliert, die es ermöglicht, zukünftige LULC-Szenarien mit Daten zu simulieren, für die keine Zeitreihen verfügbar sind. Die Daten zur landwirtschaftlichen Biomasseproduktion wurden mit der prozessbasierten Pflanzenmodellierungsplattform APSIM auf der Parzellenebene simuliert, um die Kompromisse bei der Wahl verschiedener Pflanzen wie Erdnuss, Hirse, Sorghum, Mais und Reis zu analysieren. Darüber hinaus wurden Daten zum Wachstum der holzigen Biomasse auf Bestandsebene simuliert, indem eine logistische Kurve an Daten angepasst wurde, die nach einer umfassenden Literaturrecherche ausgewählt wurden.º

Die Ergebnisse zeigen, dass die Versorgung mit Mikronährstoffen (Eisen und Zink) durch die regionale Landwirtschaft ausreicht, um den Nährstoffbedarf der gesamten Bevölkerung zu decken, nicht aber die Versorgung mit Kalorien. Ackerland ist nicht nur die Landnutzungsart, die

die größten Mengen an Nahrungsmitteln, sondern auch an Brennstoffbiomasse liefert. Daher schneiden Szenarien mit einer stärkeren Ausweitung der Anbauflächen bei allen bewerteten Indikatoren besser ab. Das größte Manko der Methodik, die zur Information über reale Landnutzungsplanungsprozesse angewandt wurde, besteht darin, dass die räumlich-zeitliche Simulation von regulierenden Ökosystemleistungen nicht berücksichtigt wurde. Daher wurde der Beitrag der nicht kultivierten Landnutzungsklassen zur Erneuerbarkeit der Biomasseproduktion nicht vollständig berücksichtigt. Die Modellierung und Simulation eines breiteren Spektrums von Landnutzungs- und Biomassearten in räumlich expliziten Modellen würde auch dazu beitragen, den Wert dieser Studien zur Unterstützung von Landnutzungsentscheidungen und zur Information über bessere politische Maßnahmen erheblich zu steigern. Verbesserungen in der gesamten Kette sind erforderlich, um die Effizienz der Biomasseerzeugung und -ernte zur Deckung des menschlichen Bedarfs zu steigern. Die Integration von räumlich expliziten Biomasseproduktionsbewertungen mit Modellen, die für die Entwicklung der Wertschöpfungskette relevant sind (z. B. Transportkostenmodelle oder Kosten-Nutzen-Analysen von Verarbeitungsanlagen), könnte dazu beitragen, die mit Landnutzungsänderungen verbundenen sozio-ökologischen Risiken zu verringern.

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ACRONYMS

AFPA	Afforestation of Protected Areas scenario
AGB	Aboveground Biomass
APSIM	Agricultural Production Systems siMulator
CEXP	Cropland Expansion scenario
CAI	Current Annual Increment
CN	Runoff Curve Number
FLAF	Farmland Agrofrorestry Management scenario
Fe	Iron
GSS	Ghana Statistical Service
Kcal	Kilocalories
LULC	Land Use/Land Cover
LULCC	Land Use/Land Cover Change
MAI	Mean Annual Increment
ME	Metabolizable Energy
MoFA	Ministry of Food and Agriculture
NCV	Net Calorific Value
N	Nitrogen
NPP	Net Primary Production
P	Phosphorus
RCP	Representative Concentration Pathway
UER	Upper East Region of Ghana
UWR	Upper West Region of Ghana
Zn	Zinc

1 INTRODUCTION

1.1 Background

1.1.1 West Africa within the global food security and bio-economic transition context

Human material and energy use increased quickly during the 20th century, and has accelerated again since the beginning of the 21st century (Krausmann et al., 2016) while global trade has been expanding, offering new livelihood opportunities all over the world but also exposing them to new threats derived from the impacts of market failures on a wider scale. Meanwhile, rising human demands are exerting an increasing pressure on ecosystems' primary production capacities. Global food demand will increase quickly, at least until 2050, especially in developing countries (Kaminski et al., 2013; Bodirsky et al., 2015; Andam et al., 2017).

On the other hand, concerns related to the fossil resources-based economy are driving a change of the paradigm, and that of the bio-economy is being shaped. The main concerns vis-à-vis the sustainability of the fossil resource-based economy are the high amounts of greenhouse gases emitted by their combustion, the harmful impacts that their derived plastic materials have on the environment once they are littered as waste, and the eventual collapse of the productive system due to resource depletion. This is an additional driver rising human pressure on ecosystems' primary production capacities, as it contributes to increase the demand for a wide variety of (potentially renewable) plant-based products, and has global implications. The paradigm of the modern bio-economy, which emerged by around 1970s, driven by national energy sufficiency concerns (Abelson, 1980), has been evolving since then into a more holistic vision of a self-sustained economy in which production technologies ensure the provision of not only energy but also a wide array of (biomass-based) materials without exhausting the ecosystems' capacities to sustain their provision (Brüll, 2015; Kircher et al., 2018; Sillanpää and Ncibi, 2017. To achieve such goals, structural changes in production and consumption patterns must be implemented.

The vast majority of biomass products are provided by land ecosystems. Their capacity to ensure the continuous provision of plant-based products depends considerably on the rate at which biomass is returned to the ecosystem, ensuring the recycling of nutrients that are the base for the next cycle of biomass reproduction. As the social demands for biomass products increase, so do the harvested amounts, and therefore the rate at which nutrients are returned to the ecosystems diminishes, degrading their capacity to support biomass production. Such capacity can be maintained or restored through land management, including nutrient transfer, as well as by increasing the efficiency by which harvested biomass satisfies human demands, which depends on production, processing and transportation technology, socio-economic relations and consumption patterns.

Recent studies suggest that global food production would need to double unless there are radical changes in global consumption patterns (FAO, 2009; Cirera and Masset, 2010). In some regions, such an increase in food production would need to be even more drastic. For example, for sub-Saharan Africa to meet internal demand, its food production would need to triple the levels of 2010, which would require an increase in yields up to about 80% of their technical potential (van Ittersum et al., 2016). But so far, food production increases in the region have been achieved mainly through cropland expansion without a relevant increase in yields. Since many decades ago, this has implied a decrease in the capacities of African lands to support the production of plant-based products (López, 1997; Niedertscheider et al., 2016; Palmer et al., 2019), a process in which the consumption patterns in Northern America and Europe (Hickel et al., 2022a, 2022b).

Africa is the only continent in which the increased consumption of fuels has been driven by an increase in both non-solid and solid fuels, mainly biomass (Bonjour et al., 2013). This occurs in a continent whose population depends highly on the resources of their local ecosystems (Shanahan et al., 2003). The case of the West African region is particularly illustrative of this trend because, over recent decades, it has been experiencing the fastest increase in the pressure of human exploitation over the capacities of its land use systems to reproduce biomass (Fetzel et al., 2012). For example, the demand for Net Primary Production (NPP) across the Sahel increased steadily between 2000 and 2010, mainly driven by the demand for food and feed products, but the overall NPP supply was kept near-constant (Abdi et al., 2014). Given that the land systems of the Sahel receive very low external input; such evidence suggests that this increased NPP harvest has been the result of mining ecosystem resource pools and, as a consequence, of the degradation of the ecosystems' reproductive capacities.

It must not be forgotten that many of the benefits to human society provided by ecosystems can also be provided by industrial alternatives. The added social value of man-made processes and goods can replace, to a high degree, the social value of ecosystem services. Nowadays, technological alternatives to ecosystem services can contribute to the satisfaction of the vast majority of social demands, particularly in the provision of energy, medicine, water, construction materials, aesthetics, leisure and cultural identity (van Noordwijk et al., 2018). But in the African continent, the dependence on ecosystem services is very high, and their degradation occurs mostly as a result of resource overexploitation. Global socio-economic drivers play an important role in land use systems and biomass exploitation (Erb et al., 2009; Weinzettel et al., 2013; Kastner et al., 2015; Wu et al., 2018), and under an increasing penetration of the bio-economy paradigm in the transformation of the global productive and commercial system, they are likely to become even more prominent. Solutions must be developed to overcome the social and environmental trade-offs derived from the replacement of fossil- with biomass-based materials.

The economy of African countries, as opposed to those of Europe, is already largely biomass-based, because most of its population is engaged in biomass-extraction activities. Despite the fact that dependency on fossil fuels by African countries is likely to increase, particularly in the producing ones (such as Angola, Equatorial Guinea, Gabon, Nigeria, and the more incipient case of Ghana) (Abass, 2014), traditional biomass combustion technologies (those fed by firewood and charcoal) will continue to be the main fuel resource for the next decades. African societies are still vulnerable to the pervasive impacts of the global competition for land, such as environmental degradation, changing conditions of economic production and new forms of social exclusion (Ouma et al., 2013; Wardell and Fold, 2013; Elias and Arora-Jonsson, 2017; Ayelazuno, 2019). Due to diminishing natural capital, the scarcity of wood-based resources is widening the use of crop residues and dried manure as a fuel substitute, exacerbating soil nutrient mining and limiting the productivity of primary production harvesting activities.

Therefore, the improvement (or even maintenance) of livelihood opportunities in tropical Africa, whose population is projected to double by 2050 (OECD, 2013), faces serious challenges posed by the changes in the global geo-political system that are being introduced by the shift towards a biomass-based economy. Despite the generally steady growth of most African economies over recent decades, rising food demand has been satisfied by higher expenditure on imports, resulting in diminishing returns from the international trade of biomass (Demeke et al., 2013; Darfour and Rosentrater, 2016). For example, by the end of the first decade of the 21st century, grain production per capita in Ghana was less than half the value in 1965 (MoFA, 2008) while the structural transformation towards a diversified economy has not occurred. Food insecurity may worsen as global and continental bioenergy crop area expands and competes with food for the use of land, climatic disturbances become more common and wider penetration of international markets increase the risk of being affected by food price shocks (Godfray et al., 2010; Naylor, 2011), particularly in a "business-as-usual" context in which the global comparative advantage of African countries as exporters of primary commodities is being reinforced (Taylor, 2016).

During the 1980s population density, poverty, urbanization and resource degradation increased considerably (Jazaïry et al., 1992; Cour and Snrech, 1994). For example, the devaluation of national currencies in West Africa led to growing economic disparities between their grain-producing inland regions and their coastal zones, because although the price of food crops increased, it did less than the prices of imported inputs and exports crops such as cocoa and palm oil (produced in those regions close to the maritime ports) (Bachmann, 2000; Nyantakyi-Frimpong and Bezner Kerr, 2015). Such regional disparities pose a challenge to the overarching national development goals. As agriculture is not a profitable activity for great part of the rural population, this situation contributes to the maintenance of large migration flows towards the cities, specially of the youth, which is potentially the most productive sector of the population and the one with the capacity to increase farm productivity by improving upon the management knowledge of their predecessors and the integration of relevant innovations. But due to the scarcity of investment capital, urban areas grow at a faster pace than the development of infrastructure, leaving great sectors of the population thriving in precarious conditions and hampering their professional development (Donkoh, 2017; Assan et al., 2018). National economies barely diversify, lacking key industrial sectors that could increase the value of national exports and the availability of funds to invest in infrastructure, innovation and development. While this economic pattern is reproduced, environmental degradation deepens in many areas, both rural and urban.

Searching for landscape configurations and land use management strategies that enhance and ensure the flow of biomass-based goods is essential to improve regional food security and drive the structural transformation of economies towards more resilient, stable and sustainable ones. The bio-economy sector is widening, changing demands and transforming the aim of agriculture from a mainly food- into a more diversified biomass-producing sector (Virchow et al., 2016). This implies that the potential array of product types that can be provided by agriculture and the other primary production-based sectors, such as forestry, is becoming more similar. Therefore, bio-economic transitions require integrated landscape planning policies that recognize and account for the whole ecosystem in order to reproduce the conditions that sustain the base of the economy (Souza et al., 2017). However, such holistic strategies have been, and still are, scant in the history of modern national states. Instead, separated agricultural and forestry policies are the most common approach to tackle land use strategies. This approach has been highly ineffective because it does not acknowledge the land use reality, in which trees are an integral part of agricultural landscapes, whereas annual crops are cultivated inside forests. Therefore, tools that help inform spatial planning processes need to account for the biomass potential and provision dynamics of both perennial and annual vegetation.

1.1.2 Spatial planning tools to support policy-making in West Africa: state of the art

One key element of the vision for a sustainable bio-economy is the development of productive systems that can sustain the satisfaction of human demands by producing and consuming renewable resources. Well-functioning ecosystems are necessary to ensure this flow of goods and services. Such functioning is correlated to land use pattern and, hence, landscape level biomass provision assessments are necessary to enhance the resilience of regional and local economies to global change impacts.

Assessing opportunities for the more efficient use of energy in agricultural and forestry landscapes is key to improving the food security status of African societies (Fritsche et al., 2017) and their overall development. Adoption of improved technological infrastructure is necessary to increase the supply of reliable electricity and biomass-based products; however, the disadvantaged position of the economies of tropical Africa in the current global context, resulting from the international structure of biomass trade, poses great limits for most of their stakeholders to access the necessary financial resources. The implication of the private sector, and hence the attraction of financial capital, will depend on the profitability of the value chains (Lambin et al., 2014b), which is highly determined by the amounts of the raw product base, the efficiency of its extraction and the maintenance of the ecosystem processes that ensure its reproduction.

Smooth functioning value webs, i.e. those in which all the actors involved can earn a living out of their participation in the value chains while ensuring a balanced bargaining power among actors, are necessary to increase income flows while enhancing regional food security and a more efficient use of resources. For the generation of livelihoods, West African rural communities rely on a wide variety of plant biomass types, both provided by herbaceous and perennial vegetation. Clustering of stakeholders, with the aim of increasing regional productive capacities, is key to achieving better biomass-based value chains, i.e. a more efficient conversion of environmental resources into economic goods. Clusters require investment and long-term vision because they involve several stakeholders. But scarce resources for financial investment and little collaboration among smallholders are among the main factors limiting the productive capacity of biomass producing systems (agriculture, forestry…). Tools that allow prospective evaluation of the temporal dynamics of biomass provision would increase available information. This would better support decisions regarding which investments are necessary to improve baseline situations and reduce the risk of investment failure, thereby attracting the capital necessary to achieve long-term, landscape scale, efficiency in the production of biomass. Therefore, in the transition towards a more efficient bio-economy, spatially and temporally explicit estimations of the potential production levels are key to economic development.

Three factors are essential for biomass production: light, water and space. The importance of spatial planning becomes particularly prominent at landscape, district or provincial levels, which are the ones at which most land use decisions are taken. However, in most post-colonial nations, governance takes place mainly at the national and village level, whereas intermediate organizational levels have little capacity to take action (Rudel and Meyfroidt, 2014). Over the last decade, one of the main concepts used in the discipline of land use science is the Integrated Landscape Approach, which refers to the implementation, with the continuous participation and cooperation of the different local stakeholders, of a series of actions over the landscape and the organizational system to ensure the economic and social sustainability of land use (Foli et al., 2018; Frost et al., 2006; Freeman et al., 2015; Minang et al., 2015; Reed et al., 2016). Assessment tools that help to anticipate and visualize the spatial-temporal distribution of biomass provision at local and regional scales can be helpful to inform land development strategies at these intermediate governance levels (Hauck et al., 2013) and achieve the ultimate objective of contributing to the organization of stakeholders into benefit-sharing biomass-based value webs (Deans et al., 2018).

The main information base of spatial planning policies is land use-land cover (LULC) maps, i.e. spatially-explicit representations of the land surface which classify it into categories of pieces of land with similar characteristics. Two criteria can be used to establish LULC categories/classes: the intrinsic characteristics of the land surface (i.e.: land cover or LC) or the way in which humans interact with it (i.e. land use or LU). In modern times, categorization of LULC maps is mainly done through remote sensing image analysis, assigning to each pixel a category defined by its spectral characteristics. The intrinsic characteristics of the land surface can be easily detected by these methods, and can be defined at low cost for large extensions of land. However, the value of the ecosystem services and goods provided by a piece of land is mostly determined by the ways in which humans interact with it, and in this case, remote sensing analyses can hardly provide accurate information. Hence, those maps that contain more accurate land use information are of considerably higher value because they will allow provision of more accurate quality values to each LULC category.

Common LULC map classifications are based on the intrinsic characteristics of land, whereas information on the way in which humans interact with it is very shallow. A common categorization is based on the differentiation between "agricultural lands" from "(semi-)natural vegetation", segregating the landscape into two rough levels of land use intensification. But such categorization provides very scarce information on land use, and does not provide any accurate information regarding land cover characteristics meaningful to ascertain the types and levels of products and ecosystem services provided by a piece of land. More precise categorizations may segregate the land into the different types of vegetation cover, such as "grass", "tree", "shrubland", etc. The category "cropland" is also common, referring to lands in which herbaceous crops are cultivated by humans for the production of consumable goods. Differentiating between vegetated lands that are intensively managed and those that are not can be done through the analysis of spectral indices because of their typically different patch shapes and phenological temporal dynamics. This is easier in the case of the differentiation between croplands and (semi-) natural grasslands. If intra-annual time series of images are available and the farming calendar is known, a relation between the different spectral indices in cropped and non-cropped lands can be established. However, the definition of different categories on lands covered with perennial vegetation is more expensive, and rarely available, due to their decades-long ontogenic cycle. Such a long ontogenic cycle also implies that the level of land use intensification in lands occupied by plantations of perennials is lower than the land use intensification of croplands (with the exception of fast-growing, highly-productive species) and therefore, the differentiation from their (semi-)natural counterpart through remote sensing analysis is more difficult to capture.

In savanna landscapes, where vegetation forms are dispersed and land cover patterns patchy, the classification of LULC units through remote sensing analyses is particularly difficult, especially in small-scale farming regions, where field management is heterogeneous across the landscape and the distribution of perennial vegetation is the result of the historical management of natural regeneration processes, rather than active planting. Land cover categorizations of African savannas are commonly based on the density of perennial vegetation. Common terms are (ordered from lower to higher density of perennial vegetation cover): grass savanna, shrub savanna, tree savanna, woodland savanna and forest. Such categories are also based on the structure and distribution of perennial vegetation, and are used in local/small landscape extent studies based on observations on the ground. However, they cannot be captured with medium resolution remote sensing data (which so far are the only products with a time-long archive available to analyze past landscape changes) because such products fail to identify single trees and isolated tree-clumps (Kuyah et al., 2016), and therefore cannot be used in spatially-explicit studies at scales relevant to land use planning, such as those of the administrative districts.

Moreover, the highly dynamic nature of land cover in savannas, accentuated by the human use of land, makes problematic the differentiation of vegetated land use classes. In West African savannas, these are usually classified in four broad categories: uncultivated savannas, parklands, fields without trees and fallows. Uncultivated savannas are the typical grazing fields for livestock herds and source of environmental products, and have been traditionally managed under some sort of common access arrangement. Parklands resemble the land cover characteristics of uncultivated savannas, with the main difference that crop cultivation is practiced. Most of the same environmental products that are provided by uncultivated savannas can also be collected from parklands, with the exception of some particular products which are available only in the former because of their richer biodiversity. Fields without trees are less common but their extension is increasing, driven particularly by the adoption of animal ploughing and tractors. Fields without trees and parklands can be abandoned for a varying period of time, becoming fallows. This land use category refers to land experiencing the replacement of crops by grass and tree populations through natural regeneration processes, at a pace and up to a level which will depend on the soil seed bank, the length of the fallow period and the local conditions introduced by soil type and disturbances (fires and grazing). Lands where the soil fertility has been exhausted remain bare during several years before they become covered by vegetation again, and intervention may be necessary to avoid further degradation through erosion. Built up lands constitute a fifth main category. The five land use categories are linked through transition zones, with uncultivated savanna being usually far away built up land, and fallows being more common and longer the closer the land is to uncultivated savanna (Gautier et al., 2006). The differentiation between natural open woodland and fallows is difficult to recognize through remotely-sensed images, and whenever such fallows are cultivated again, many of the trees are conserved on the field (Timberlake et al., 2010). The so far short temporal extent of the archive of high resolution remote sensing data implies that the classification of savanna landscapes on the basis of the mentioned categories still relies heavily on long and in-depth field observation campaigns, which are very costly.

Establishing LULC categories allows, in combination with other mapped socio-environmental factors, assignment of an assumed value of a certain quality of interest to each piece of land (Leh et al., 2013). This value can be assigned based on on-site observations, transferring data collected from other sites, meta-analysis, expert knowledge, official statistical data or model-based simulations. The categories of a landscape are assigned specific values describing a certain quality or the levels of services/goods that they are expected to provide. This is done following a tiered approach (van Ittersum et al., 2013; Vallet et al., 2016). This means that available information on observed values, either within the study region or elsewhere, of the qualities and LULCs of concern is surveyed, and the selection of values is assigned following a hierarchical prioritization, determined by the geographical closeness and the environmental similarities of the places where those values where observed in regard to the study region and the LULC under concern.

The search for appropriate indicators of landscape productive capacities is a matter of rich literature nowadays (Pandeya et al., 2016). In developing countries, available data regarding primary production is particularly scarce, such is the case of Ghana (Dietz et al., 2004; Quiñones et al., 2011) where the model region used in this study is located. In the case of agricultural data, substantial inaccuracies can result additionally from shortfalls inherent to the collection process (Reynolds et al., 2015). In the case of wood resources, national inventory programs have been largely restricted to the forest belt regions, whereas data on the dynamics of savanna vegetation is therefore non-existent and poorly described (PROFOR, 2011). Global assessments are frequently run with data that disregards many important factors of primary production efficiency, herein failing to accurately locate and define the regions where productivity increases are possible or to estimate with reliable accuracy the potential level of increase (Guilpart et al. 2017). They may also fail to define what best management practices for each location means, and they lack the relevant scope to suggest pathways of action to implement best management practices. Therein, inadequately informed assessments are likely to misguide policy, driving undesired social, ecological and economic outcomes (Dooley and Kartha, 2018; Luedeling et al., 2019).

Given the high uncertainties regarding the available data on LULC classifications and biomass provision levels, particularly on landscapes/regional scales relevant to decision making (Pandeya et al., 2016) and especially in savanna landscapes, an explicit description of the assumptions associated with definition of each LULC class and its associated values must provide as much information as possible, in order to better guide regional policy. A useful approach describes LULC classes and the assignment of them to quality values in consultation with local populations or experts (Fagerholm et al., 2012; Vrebos et al., 2015; Koo et al., 2018). However, the inherently subjective nature of this approach reduces its robustness to envisage future quality value changes that may result from changing management and ecosystem functions. Furthermore, such land-cover based approaches have neglected, so far, the ontogenic growth of perennial vegetation and, hence, the age-dependent values of their characteristics. Here, simulation of primary production dynamics can be a good approach to extrapolate LULC quality values both in space and time.

Once the LULC map and the assignment of LULC values has been completed, analysis of LULC change (LULCC) is performed in order to assess past or estimate future changes in a given variable of interest (Leh et al., 2013), e.g. biomass provision. This is done with LULCC models which simulate the responses of LULC transitions to a set of environmental factors (Verburg et al., 2002). These types of analyses allow exploration of the processes that have driven landscape change during the period for which LULC maps are available and, through such interpretations, formulate hypotheses on how it may evolve in the future. Such hypotheses are drawn in simulated LULC maps representing how the landscape might look at some point in time (past or future) for which LULC information is not available. These assumptions can be represented by changing the LULCC simulation input data. For example, by changing the modelled projected area of each land use class, restricting LULC transitions to locations that meet a certain condition (e.g. time that a pixel has not experienced change, or type and number of neighbors of certain LULC classes), or changing the weight of importance that each of the environmental variables (drivers) plays on the statistical analysis performed by the LULCC model (Moulds et al., 2015). In this regard, again, the short temporal extent of high resolution LULC map time-series limits the value of conventional LULCC simulation models to perform spatio-temporal explicit assessments of ecosystem functions and services.

1.2 Research needs

Regional planning relies highly on good quality spatial data. However, the production and actualization of topographic maps for rural areas in West Africa is rare. Most available spatial information is very recent, and has been produced through the classification of remote sensing images.

Regarding biomass density distribution, mapping exercises based on medium pixel size products (Gessner et al. 2014) can accurately describe broad spatial patterns, which can be useful, for example, to explore the impacts of changes in tree cover on the capacity of land systems to regulate regional climate (Mande et al., 2015; Ceperley et al., 2017). But these products cannot capture the dispersed trees of agricultural areas, a key element of rural savanna landscapes and their farming systems, and hence, can barely be used to account for the performance of primary economic sectors. Hence, when tackling food security and value chain development, medium resolution is too coarse to be effective enough to inform decision-making. In this context, a smaller pixel size is necessary to represent aboveground biomass distribution (Bouvet et al., 2018) and the crop species diversity of rural West African savannas (Forkuor, 2014; Narvaez-Vallejo, 2016).

Moreover, data regarding the LULC performance is very scarce. In the case of Ghana, agricultural statistics do not offer precise information that can be used directly in spatially-explicit assessments (Dietz et al., 2004; Quiñones et al., 2011). On-site studies are very useful to collect the necessary information to assess the value of current land uses (Leh et al., 2013; Koo et al., 2018). But land use planning processes imply an exercise of exploring pathways into the future. For this purpose, information on current land uses can be complemented with simulated data obtained from production models, allowing one to explore performance of land uses which are currently not practiced in a given study region of interest, as well as to replicate the analysis at low cost in other regions with similar environmental characteristics. Therefore, it is key that prospective land use scenarios explicitly describe both the management associated with an expected level of production as well as the necessary temporal scope to achieve it.

Spatially explicit scenarios are useful tools to enhance and smooth discussions in regional planning processes because they provide an easy visualization of data and, hence facilitate discussions dealing with a common information base. But so far, land use scenarios have usually been presented in a non-temporally-explicit way, i.e. representing a plausible future but without specifying the specific time in the future that they represent, or without simulating the temporal continuity of ecological processes. These scenario exercises have serious limitations to facilitate the operationalization of regional planning strategies. This is particularly the case of land use scenarios in the current debate of African land use, usually articulated around the carbon sequestration topic. Temporally ambiguous scenarios disregard the growth pace of perennial vegetation, which is at the nucleus of such debate. This study also focuses on filling that gap by linking both annual and perennial vegetation growth models to a simulated time series of LULC maps representing scenarios of prospective LULCC dynamics.

This kind of approach is necessary to disentangle the complexities associated with enhancing the value and sustainability of local biomass-based economies, and contribute to triggering the structural transformation of African national economies in order to improve livelihood opportunities and increase their resilience.

1.3 Hypothesis

The overarching concern of agricultural and forestry research in modern times is, as posed in the Sustainable Development Goals (SDGs), how to develop land use systems that contribute to enhance food security while minimizing the negative impacts that such activities can have on the environment, and that compromise their future capacity to ensure food security. According to meta-analysis of research observations conducted across the world, and to the SDGs, the contribution of ecosystems to human well-being, including food security, is enhanced by biodiversity. This is the central hypothesis motivating this study.

Supply-demand studies based on trend analyses and projections show that, assuming the maintenance of global food trade patterns, increases in cereal production are urgently needed in tropical Africa. In light of these studies, it is not uncommon that scientists and policy-makers advocate for a wider adoption of crops with high yield potential (such as maize, rice and soybean) (Dao et al., 2021). Such cropping systems' transformation pathway would be optimal for balancing the trade-offs between closing the production-demand gap and minimizing tree cover loss. The adoption of high-yielding food crop species would minimize the conversion of areas covered by trees into croplands, hence facilitating the reproduction of the ecological conditions necessary on the landscape scale to ensure agricultural production in the future, thanks to the regulating functions of trees on the reproduction of water and nutrient cycles. However, such conclusions are drawn while disregarding the wide variety of biomass-based products necessary for the functioning of rural economies (i.e. fuel, feed and raw materials from non-edible biomass), as well as the socio-economic factors, from local to global scales, that drive the adoption of high-yielding crops. They also disregard the resilience of agro-ecosystems, which is linked to agro-biodiversity and is a key factor of food security. Policies aimed at expanding the area cultivated with high-yielding crop species and varieties, and the application of the material inputs required for the realization of the expected added protein yields, have been promoted in tropical Africa since a long time ago; more recently as well in the Sudanian savanna belt of West Africa, however the increase of agricultural output experienced over recent decades has been still slower than the increase of demand.

This study aims to make the best use of available LULC and plant growth data and models to explore the hypothesis that a reduction in biodiversity would reduce landscapes' capacity to provide the goods demanded by society (particularly by those in charge of producing biomass products). Given the scant information that the available spatially-explicit data can provide in terms of biodiversity, it has been addressed in a simplified manner by analyzing two factors that are considered to have a positive effect on ecosystem functioning. On one hand, the renewability of biomass production rates, which highly depends on the maintenance of the spatial distribution pattern of biomass in savanna landscapes, characterized by wooded open spaces covered by grasses (Pringle et al. 2010); and on the other hand, the maintenance of diverse cropping systems (Tamburini et al. 2020), analyzed by comparing the productivity of the main food grain species cultivated in the study region.

1.4 Aim

The aim of this study is to conduct a prospective and explorative scenario assessment of the biomass products (food, feed and fuel) provision dynamics in Sudanian savanna regions, complemented with an estimation on how such provision dynamics can improve future demand. It has been conducted within the framework of the BiomassWeb project, focused on enhancing the value of biomass-based value chains in Sub-Saharan Africa. It has also been conducted in close collaboration with the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL).

The assessment of regional baseline potentials to produce different types of biomass, as well their expected value (either nutritional, energetic or monetary), and their plausible future dynamics, can highly contribute to increase the value of the economy within the biomass-producing regions while ensuring the sustainability of the ecosystem capacities to provide biomass. A large percentage of the biomass yielded by land systems in Africa is lost due to insufficient storage capacities, and most of the production exported out of the producing regions are raw products that generate low income. The implementation within producing regions of the different processes associated with the generation of value of biomass-based products, such as storage, processing and marketing, has the potential to both increase food and other biomass availability, and wealth through higher income. Therefore, improving the understanding of the implications of land use change on regional biomass production potentials can help to improve local livelihoods by developing more robust and diversified biomass-based economies.

However, the development of high-value, benefit-sharing, biomass-based economic clusters requires investments which face high risks because the expected production levels on the medium- and long-term are highly uncertain due to data scarcity and erratic yields. Thus, through land use change and management simulation, this study aims at assessing the plausible trends of biomass provision and their potential to satisfy nutritional, fuel and feed demand under different land use expansion and intensification scenarios. Many modeling and simulation studies have been conducted to make a medium- or long-term prospect of biomass provision, but none yet has taken into consideration the variability of perennial vegetation biomass provision according to age-linked LULCC simulations.

Decision-making processes related to land use planning and the development of biomass-based clusters take place mostly on the meso-scale, i.e.: between the size of a district up to a province/region. Therefore, to test the applicability of the methodology, a model region has been selected that covers two districts in northern Ghana, Bolgatanga Municipal and Bongo which are considered an appropriate unit of spatial analysis for being part of the same historical region, sharing very homogeneous cultural characteristics and the same urban market.

The set of drivers of land use change and biomass production was simplified due to data scarcity and the derived challenges of modeling them on finer scales, as well as due to limitations of the computational simulation and storage capacity available to conduct this study. Therefore, the aim of these scenarios was to explore alternative land use and management pathways, whereas predicting the impact of climate change on vegetation distribution and biomass growth was not addressed. This decision was based on widely published evidence suggesting that the main drivers of landscape change in West African savannas are human activities.

1.4.1 Research objectives

The specific objectives of this work are:

- Collect extensive information on the land uses dominant in the model region, so that their assumed intrinsic characteristics, management and inputs levels used for data simulation purposes is explicitly-described.
- Simulate dynamic LULCC scenarios through the generation of time-series of LULC maps.
- Simulate the plausible biomass-products yields of each of the dominant land use classes, including both annual crops (grain, leaves and stems) and perennial

vegetation (wood) and, in the case of the latter, accounting for their longer ontogenic development.
- Link simulated biomass growth and land use change data to explore, in a temporally-explicit way, the likely dynamics of biomass provision, its potential benefits and the change of their balance in relation to demands, under different population growth projections, LULC spatial pattern, LULC intensification and biomass-use technology pathways.

1.4.2 Research questions

- Given the available LULC data and crop and tree/forest growth models relevant to the study region, which are the key LULC classes whose productivity can be integrated in a spatially-explicit regional assessment?
- Which are the dominant narratives of LULCC in West African savannas and how can they be simulated in a spatially-explicit way?
- What are the potential yield levels of the different biomass compartments (grain, leaf, stem) provided by each LULC class under plausible management intensification pathways?
- Which are the plausible trends of the regional feed, fuel and food provision under different land use change and intensification scenarios?
- Which are the plausible trends of the number of people that can satisfy their nutritional and fuel demands within the region by consuming local biomass products under different population growth, LULC and technological scenarios?

1.5 Dissertation outline

In this study, the yields of the main types of plant-based biomass products produced in rural regions of the Sudanian savanna belt of West Africa are spatially-explicit simulated on a field-scale. This production data is then allocated on a pixel-base to a baseline LULC map and those of three time-series of LULC maps that represent three alternative LULCC scenarios. The balance between potential regional biomass production and demand has been assessed in a temporally explicit manner by comparing it with two population growth projections and, in the case of fuel demand, also including the impact of two different pathways of biomass-to-energy conversion technologies.

Biomass provision has been simulated at the field-scale, and used in a land-cover based assessment to estimate regional changes in the provision of biomass under different LULC and management change scenarios on a five-year time step basis and across a forty-year time scope. In the case of annual crops, data have been simulated with a process-based model. To ensure that the comparative assessment accounts for both the inputs and outputs of agricultural production, yields are simulated under equivalent levels of management intensification. Woody biomass growth has been simulated with an empirical model fed with data selected after extensive literature review. A visual scheme of the workflow is presented in Figure 1.

Input model data has been selected based on applying the tiered approach to available published data. Three projections of population growth have been also included to estimate the future food demand.

Chapter 2 presents the ecological and social aspects of the study region, serving as a starting point to conduct the tiered approach of input data selection. It also presents a brief introduction of its socio-economic development in relation to its broader geographical context over the last one hundred years, which would be key as a starting point to analyze developmental narratives, design and discuss future land use scenarios. Chapter 3 describes the different tools and methodologies used to simulate LULC change (GISCAME), biomass provision from annual (APSIM) and perennial (empirical modeling) LULC classes, their integration and the estimation of projected demand. Chapter 4 presents the simulation results and, as a method of validation and uncertainty analysis, compares them to observations reported in published literature. Chapter 5 discusses methodological constraints in the approach and changes that could be introduced to enhance its capacity to simulate spatial-temporal biomass yields. Finally, Chapter 6 briefly sums up the previous ones and reflects upon the contribution of this research to support policy-making in the broader context of developmental goals.

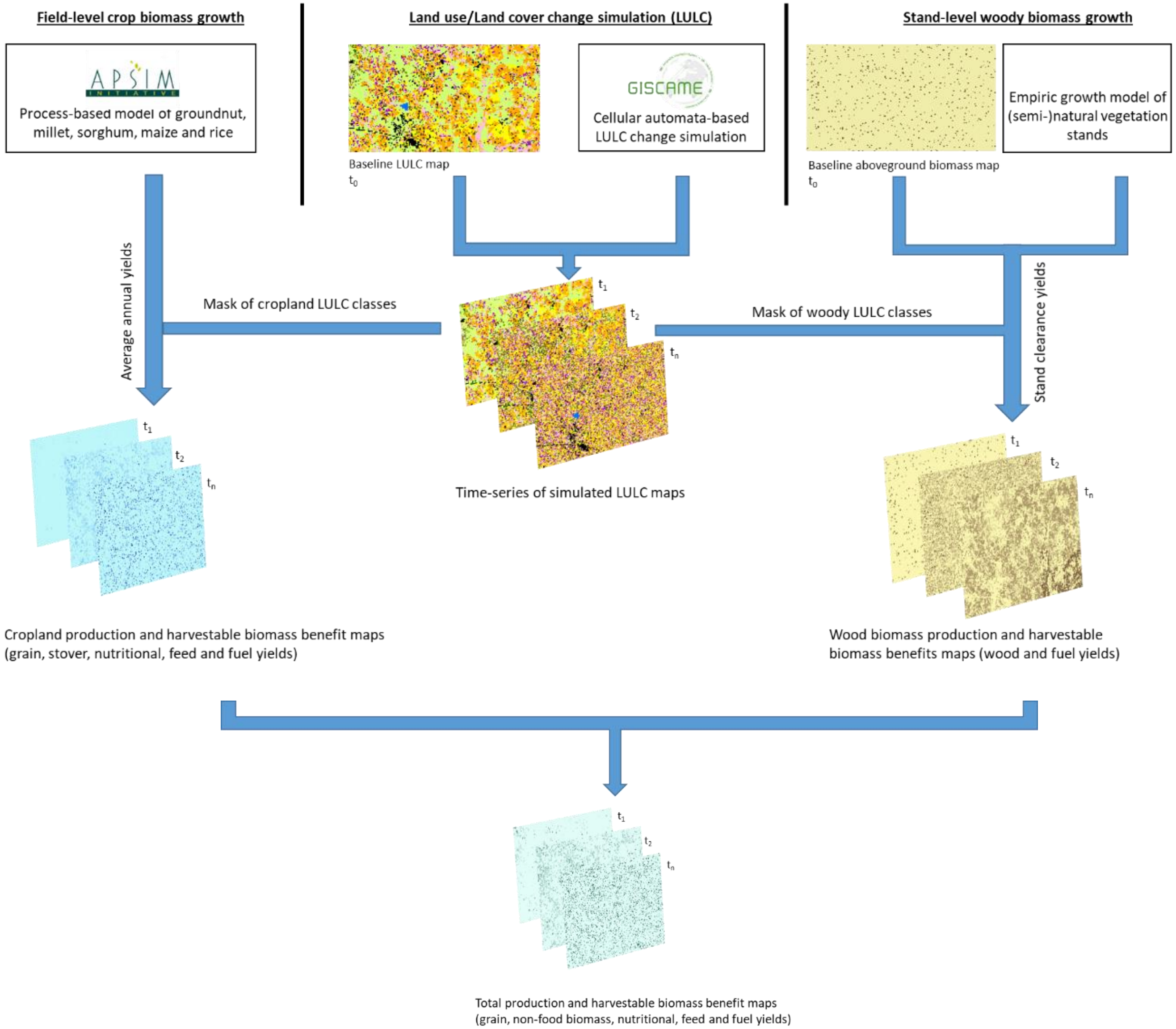


Figure 1.1Workflow scheme

2 MODEL REGION

2.1 Location and its context

This research explores an approach to inform regional planning, especially at landscape level, addressing food security in the face of the global bioenergy transition. The proposed methodology will be illustrated in a model region, located in northern Ghana in the border with Burkina Faso. The study region comprises two neighboring districts: Bolgatanga Municipal and Bongo (Figure 2.1), covering a total area of 1,127 km².

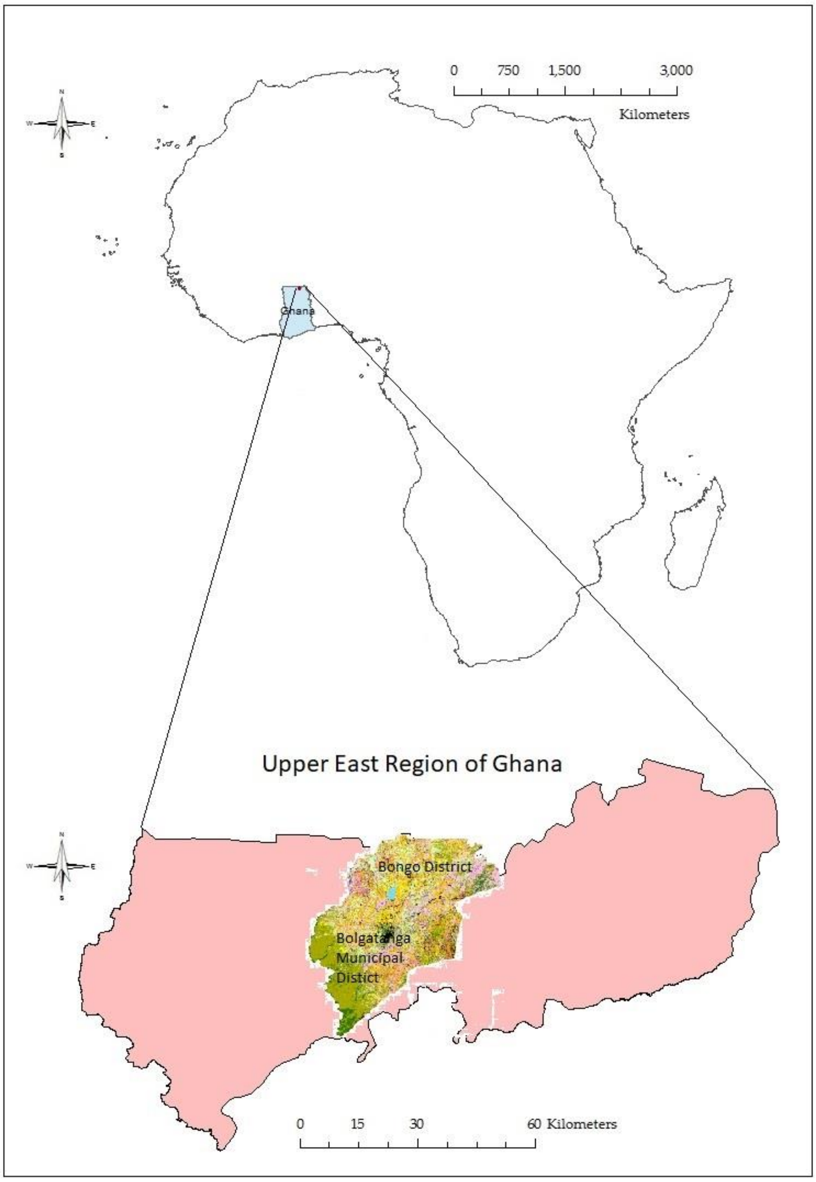


Figure 2.1Location of the study region.

According to the Census of the year 2010, the district of Bolgatanga Municipal had a population of 131,550 inhabitants, and the district of Bongo 84,545, summing up in total 216,095 inhabitants. The population density is high for a predominantly rural region (178 inhabitants km^{-2} in 2010). The town of Bolgatanga (inhabited by roughly more than 65,000 persons), is the administrative capital of the Upper East Region of Ghana (UER) (GSS, 2014a 2014b). It is also an important node of the main road communicating Ghana with Ouagadougou, the capital of Burkina Faso and one of the largest market centers within the savanna zone of Ghana. National development plans consider that the construction of new agro-industries and storage facilities in the peri-urban area of Bolgatanga is key to develop a geographic production cluster expanding all over the UER and which might include great part of the neighboring Mamprusi districts (Abugre, 2016).

In order to advance on an understanding of the production systems of the study region, it is important to consider its geographical setting: in the northern border of a coastal West African country, within the South Sudanian savanna belt. In the coastal countries of West Africa, such as Ghana, the study of these ecosystems had been largely neglected at the expense of their more forested regions in the South, in spite that bout two thirds of the total area of Ghana are located within the typical bioclimatic belt of the African savannas (PROFOR, 2011). The food security of farming households, which forms the majority of the population, is highly dependent on weather conditions (Ekpe et al., 2014; Jonathan et al., 2020), and it is common that, in many areas, over half of the households experience food shortages, at varying degrees, especially during the period that spans between the beginning of the cropping season until the harvest (Abdoulaye et al., 2012; Kleemann et al., 2017b).

The region lies within the mid-Volta basin, and is crossed in a North-to-South direction by four hydrological catchments whose waters join the main collector, the White Volta river, right South outside the boundaries of the study region. Two of the catchments span almost entirely within the study region: Yaragatanga, whose head-waters are collected slightly beyond the boundary with Burkina Faso and whose runoff is interrupted by the Vea dam; and Agrumatue, which crosses the town of Bolgatanga. These two catchments are almost completely used for agriculture, with the exception of their uncultivated downstream sections. The Vea reservoir serves a medium-scale irrigation scheme and provides the main processing facility of drinking water in the study districts (Sekyi-Annan et al., 2018a). The western of part of the study region falls within the Tankwidi river basin, shared with the neighboring district of Kassena Nankana. The distribution of land use here is the same as in Yaragatanga and Agrumatue. The downstream sections of these three catchments are covered by the uncultivated savanna and woodlands of the Tankwidi Forest Reserve. The northeastern part of the study region, covered mostly by uncultivated savanna, extends over the right bank of the Nazinon watershed, also known as Red Volta. This catchment is one of the main biodiversity corridors of the Volta basin.

Before the advent of the modern state, the lands of the mid-Volta basin north of the Gambaga scarpment -between the territories controlled by the dynasties of the Mamprusi and Dagomba, to the South, and the Mossi to the North-, were settled by societies without a centralizing regional authority. This region suffered frequent raids and witnessed civil wars during the second half of the 19th century. It started to be military occupied by the British colonial system by the end of the 19th century, who integrated it into the Protectorate of the Northern Territories. By the second decade of the 20th century, European laws administratively divided it between the Upper Volta Administration of France (nowadays known as Burkina Faso) and the British Gold Coast (nowadays known as Ghana). Local revolts were common during this period, against which the colonial administration frequently retaliated by using fire to destroy croplands or settlements. A bridge crossing the White Volta was constructed in 1937 in Pwalugu (close to the Southern border of the study region) as part of the development of the Great Northern Road, driving the growth of Bolgatanga as the main town of the northeastern part of the Northern Territories. However, the colonial administration (which lasted until 1957) had no real economic interest in the region, and it administered it with the sole purpose of territorial control. During these one hundred years between the mid-19th and mid-20th centuries, the population was subject to external control of its labor, including displacement (Azaare, 2017; Rouch, 1990).

According to Plange (1979, 1984), forced labor was indeed the main mechanism of the colonial state to dominate the Northern Territories, which in turn favored the occupation of local stores by expatriate capital and foreign entrepreneurs. Thereby, relevant participation in the regional economy was *de facto* denied to locals. Human capital available for farming was undermined because the most productive segments of the population were displaced to work in the plantations and mines of the South, leaving the farms in the hands of elders and children. Therefore, returns from farming activities diminished and cash was needed to compliment them. This was provided by the family members working in the plantations and mines. But mine managers and District Commissioners thought that workers were more likely to desert if they were able to collect a good amount of savings, and therefore kept wages low. Due to their poor working conditions, when migrant workers returned home their health was too deteriorated to add any substantial value to the household farm economy. Remittances were seldom invested in production because families had lost their most active members, the ones who could generate wealth out of the cash inflow. Hence, the increase in local expenditure resulted in an increase of imports, rather than expansion of local production. Frequently, the pressure for cash was so high that pre-payments of part of the migrants' earnings were remitted to the families, bonding the family to supply labor to the plantations and mines. The general effect was the delay of any process of social differentiation and the reduction of the size of internal markets. This process was accentuated by the lack of a clear economic policy by the Colonial Administration, which would eventually withdraw from the trade of local products such as shea butter, silk cotton, hides and other crafts. Hence, the economic structure of Northern Ghana came to be characterized by the export of human labor and the import of manufactured goods. Meanwhile, farm production continued to be organized around pre-capitalist relations of production. Colonial education trained youths for jobs that were not available in the region, incentivizing them to move to the cities of the South, where they were not formed enough to find highly-remunerated jobs. Many of them were able to earn savings and return home. But their skills were not suited to increase productivity, whereas their "modern" lifestyle attracted others to pursue the same path, gradually creating in the North an ideology of migration which has maintained, without the use of force, the characteristic North-to-South migration flows (Plange, 1979; Plange, 1984, Wardell and Fold, 2013).

During the last 30 years, urbanization and the average national income per capita have increased continuously in Ghana. The most important sectors of the Ghanaian economy are basically still the same as those of the Gold Coast Colony: the exports of raw products, dominated by cocoa and gold, followed by other high-value cash crops such as palm oil, coffee, rubber, coconut, and increasingly cassava, all of them produced in the agro-ecological zones of the South, with more forest cover. The production levels of many of these crops has more than doubled during the 21st century, driven by plantation-based businesses well connected to international trade networks. With the exception of the above-mentioned sectors, agricultural productivity has not significantly increased, pushing many people from farming households out of agriculture. However, most workers get involved in low-productivity service jobs in the informal economy and the country is barely industrialized. Meanwhile the production of grain per capita has for many decades been declining. Hence, the need for imported food is increasing and the state remains weak (MoFA, 2011; Kolavalli et al., 2012; Diao et al., 2019a). In Ghana, the production of savanna crops that are typically given priority in the export strategies of other

West African countries, has either declined over recent decades (cotton), is stagnant (shea), or outcompeted by the production of neighboring countries because it is still marginal (sesame) or incipient (mango). Hence, the most widely cultivated crops in the study region (cereals and legumes) have low value under the current commercial system (MoFA, 2014). Global value chains are incipiently moving into the interior savannas of Ghana, changing the conditions of economic production (Ouma et al., 2013; Wardell and Fold, 2013; Elias and Arora-Jonsson, 2017) and, in some cases, involving the control of large extensions of land (Ayelazuno, 2019).

General poverty trends trends over the last three decades in the study region are a matter of debate. Whereas some argue that poverty has fallen proportionally more in Northern than in Southern Ghana, and particularly in the districts without cities (Diao et al., 2019b), others argue that the progress in poverty reduction in the North has been minimal (Abane, 2015; Schraven and Rademacher-Schulz, 2015). There is consensus, however, that the sustainability of the economic system is under risk due to land degradation. For example, carbon losses in the UER have been considerably high compared to its neighboring regions (Brandt et al., 2018b).

2.2 Climate

The region is located at the core of the West African savanna belt, affected by a climate whose main features are the warm temperatures throughout the year and the differentiation between a hotter dry season and a milder rainy season. The length of the latter spans over four to six months, with the period from July to September at the core of it. Total annual rainfall is highly variable and its distribution throughout the rainy season irregular. The “normal” annual rainfall over the first decade of the 21st century ranged 900-1,000 mm (Bliefernicht et al., 2018), but it can range between under 700 mm and 1,200 mm. Over the last century, the climate over Northern Ghana has tended to become warmer and drier (Abungba et al., 2020).

The erratic rainfall pattern, the shifts of cropping seasons, unpredictable drought periods and frequent flooding, imply that decisions-making regarding the farming calendar are taken under a high degree of uncertainty, and are seen by local populations as strong limitations to making agricultural production profitable (Dumenu and Obeng, 2016; Adole et al., 2018). During recent decades, the onset of the rainy season has tended to move from April to end-of-May or even June. Drought spells are common and limit vegetative growth. These are particularly frequent in June, leading to crop failure, which drives many farmers to plant the start of their cropping season by the end of June or July. The end of the rainy has also shifted from October to November, and it tends to occur more abruptly. Drought spells during the second half of the rainy season are also common, although less frequent. However, this changing characteristic of the end-of-the-season has a higher impact on grain yield, leading to harvest failure (Abdul-Rahaman and Owusu-Sekyere, 2017; Adole et al. 2018; Bamler, 2015; Danso et al., 2018a; Laube, 2007; Laux et al. 2008; Kasei et al., 2010). Although the length of the rainy seasons has in general shortened in the study region, significantly reducing the operationally safe crop-growing period (Dumenu and Obeng, 2016), this observation is not extrapolable to the entire central belt of the West African Sudanian savannas, and some areas have been experiencing longer rainy seasons (Yegbemey et al., 2014).

2.3 Orography and soil

The region extends over a highly weathered landscape over acidic metamorphic bedrock, namely granites and sandstone. The topography is flat: most slopes are lower than 3% and they rarely exceed 5%.

Most of the region is covered by leached ferruginous soils, mostly of loamy sand texture, of the lixisols and luvisols subdivisions (Da Costa et al., 2015; Bliefernicht et al., 2018). Soil depth is rather shallow and root density below the 30-40 cm depth is very sparse. Another big share of the region is occupied by lithosols (also known as lithic leptosols). These are raw mineral soils usually originated from sandstone, and whose root activity depth is even lower than in the leached ferruginous soils. Above the parent rock, laterites may form, in many cases close to the surface, hampering the penetration of roots and inhibiting plant growth, especially trees. These lateritic crusts facilitate the formation of groundwater deposits (Duadze, 2004). Lateritic crusts are particularly common in the plateaus, being extremely dry during the dry season and often waterlogged during the rainy season (Nichol, 1989; Devineau, 1999; Leroux et al., 2017; Ouedraogo et al., 2019). About 40% of the area of Bongo District, is covered by this type of soil, significantly contributing to the rocky character of the landscape (DPCU Bongo, 2010). In the valley-bottoms develop fluvio-lacustrine deposits, hydromorphic soils of the subclasses gleysol and cambisol (Table 2.1 and Figure 2.2).

Table 2.1 Soil types of the study region. Source: Da Costa et al., 2015

Description	Subdivisions	Other synonyms
Leached ferruginous soils developed from granite or sandstone (subdivision based on clay leaching)	Lixisols Luvisols	

	Plinthosols	
Raw mineral soils, usually sandstone	Lithosols	Lithic leptosols
Developed hydromorphic soils, can also be developed from fluvio-lacustrine deposits	Gleysols Cambisols	Fluvisols

All of the soils of the study region are moderately acidic (Kranjac-Berisavljevic et al., 1999), and usually distrophic, meaning that their cation content is low. These characteristics impose limitations to vegetation growth, which can only be counteracted with erosion control measures and (micro)-nutrient-balanced fertilizer application (Montgomery, 1988).

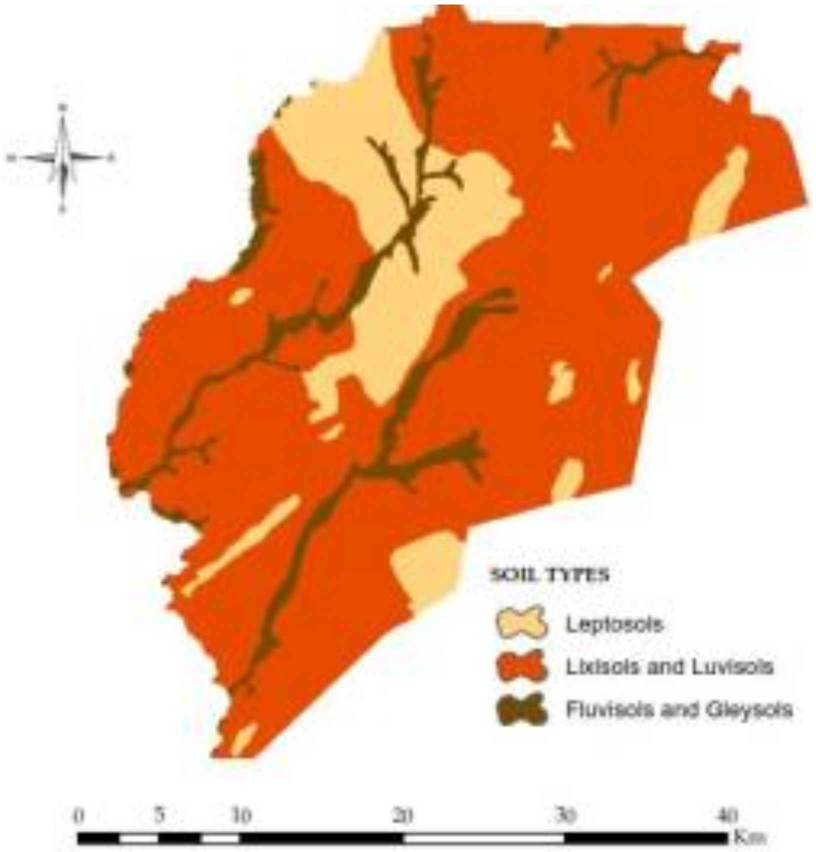


Figure 2.2 Soil types map. Source: Author based on CSIR data, WASCAL database.

2.4 Vegetation and land use

The study region lies in the central core of the West African savannas and it is very unlikely to experience biome shifts, at least up to the mid-21st century (Heubes et al., 2011). Many sources classify it within the bioclimatic sub-division of the Guinean savanna, due to the average annual rainfall. However, the vegetation pattern is typical of the Sudanian sub-division. The vast majority of the area is covered by cropping fields (Gessner et al., 2015; Hackman et al., 2017), which contribute to most of the regional Gross Primary Production (GPP) (Machwitz et al., 2015). Only the northeastern (Red Volta) and southern (Tankwidi) areas contain extensive areas of uncultivated shrub and tree savanna. These are part of the corridor of the Forest Reserve corridor of the White and Red Volta. They had been occupied until they were gazetted between 1939 and 1955, when tens of thousands of people were reallocated by force with the purpose of basin headwaters protection, as the colonial administration was afraid of an increased risk of the absence of forest formations. Since then, cultivation in these areas is illegal. These protected areas exclude cultivation in 20% of the area of the study region, although it is informally permitted to some extent (Wardell et al., 2003; Wardell and Lund, 2006). Tree cover in the majority of these protected areas lies below 10%, with higher densities mostly concentrated along riverbanks or around water bodies (Owusu, 2009; Nindel, 2017). Indeed, forests, in the strict meaning of their ecological definition, are absent. Most dense formations of perennial vegetation are shrublands, thickets and open woodlands with an average tree height of 5 meters. They appear only in areas not suitable for profitable agricultural production, such as hills, and in Forest Reserves, particularly along their riparian corridors (PROFOR, 2011; Kleemann et al., 2017a).The latter, although subjected to conservation regulations, have experienced a significant decrease in tree cover over the last decades (Emmanuel et al., 2015; Brandt et al., 2018a).

Very little of the vegetation exists in its original form. Vegetation structure, both in agricultural and in non-agricultural lands, is characterized by the coexistence of grasses and trees. The growing period of grasses usually starts in June, whereas leafing of woody vegetation begins before the start of the rainy season, extending the growing season of woody plants up to 9-10 months, starting in February or March (Adole et al., 2018). Trees are dispersed over the landscape, either isolated or clumped, in a somewhat random pattern. Root activity beyond a depth of 40 cm is very low (Diao, 1995; Tomlinson et al., 1998): herbaceous vegetation typically reaches up to 35 cm depth, competing with the roots of woody species' seedlings mainly in the 25-35 cm depth layer (Kambatuku et al., 2013). The "natural" spatial pattern of woody vegetation density follows a toposequence, increasing towards the lower valley positions (Ouedraogo et al., 2019). This spatial pattern, largely driven by the distribution of soil water availability across the landscape, has being altered over recent decades due to the occupation of riverbanks with cropping fields, facilitated by the eradication of disease vectors (Wardell,

2005) and causing the deforestation of large tracts of riparian forests. Woodland area by the year 1990 was 32 km2 in the Bongo District and 688 km2 in the Bolgatanga District. Extensive reduction of these woodland areas occurred in Bolgatanga from 1990 to 2000 led to 181 km^2 (74% tree cover reduction in ten years), in a magnitude slightly higher than the average of the Ghanaian part of the White Volta basin (Codjoe, 2004; Laube et al., 2012).

Nowadays, the only difference in the spatial vegetation pattern between agricultural areas and uncultivated savannas is the recruitment rates of woody vegetation into juvenile and adult stages, and their biodiversity, much lower in agricultural areas than in less disturbed areas. Most of the agricultural fields contain a varying number of relatively regularly dispersed, usually big-sized, trees. This landscape is known as parkland. In the study region, parkland trees are widely scattered in densities ranging from 6 to 10 trees ha^{-1}, or in certain areas, particularly in the areas surrounding settlements, increasing up to 20 trees ha^{-1} (Kadyampakeni et al., 2017). On temporarily cultivated fields, further from the village, woody plant distribution is less regular and species diversity is more variable, due to more differentiated land use histories (Gautier et al., 2006). The few indigenous tree species remaining in agricultural lands are mainly those of economic value, in particular: *Vitellaria paradoxa, Adansonia digitata, Parkia biglobosa* and different species of acacia. *Balanites aegyptiaca* trees are common in more unfertile fields and *Borassus aethiopum* along the irrigated ones. Main exotic tree species are *Azadirachta indica, Tectona grandis, Mangifera indica* and *Tamarindus indica* (DPCU Bongo, 2010; Biyogue and Dioggban, 2015), which started to be introduced in the region after the second decade of the 20th century. Eucalypt plantations have also been established since the second half of the century, but to a lower extent than in other Sudanian savanna regions. In the Forest Reserves, non-indigenous tall tree species, such as kapok, mahogany and teak, remain since their introduction in the 1940-1950s, when the reserves were gazetted (Boateng, 2017).

The few and small open canopy forest stands are dominated by planted *Anogeissus leiocarpa* and *Tectona grandis*, although they also host a range of another species that regenerate naturally. Here, the vegetation consists of widely spaced short deciduous trees (*Combretum* sp., *Diospyros mespiliformis, Annogeisus leiocarpa, Lannea* sp., *Piliostigma thonnnigi, Ximenia americana, Sterculia setigera* and *Sclerocarya birrea* as the most common) and a ground flora composed of grasses (*Andropogon* spp., *Brachiaria* spp. and *Spermacoce* spp.) which get burnt by fires or scorched by the sun during the dry season. Maximum grass height in protected areas is around 2.5 meters. Where grazing pressure is mild it reaches only about 1 meter, and where grazing pressure is severe it gets reduced to 10 cm (Biyogue and Dioggban, 2015; Bliefernicht et al., 2018). In riparian areas, common species are *Mitragyna inermis, Anogeissus leiocarpa*, *Vitex doniana* and *Pterocarpus erinaceus*. Farmed riparian lands contain a high abundance of *Ficus sycomorus* and *Acacia sieberiana.* Species typical of Sudano-Guinean dense formations, such as *Daniellia oliveri, Burkea africana* and *Isoberlinia doka*, are absent in the study region. (Emmanuel et al., 2015).

The only landscape units devoid of trees are in most cases former cultivated lands that have been abandoned and degraded due to timber extraction, overgrazing and lack of protection against fires (Takimoto, 2007). These situations are particularly common in plateaus covered with shallow soils, and whose productivity is particularly prone to exhaustion. However, where the pressure of environmental disturbances is not severe, these habitats are covered by shrubby thickets of small thorny trees such as *Balanites aegyptiaca*, or a lightly stocked savanna dominated in its top height by acacia species (Devineau, 1999; Biyogue and Dioggban, 2015; Qasim et al., 2016; Leroux et al., 2017).

From the human occupation point of view, it is a very densely populated area with a dispersed settlement pattern articulated in compound dwellings separated from each other by farmlands provisioning food to each of them and connected by paths crossing those farmlands. This form of settlement forms a rather continuous network of human settlement and land use. The penetration of centralized forms of organization typical of the colonial and national states sparkled the development of some nuclear towns, but the historical settlement pattern of the UER has remained largely the same (Cristofaro, 2020; Gould, 1960). This articulation of the territory and the absence in the past of a centralized power controlling food surpluses (i.e.: the organization of production in largely self-sufficient units) might explain why the UER already had the highest population density of Northern Ghana by the time that the first European explorers arrived to the region. Nowadays, the town of Bolgatanga is still the only urban center in the region. Its population is difficult to estimate with precision because it is growing fast and the limits of the “urban” are diffuse and expanding, but the census of 2010 estimates it on more than 60,000 inhabitants. The town of Bongo, as seat of a district administration, has also many urban features but, with barely more than 5,000 inhabitants, its economy is much less diversified. The other nucleus villages are Sumbrungu (West), in the main road towards Ouagadougou; Namoo, Lungu and Zoko (NW sector); Zuarungu and Kumbosco (East), in the primary road to Bawku; and Soe (NE), neighboring the Red Volta Reserve. The electrification network is not developed much beyond these nucleus towns. Indeed, the town of Sumbrungu was only electrified after 2000, and the extension of infrastructure over its neighboring settlements towards the North was still ongoing by 2014, when a field visit was conducted.

Millet, sorghum, rice and groundnut are the most widely cultivated crops. The latter two are also important cash crops (of which the UER has been historically the major producer in the country), whereas a large share of the sorghum production is destined to be marketed through its local processing of brewed beverage. Groundnut was introduced, through transatlantic trade, many centuries ago, whereas the cultivation of rice spread fast during the decade of the 1990s (Dessalegn, 2005), and has stabilized since the beginning of the 21st century due to the lack of more fields suitable for the profitable cultivation of lowland rice. Yields have declined over the last decade, affecting the food security status of rice producing households. However, the UER is still the main rice-producing region of Ghana (Zakaria et al., 2020). Rice shares the irrigated fields with vegetables, mainly tomato, which is another major cash crop of which the UER is a net exporter (even to near markets such as Tamale and Wa). Maize is another main cash crop, whose expansion became significant only after the turn of the century, and it has started to be cultivated also as a staple by many households practicing intensive farming.

The spatial pattern of crop species distribution is very heterogeneous because crop diversification is widely practiced by farmers to deal with the uncertainties of the growing season, derived from the erratic rainfall pattern (Dumenu and Obeng, 2016). It is firstly driven by the demand of the farming compound, allocating the fields surrounding it to the cultivation of staple crops, namely millet and sorghum, as well as vegetables. Planting of field boundaries is also common in compound fields, mainly with smaller cash crops that complement the farm economy, such as legumes, sesame and tubers. The major tuber crops of the region are Frafra potato and sweet potato, although the former is becoming very marginal, whereas the latter is an important cash crop, of which the region is the main producer within Ghana and also across the whole interior of West Africa (Gould, 1960; Blench, 1999; ODI and CEPA, 2005; MacCarthy et al., 2009; Noma, 2012; Sugri et al., 2013; Sugri et al., 2017). The main tuber crops of West Africa, namely yam and cassava, are absent from the study region. These tubers require deep fertile soil, which usually requires rotational perennial fallows, and may explain why they are absent in the densely populated study region. The major cash crops such as groundnuts, rice and maize, are more common in fields located further from the homestead.

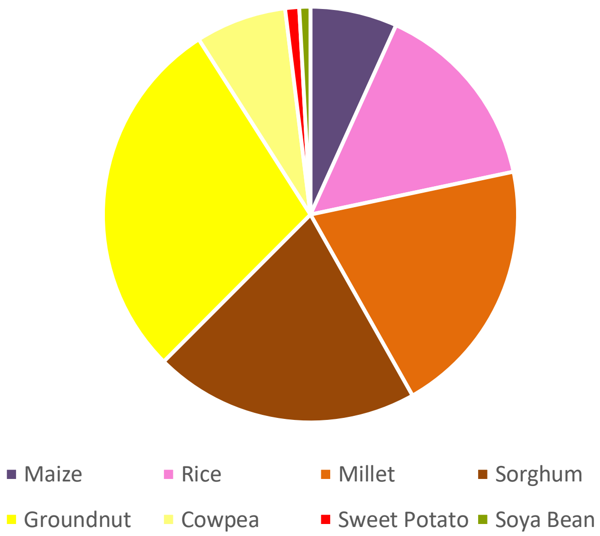


Figure 2.3 Shares of harvested cropland area by crop specie in the Bolgatanga Municipal and Bongo districts. Source: MoFA (unpublished).

However, this simplistic scheme does not properly describe the regional agricultural system, which is characterized also by the common practice of mixed-cropping and the rotation of millet and sorghum. Fields which are not supplied with enough fertilizer inputs are commonly mixed-cropped, or rotated, with legume crops. Fields in locations with better access to markets, such as those around towns and along major transport roads, are cultivated with crops of high yield potential, mainly maize. Moreover, in West African savannas, relevant soil fertility gradients usually exist over community territories. As a way to share risk, traditional community land use allocation has solved these intrinsic fertility spatial differences by dispersion of the fields which are managed by common households, resulting in relatively uniform yields across households. A characteristic spatial pattern of semi-arid African agro-ecologies is the inverse relation between soil fertility and distance to the compound, because the intensity of nutrient inputs is largely influenced by this relation (Kpongor, 2007; Akponikpé, 2008). However, this pattern is becoming less evident recently (Turner and Hiernaux, 2015), and does not necessarily have to be relevant to describe major spatial differences of soil fertility in certain contexts. For example, it has been found that uplands in the UER, far away from the compounds, may have richer soil than the nearest homestead farms (Kadyampakeni et al., 2017). Additionally, the wealth of farming households may also introduce relevant spatial differences in the distribution of soil fertility (Tittonell et al., 2010). Finally, the gradient of soil water availability across the landscape acts as a background driver of cropping system spatial distribution, imposing restrictions on the allocation of crop species. The shallow and dry soils occupying the top landscape positions tend to be cropped with groundnuts, and towards the valley-bottom crop allocation tends to follow the water requirements of different crops, with millet and sorghum occupying the middle slopes, followed by maize and finally, rice preferentially occupying the valley bottoms and other areas covered by soils with high soil moisture-retention capacity (Gould, 1960; Diallo et al., 2016).

Annual crops are often mix-cropped at the field-scale, usually sown in succession (one crop is sown first, and the second two to four weeks later). This practice buffers against risks of total crop failure, and is an essential farming strategy in a context of high meteorological variability and limited access to credit or reliable off-farm income opportunities. In savanna agro-ecologies, this is particularly the case of cereal associations (millet and sorghum and, to a lesser extent maize), sometimes also including annual legumes, mainly groundnut and cowpea. In regions where the agricultural production is prone to suffer water stress, the dominant crop is millet, and it is usually planted first. Early maturing millet varieties are common in these agro-ecologies, fulfilling the requirements to follow this strategy. Whereas millet, sorghum and cowpea are virtually always part of field-scale crop mixtures, rice, maize and groundnut are more commonly sown as monocrops. Groundnut is also sown sometimes in a double-up legume intercrop with Bambara groundnuts. This core crop set is complemented with vegetables, sweet potatoes and oil seeds cultivated along field boundaries or on small parcels (Abdoulaye et al., 2012; Amadou et al., 2018; Boateng et al., 2016; Kadyampakeni et al., 2017; Kleemann et al., 2017b; Koo et al.; 2018).

A medium-scale irrigation scheme, established in 1965, occupies the central part of Bolgatanga Municipal District, supplied by the Vea dam, which is also the main source of drinking water for the population of the two study districts (Sekyi-Annan et al., 2018a). The irrigation scheme was planned to supply water to 850 hectares of cultivation fields, but only 300-350 are actually being irrigated due to lack of maintenance and/or underutilization, which is common in irrigation schemes of Northern Ghana (Adongo et al., 2015; Peprah et al., 2015). Soil bunds are commonly used only for flooding rice fields, but they frequently collapse, resulting in runoff losses of irrigation water flowing out of the fields (Sekyi-Annan et al., 2018b). This makes it difficult to maintain the facility due to the huge cost involved in comparison to the small biomass returns generated (Danuor, 2012). Besides the major Vea dam, the study region is dotted with numerous medium- and small-scale dams, some of them serving irrigated agriculture. Indeed, the UER was the first region of the country to experience significant proliferation of small-scale irrigation projects, starting with the decade of the 1980s. During the first decade of the 21st century, small-scale reservoirs for irrigated agriculture significantly expanded. This might have been motivated by the increasing purchasing capacities of the urban populations of southern Ghana, and the resulting increased demand for rice, vegetables (mainly tomatoes) and, to a lesser extent, maize products. However, failures in the maintenance of irrigation infrastructure have also kept many of these schemes out of function (Namara et al., 2010; Venot et al., 2011; Douxchamps et al., 2012). However, irrigation is still regarded as the most efficient measure to sustain agricultural livelihoods (Ndamani and Watanabe, 2015; Limantol et al., 2016). Spontaneous technologies, used for the irrigation of small fields, have been more effective for returning profit margins to the farmers; such is the case with temporal shallow wells, alluvial dugouts and water pumping of surface water at the individual level (Ofosu et al., 2010). Mineral fertilizer is applied mostly in irrigated fields, whereas soil fertility in rainfed fields is managed by crop rotation without fertilizer because of the risk of end-of-season dry spells, which may result in higher economic losses whenever fertilizers have been applied. Double sowing is a typical strategy to cope with start-of-the-season drought spells: when farmers notice that the first sowing has not being successful due to water stress or other factors such as flood or livestock grazing, they make a second round of sowing (Yegbemey et al., 2014). Cereal stalks are the most common source of cooking fuel due to the shortage of firewood.

Livestock production is another main specialization of the UER within the Ghanaian economy: about 17% of the registered nation’s cattle herd is found in the UER, which occupies less than 4% of Ghana’s land area. However, although the productive systems of the region are considered as mixed crop-livestock, synergies between the production of both are not optimized: livestock is kept away from the cropping fields during the growing season to prevent crop raiding, but by doing so, most of the manure is lost for the farming productive system due to the lack of cheap transportation methods (Blench, 1999; Owusu, 2009; Choudary et al., 2015). The UER has also held a smaller specialization within Ghana regarding some commercial fruits, such as mango, and to a lesser extent papaya (MoFA, 2014), although its production lies behind that of other northern regions. They are mostly cultivated in mixed-species orchards, and used for domestic consumption or marketing at the regional level. Mangoes are also cultivated in plantations, particularly around the banks of dams and their outlets, producing a higher surplus. Global mango value chains are penetrating into West African savannas, particularly in Senegal, Mali and Burkina Faso, but in the Northern Region of Ghana it is a more recent trend (van Melle and Buschmann, 2013). To the knowledge of this author, however, mango production has not yet arrived in the UER.

The local population demonstrates, in general, an interest in planting and maintaining wood resources. Nevertheless, an entanglement of systemic interactions derived from practices related to social traditions, the colonial heritage and laws restricting access to woodlands explain why populations sometimes show little interest in true protection of existing resources or new plantations Sometimes, local populations show little interest in the protection and maintenance of plantations that are promoted by reforestation policies oriented to collective management. It has been argued that planting trees had been seen in the cosmology of the interior savanna peoples as being opposed to nature, and preferable to avoid. The use of trees is therefore regulated by customary norms, and in many regions the rights regarding tree product exploitation is independent of the rights over the land where they are located. The practice of planting local and exotic trees, or systematic development of plantations, for economic benefits in savanna regions of interior West Africa seems to have increased only in the last ninety years during colonial times, with the return of migrants from coastal regions. Because the total adherence of a population to a practice may take several decades, this may explain why tree planting may have experienced, or even still experiences, a certain level of resistance (Langewiesche, 2004). Moreover, parklands provide most of the same array of products provided by woodland savanna, implying that forest clearance and degradation is profitable for many different stakeholders (Pouliot et al., 2012).

Lastly, gold mining is a main focus of the Ghanaian economy, widely extended throughout the Southern parts of the country. In Southern Burkina Faso there are also important gold-mining hubs. In the study region, despite being marginal regarding the sector, small-scale mining activities have been spreading over recent decades. There is a quarry in the neighboring Talensi district, which was not established without controversy (Doyi et al., 2013), and a constellation of other small-scale illegal mining sites in their surroundings. These are located mainly within forests in the periphery of the Bolgatanga urban area, due to their isolation and relatively close distance to trading markets.

2.5 Economic, demographic and administrative profile

The last years have witnessed an increase of the number of districts in Ghana by fragmentation of the existing ones. This has been common in the UER, posing limitations to spatial-temporal analyses based on historical statistical data. Indeed, the district of Bolgatanga has been split several times since the foundation of the Ghanaian state, the most recent in 2018. The demographic data used in this study is based on the 2010 census (Figure 2.4).

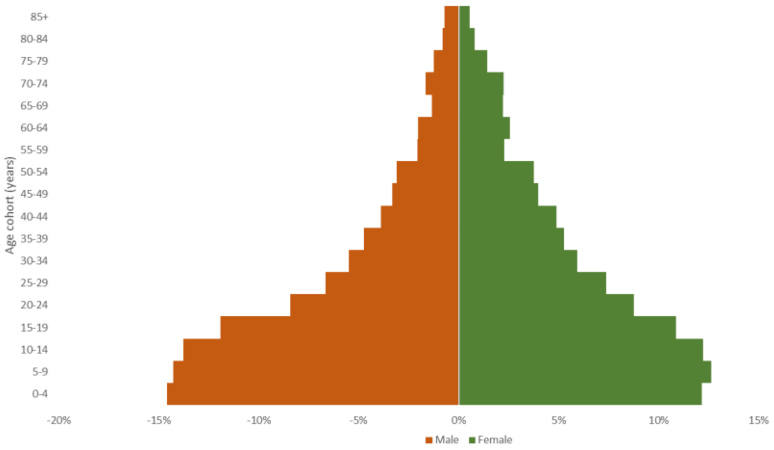


Figure 2.4 Population pyramid of Bolgatanga Muncipal and Bongo districts (combined) according to the 2010 census (GSS 2014a; 2014b).

The population is very young, with 39% under 15 years old. The mainly emigrant profile of the population can be observed in the substantial reduction of the number of males aged 20-24 in relation to the age group 15-19.

The economic profile of the region is overwhelmingly agrarian. By 1960 more than 90% of men were engaged in agriculture (Wardell, 2005) and migration flows to the South accelerated since the integration within the Colony of the Gold Coast. During the 1980s many migrants returned due to the crises of the industrial sector in the Southern Regions (Awo, 2012). During the same period, the neighboring areas of southern Burkina Faso also received substantial migration, in this case coming from the Sahel, driven by persistently dry consecutive years. This migratory flow has been maintained ever since (Ouedraogo et al., 2012). There is also substantial internal migration within the region, as well as the more recent immigration of gold-miners from other parts of West Africa (Blench, 1999; Schraven and Rademacher-Schulz, 2015). Farmers were severely affected by the liberalization of agricultural products following the structural program in the early 1990s, as their capacity to purchase inputs was low, which can be seen in the small progress made in the region in terms of hunger alleviation (Abane, 2015). Hence, the government reintroduced fertilizer subsidies in 2008 (Scheiterle and Birner, 2018).

Urban population in the UER increased steadily, from 4% in 1960 up to 21% in 2010, but it remains below the urban population of the other regions of northern Ghana, indicating the high population density of the rural areas of UER. In Bolgatanga Municipal more than half of the households are urban, while in Bongo only 8%. The average population density over the whole study area in 2010 was 178 inhabitants per km^{-2}. The population of the town of Bolgatanga doubled between 1984 and 2010, from 32,000 to 65,000 inhabitants, although most of its growth occurred before 2000, a period in which the structural programs severely affected the rural areas of Northern Ghana (GSS, 2014a, 2014b; Owusu and Oteng-Ababio, 2015).

The role of the model region within the Ghanaian economy, same as the whole UER, is the production of some staple foods such as rice, tomatoes, millets, livestock and a variety of nuts (Forestry Commission, 2016). The economic returns from biomass harvesting activities are low (Kyereh et al., 2015), and hence a significant part of the smallholders rely mostly on off-farm income, lacking incentives to increase land productivity (Nin-Pratt and McBride, 2014). The lack of biomass-products processing facilities significantly reduce the marketability of local agricultural production (Sedem Ehiakpor et al., 2017) and the adaptive capacity of small-holder farmers to climate change is low (Assan et al., 2009; Ndamani and Watanabe, 2015; Abdul-Razak and Kruse, 2017; Aniah et al., 2019; Danso-Abbeam et al., 2019). Increases in rural household incomes are required to increase farm productivity, for example through off-farm activities, but these opportunities are scarce (Nimoh, 2012; Dumenu and Obeng, 2016; Kleemann et al., 2017b). In some rural communities, off-farm incomes account only for a very small proportion of rural livelihoods (for example, 3%-15% of total household income in communities of Eastern Bongo District). Such activities involve street food cooking, charcoal production, crafts (mostly baskets, ropes and hats) and galamsey (small-scale mining). For women, catering services are the most common (Bacho, 2005). The number of employing companies in the study districts is minimal, as 95% of the private firms refer to individual enterprises. Therefore, the main employer in the region is the state. Specialized economic activities are mostly undertaken in district capitals, involving dressmaking, vehicles repair, manufacturing of agricultural implements and baskets. The majority of women are involved in small-scale marketing in the community or district markets, trading primarily agricultural surpluses and shea butter. A very small proportion of business is registered in the official census. However, a significant part of them are exclusively focused on markets outside the district (Awo, 2012; Asare et al., 2015), which might be an indicator of the function of the region within the Ghanaian economy as an exporter of certain biomass products.

Current national policy gives high priority to the transformation of agricultural technologies with the aim of doubling farmers' yields with a focus on northern Ghana, through initiatives that include the Ghana Poverty Reduction Strategy (GPRS), the Food and Agriculture Sector Development Policy (FASDEP), and the Savanna Accelerated Development Authority (SADA) (Nyantakyi-Frimpong and Bezner Kerr, 2015). The spatial policy of SADA has been elaborated in collaboration with a Brazilian company. Two main economic hubs are promoted within this regional policy unit: Tamale, the most populous city of the savanna zone and capital of the Northern Region; and Buipe, a commercial node at the verge of the Black Volta near the Volta Lake, in the Central Gonja District. Bolgatanga town is considered as a Potential Special Economic Zone that should be driven by "processing industries and perhaps warehousing services", serving also neighboring countries (Abugre, 2016). Agro-industrial initiatives in the region, such as a tomato processing factory collapsed (Akolgo, 2018), and robust land use plans, which are able to ensure the continuous flow of raw biomass product supply, must be undertaken to avoid the same fate for new investments.

Another initiative put in place in Northern Ghana is the Northern Rural Growth Program (NRGP) with the aim of facilitating smallholder farmers' access to finance. It is funded by the Fund for Agricultural Development (IFAD) and the African Development Bank (AfDB), and it is managed by the MoFA. The NRGP "brings together the various value-chain stakeholders at the district level through the District Value Chain Committee" (Nwuneli et al., 2013). Non-industrial grain cereals and legumes are excluded from the program.

Construction of a multipurpose dam is projected to start in 2020 in Pwalugu, White Volta, just south of the border of the study region, as a source of electricity and water for irrigation. Irrigation is planned for the production of mainly rice and maize, and secondarily for vegetables and sweet potatoes. The planned irrigated area extends only over the west bank, falling outside of the UER, but in any case a large project like this one is likely to have impact on the economy and land use, as well as on the development of value chains of the UER, and especially in the nearby Bolgatanga Municipal (Volta River Authority, 2014).

In Ghana, two authorities overlap within the same jurisdiction: the modern state and the traditional authorities. The current system of Ghanaian traditional authorities is relatively modern. Its aim is to integrate the different local cultural identities inhabiting the state into its formal institutional system, and it is formed by a mosaic of regional institutions with similar structures and functions. However, the organizational systems of the societies inhabiting what nowadays is Ghana were in the past very different to each other. The institutional homogenization was started by the British Colony of the Gold Coast. The British administration, in order to have intermediaries with the local populations, re-assigned roles among supervising individuals. By doing so, they disregarded the local institutional system and contributed to the creation of the modern chieftaincy institution (Staniland, 1975; Wardell, 2005; Lentz, 2006). The distorting effect of the Colonial administration on the spatial distribution of authority, its hierarchy and functions has been since many decades ago a central argument on the disputes for chieftaincy in the UER (Awedoba, 2010; Azaare, 2017).

The study region is part of the Frafra Traditional Area (together with two other districts: Nabdam and Talensi, where one of the main spiritual centers of the area is located), whose delimitation calls upon historic and cultural factors. However, regions with similar cultural background can be also found in Southern Burkina Faso, whose peoples still hold strong social ties and fluid trade networks with those inhabiting the UER (Wardell and Fold, 2013).

It has been assumed that the two districts of the model region conform a suitable regional planning unit because their population share a common urban center, a language different to that of the surrounding districts, and both are part of the same Traditional Area. According to these criteria, the Talensi and Nabdam districts could also have part of this assessment unit, but the LULC data used as input in this study did not include them, as it is shown in the next section.

3 METHODOLOGY

3.1 Baseline spatial data

In order to estimate the different benefits that can potentially be derived from biomass production on a regional extent, two maps are necessary: standing (woody) above-ground biomass (AGB) and LULC. The former typically shows the distribution of perennial vegetation AGB, whereas the latter shows the distribution of the different types of biomass-producing land use classes, hence allowing estimation of the biomass production of non-perennial land uses based on additional data. Because measuring biomass production of annual vegetation over large extents is very costly, such data is usually based on extrapolation of field-scale observations or simulations. The value of combining the information of AGB and LULC maps is that it enables the integrated assessment of the provision levels of a wide-array of biomass-based products, e.g.: grains and wood.

The baseline LULC map (Figure 3.1) is based on district scale LULC data elaborated under the umbrella of the WASCAL project. This data was derived from the combination of two optical datasets (RapidEye 5m and Landsat 30m) and one radar dataset (TerraSAR-X) (Forkuor, 2014; Narvaez-Vallejo, 2016). The original map has a pixel size of 5 meters and was developed with the main purpose of improving the information on annual crop species distribution. Such information is very valuable for analysis of trade-offs among the different goods and potential benefits that can be derived from annual crop species. Moreover, the fine pixel size (5 meters) makes it the best available product to detect the dispersed pattern of perennial vegetation. Other medium resolution products were considered, such as LULC 250m pixel size and fractional vegetation cover 30m pixel size, but they do not capture the numerous isolated trees and tree clumps dispersed over the farming areas, and hence are not suitable for viable assessment of the impact of such a characteristic component of rural savanna landscapes on regional biomass provision.

The baseline LULC map identifies nine land use classes: water, non-biomass provisioning cover (i.e. built and bare), annual cropping LULC types disaggregated into four classes (cereals, legumes, maize and rice), non-cultivated grasslands, and two LULC classes containing perennial vegetation (tree/woodland and mixed vegetation, the later referring to a mix of herbs, shrubs and small trees). This latter LULC class is the one occupying the largest area in the map. The class "cereals" refers to undifferentiated traditional cereals, mainly pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*). The class "legumes" refers mostly to groundnuts, because it is the only legume extensively cultivated as a monocrop, whereas cowpea or Bambara groundnut are cultivated in mixtures with cereals or as strip crops that are barely detectable through remote sensing, and the cultivation of soybean is still not particularly extended.

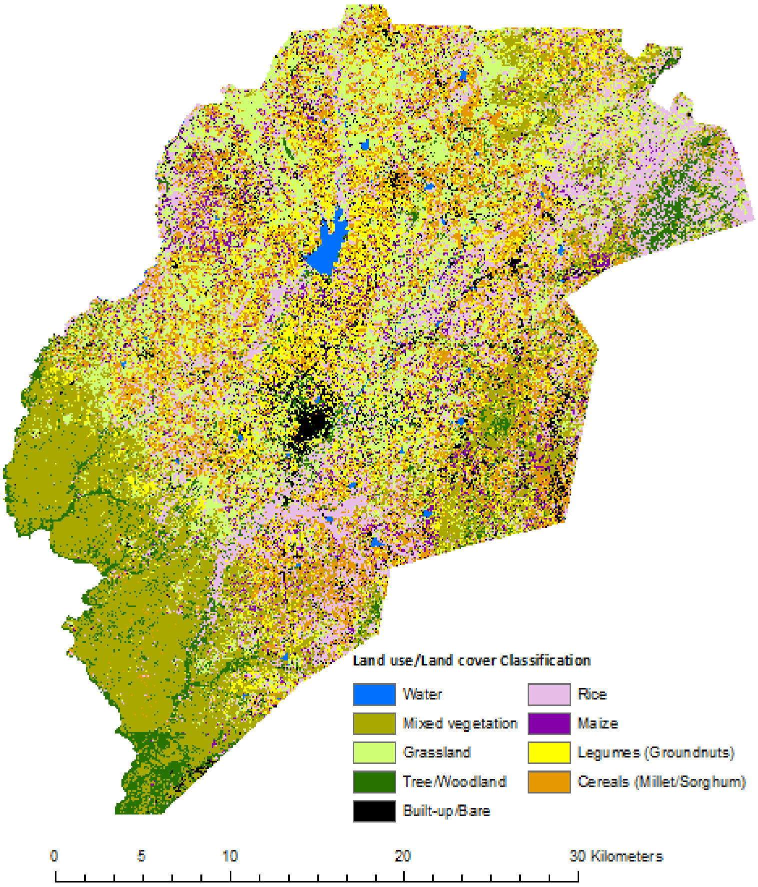


Figure 3.1 Land Use-Land Cover of the study region in 2014. Source: (Forkuor, 2014; Narvaez-Vallejo, 2016).

The pixel size of the LULC map was resampled to 25 meters to speed computational analyses while barely modifying the total area and spatial pattern of each LULC class. It has been observed that similar resampling magnitudes have no significant impact on the values of energy balance components of other open canopy landscapes (Ramírez-Cuesta et al., 2019), and hence it was assumed that such a pre-processing step has no relevant impact on regional extent biomass provision analyses in the study region.

The study region contains two protected areas, one in the Southern part (Tankwidi Forest Reserve) and the other in the Northeastern part (Red Volta Forest Reserve), which are clearly recognizable because of the dominance of woody LULC classes. Ground- truthing in the most remote parts of these protected areas was not undertaken. Therefore, there was a higher degree of LULC classification uncertainty is these areas. In the Red Volta Reserve a great part of the area was classified as rice fields. It is possible that cropland encroaching has occurred due to the lowland characteristics of this area, but it has not been confirmed by observations. In the southern-most part of the Tankwidi Reserve, there is an abrupt change between the area occupied by mixed-vegetation and tree/woodland. This is, however, less relevant for this study because all woody LULC classes were merged for the assessment of biomass provision.

The baseline AGB map (Figure 3.2) has been extracted from a 50m pixel size dataset elaborated at the continental scale (Bouvet et al., 2018). This map was elaborated with the specific aim of improving the information on biomass distribution across African savannas and can be freely accessed for non-commercial use only through the following URL (last time accessed: 7th November 2021):

https://drive.google.com/open?id=1ZYuups-pPzkuyng1ge4aHqL8Gkm7vL3k.

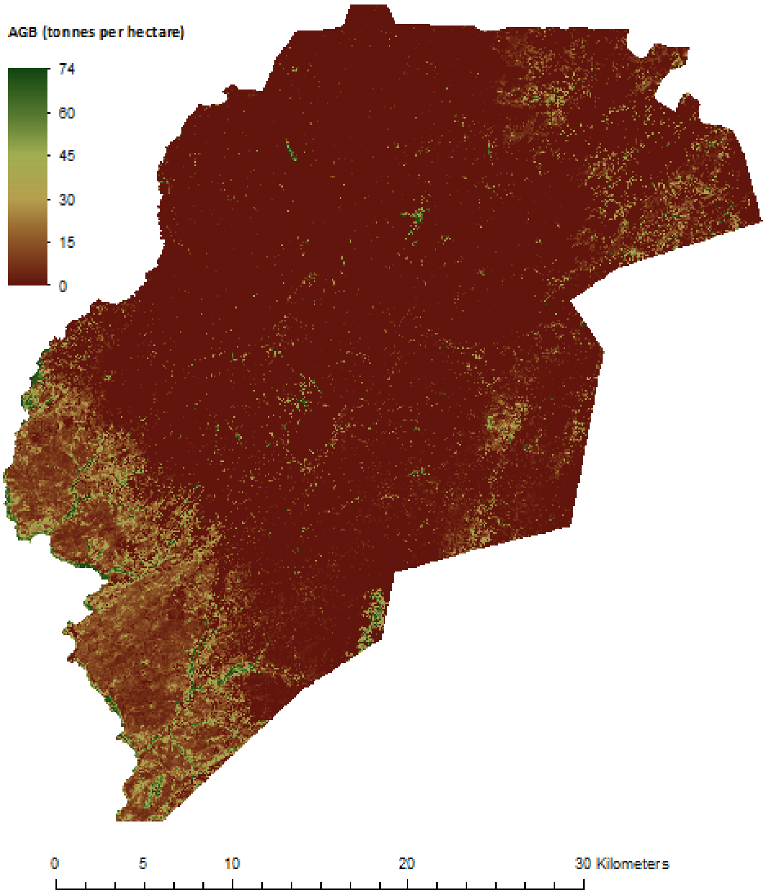


Figure 3.2 Woody Above Ground Biomass in the study region in 2014. Source: Author's adaptation from (Bouvet et al., 2018).

Both maps offer snapshots of the land surface in the year 2014, and hence can be used together to complement each other's information. However, rectification was necessary because each map was developed over different spatial extents, on different geographical projections and using different remote sensing products. This was done in ArcGIS using the shape of riparian woodlands and other remarkable wooded areas of the region as reference landscape features. Finally, the value of pixels in the baseline biomass map which overlay with non-woody LULC classes was set to 0 t ha^{-1} in order to keep coherence between the two products.

3.2 Land use change simulation

3.2.1 Methodological overview

Unlike common LULC scenario analyses, the LULC scenarios in this study were defined, in principle, as expected outcomes of land management and not as an assessment of the empirical relations between ecosystem variables (such as climate scenario bioclimatic variables) and LULCC. The approach to land use change simulation followed in this study is exploratory. Whereas most LULCC simulation studies are based on observations of past LULCC, for which a time series of observations over several years is necessary, this study relies on one single map. Therefore, no data on past LULCC has been used. This has been done in order to fully exploit the potential that high thematic and pixel size resolution LULC products have to analyze the provision of the different biomass types. Given the need for a change of paradigm in the way in which human populations interact with the reproductive cycles of the materials that they use to satisfy their demands, this high resolution is key to making comprehensive assessments of the production of different biomass products necessary to contribute to making better informed decisions regarding regional economic planning (Beuchelt and Nassl, 2019).

One of the main struggles of contemporary LULCC modeling practice is the allocation, to a specific piece of land, of a particular LULC class among competing LULC classes (Verstegen et al., 2012). This is why novel approaches to LULCC simulation focus on the spatial changes of no more than three LULC classes, typically built *versus* non-built, forested *versus* non-forested, or cultivated *versus* non-cultivated areas (Verstegen et al., 2014; Kamusoko and Gamba, 2015; Akinyemi et al., 2016; Badmos et al., 2018; Shoyama et al., 2018). The state-of-the-art presents particularly two serious constraints to the accurate modeling of LULCC change in African savanna regions. On one hand, the coarse grain and thematic resolution of the LULC data archive do not allow LULCC to be captured at the level necessary for landscape scale planning. Improved high resolution LULC data has been recently developed and is openly accessible (Souverijns et al. 2020), however, such datasets cannot yet detect a large proportion of the LULCC that West African savanna LULC systems have been experiencing over recent decades. On the other hand, available spatially-explicit digital data on candidate explanatory variables (such as population distribution change, land cadaster, land economic value, land access, forest inventories, etc.), is very limited or it simply does not exist yet. Therefore, commonly used inductive, data-driven, LULCC modeling techniques based on multiple year-time series of coarse resolution LULC maps have limited applicability to better inform how to manage regional planning dilemmas in African savanna regions.

For these reasons, this study has given priority to the precision of the LULC thematic resolution over the precision of LULCC change that is offered by an analysis of a multiple year-time series of coarser resolution LULC maps. The GISCAME software platform facilitates this approach by allowing the user to manually introduce the LULCC transition probability values that determine how the cellular automaton simulates LULCC, as opposed to models fed with time-series of LULC maps, in which transition probability values are determined empirically by the spatially-explicit statistical analysis of LULCC related to its potential explanatory variables. Additionally, the GISCAME software platform includes a function to link information on each LULC class stored in tables (of any variable of interest) with the raster LULC map (Fürst et al., 2015; Fürst et al., 2016).

The use of a cellular automaton without data to model the empirical relationships between LULCC and its drivers is not suitable for concrete regional planning questions, such as what would happen if a certain LULC class occupies a certain total area within a region in a certain point in the future. The target total area cannot be controlled, and it can only be slightly approximated if several combinations of transition probabilities are tested. Therefore, the exercise is rather explorative. Transition probabilities from one LULC class of origin into a target LULC class are required, without any particular parameterization requirement. These transition probabilities can reflect various landscape change processes, such as cropland encroachment or succession to abandoned croplands.

Transition probabilities are expressed within a range from 0 (no transition of LULC is expected) to 100 (LULC change is absolutely likely to occur), and can have up to two decimal places. One source LULC can have several target LULCs. Each rule (i.e. each row in the definition-table) is taken into consideration iteratively by the system. Hence, the order of single rules influences the outcome. The more rules that are defined the less replicable is the resulting map. On the other hand, if very few rules are applied, the similarity of the resulting scenario with any plausible real world outcome may become very low. Therefore, the main challenge is to find a balance between simplicity and plausibility. More complex simulations include the definition of conditions that must be met for the LULC transition to occur. These conditions are optional, and they can be of two types: neighborhood rules (number of cells of certain LULC classes that are neighbors to one central cell) and environmental layers (value or range of values of a certain environmental factor where the cell is located).

Each iteration of the cellular automaton simulates a new LULC map based on the defined transition rules. In this study, eight iterations have been run and the simulated time lapse between two consecutive maps represents five years. Therefore, the time scope of the explorative study is forty years.

Estimation of CA transition probabilities requires detailed knowledge on past LULC changes or sound expert knowledge on expected future development of a region. However, the estimation of transition probability values, particularly among an array of competing LULC classes, is highly challenging. Transition rates from state (LULC class) A to state B vary widely, not only due to the mechanisms of LULC change operating within a particular context, but also depending on the characteristics of the raster dataset: pixel size, length of the time period between two observations and the share of the region covered by each LULC class. Before any estimation of transition probabilities can be approached, experts – even if they have in-depth knowledge on the ground of the LULCC dynamics in the region of interest – , must know all these characteristics of the input data, as well as the range of LULC transition values that have been observed in previous LULCC analyses in similar regions or spatial data with similar characteristics, so that they can link their personal experience with plausible quantifications of such knowledge.

Additionally, each of the few openly accessible LULC maps of West African savanna regions use their particular thematic classification; furthermore, in all of them, such a classification is quite different compared to the LULC map used in this study. Not only because the map used in this study is the only one differentiating four annual crop LULC classes following the crop species' criteria, but also because the lands covered with non-cultivated vegetation are classified quite differently. Most LULC products differentiate grass-, shrub-, and forest- lands; or savannas and forests. On the other hand, the map used in this study differentiates grass-, mixed vegetation, and tree/woodland. The products containing the savanna class are difficult to compare with the map used in this study, because the savanna class does not differentiate grass from perennial woody covers and it will include many isolated trees, which in our map are, together with forests, included within the tree/ woodland class. Maps differentiating grass- and shrub- lands are more comparable to our map, because pixels classified as shrublands correspond fairly well with those classified as mixed vegetation. However, the pixels and small patches of tree/woodland, typical of the map used in this study, and representing the typical pattern of tree distribution in savannas (and particularly those largely modified by humans, such as the region modeled in this study) are also lost in such products, because they cannot be detected and classified within the forest class.

Due to these mentioned challenges, transition probability values have been estimated in this study through trial and error until reaching an outcome that seemed of an acceptable degree of plausibility, as compared with narratives and observations of LULCC change reported in literature. No systematic consultation rounds with assumed experts have been conducted. Instead, the input values and output LULC maps and LULCC matrices of this explorative LULCC scenario development exercise can be used in future participatory studies to design LULCC scenarios whose rationale and narrative can be better described and commonly understood among a wide variety of stakeholders and scientists.

No LULC change was simulated for built-up and water cover pixels because they would add further complexity to the design of LULCC scenarios and their comparison. For example, it would be difficult to design one cropland expansion scenario and one afforestation scenario while both experience the same expansion of their respective urban areas. Furthermore, the lack of a time series of observed LULC maps makes it particularly challenging to simulate the “leap-frog” change pattern typical of built-up LULC classes (Kamusoko and Gamba 2015), especially in the study region where the settlement pattern is dispersed. In the case of surfaces covered by water, their influence in LULC and production changes is mainly through their irrigation potential, but because no hydrological model was included in the study, such influence cannot be considered.

3.2.2 Selection of LULC transition probability values considering one single and aggregated crop LULC class

To guide the estimation of plausible transition values, an analysis of the transitions experienced within the study region between 1975-2000, 2000-2013 and 1975-2013 was conducted by using the West African Land Use Maps published by the US Geological Survey (Tappan et al. 2016). This analysis of past observed LULCC, on another lower resolution-dataset, has been done in order to obtain a first approximation to the quantification of LULCC transition probability values.

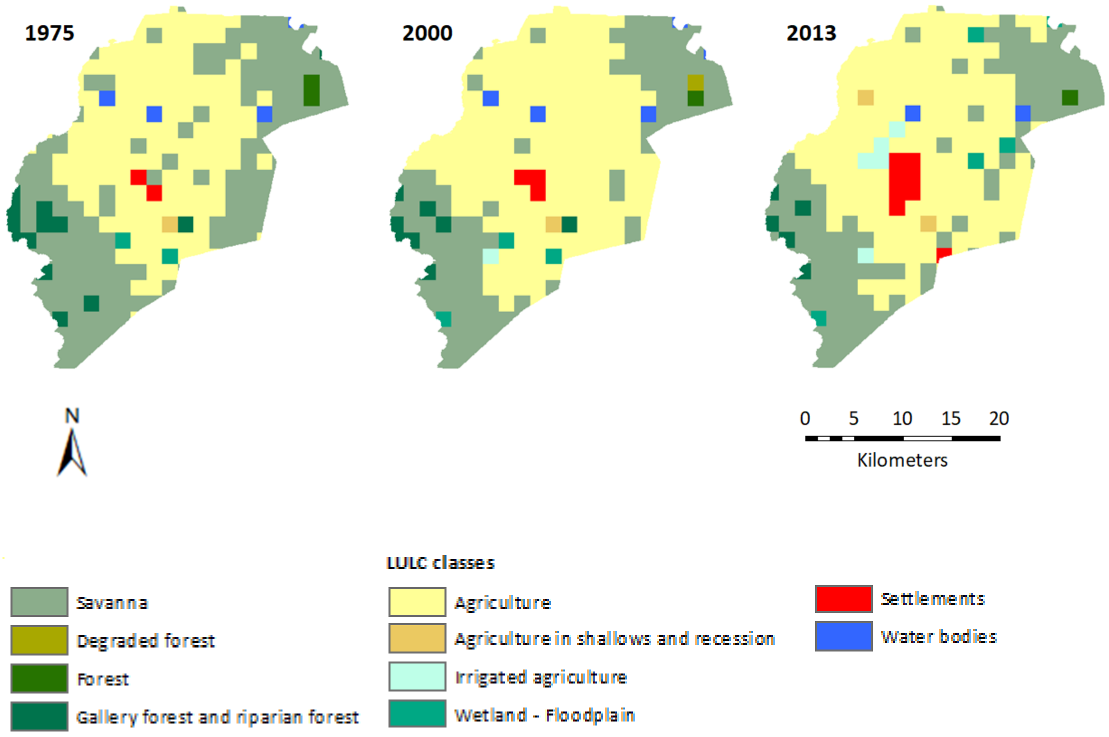


Figure 3.3 LULC maps of the study region in 1975, 2000 and 2013. Source: Tappan et al. (2016)

Resolution issues must be taken into consideration because they highly influence the resulting rate of LULC conversion. The thematic information of the US Geological Survey West African Land Use Maps, does not differentiate annual crop LULC classes based on the crop species but on whether they are rainfed, irrigated or practiced in shallows and water recession beds. Therefore, all classes referring to areas sown with annual crops have been aggregated in one single cropland class. On the other hand, LULC classes containing perennial vegetation include the "forest" classes and "savanna". In the latter, both perennial and grass cover occur, but no information is provided on the proportion of each of them. There is no class referring exclusively to grass cover. It was necessary to create a common LULC classification between the baseline LULC map used in this study and those of the US Geological Survey. Therefore, all classes referring to areas sown with annual crops in each product were aggregated in one single "annual crops" class, and all classes referring to non-cultivated vegetation in each product were aggregated in one single class comprising all "non-cultivated vegetation (regardless where this is annual or perennial) and perennial (regardless whether it is naturally growing/regenerating or planted)". Temporal resolution also plays an important role in the resulting LULC transition values. The transitions between 2000 and 2013 were chosen because they are a shorter period than between 1975 and 2000. Therefore, it is expected that the transition values at time steps of 5 years will be closer to those observed in the shorter of the two periods. Finally, pixel size also determines the LULC transitions that can be detected. Particularly in rural African savanna regions, where the land use pattern is very patchy, coarser pixel sizes will not be able to detect many of the LULCC occurring on the ground. The transition probability values of the scenarios simulated in this study will be set a bit higher than those observed in West African Land Use Maps published by the US Geological Survey because the pixel size in the simulated maps is much smaller. Therefore, they can represent more and finer-resolution LULC transitions.

The West African Land Use Maps of the US Geological Survey show an accelerating transition rate over time of the "annual crop" LULC class into "non-cultivated vegetation and perennial". Between 2000 and 2013 it was 0.092. Taking this value as a reference, the transition probability of any crop LULC class into perennial vegetation has been stablished at 0.100, and into grasslands at 0.020. This gives a total transition probability of "annual crop" LULC class into "non-cultivated vegetation and perennial" (i.e. the equivalent to savanna) that is slightly lower than 0.120. Conversely, the opposite transition, "non-cultivated vegetation and perennial" into "annual crop" in the study region between 2000 and 2013 was 0.116. In the first simulated scenario this was increased to 0.138, corresponding to a conversion rate of 0.120 of pixels containing perennial vegetation and 0.160 of pixels covered purely by grass cover. Grasslands would experience a higher reduction, both in absolute and relative terms, than LULC classes containing perennial vegetation, following the long-term trends observed across most rural West African savannas over the last century.

The output LULC maps of this simulation were analyzed before developing more scenarios. As will be shown in the results (Section 4.1), this first scenario resulted in a slight increase in the regional area covered by perennial vegetation and a higher fragmentation of its distribution by the end of the simulated period in comparison with the baseline map. Therefore, it was called the Farmland Agroforestry (FLAF) scenario, as it can represent a landscape management characterized by the increase in on-farm tree cover while farmlands expand at the expense of uncultivated areas, mainly grasslands. An increase in tree cover is a plausible scenario because active tree planting and assisted natural regeneration are becoming more common land management practices due to both to local and global drivers: on one hand, the transformation of local practices towards tree cover management (Langewiesche, 2004), and on the other hand, the spread of agroforestry policies and projects. Expectations on increased cash income from the plantation of orchards can also result in a maintenance or increase of tree cover coupled with degradation of wild re-growth tree formations and even in detriment of annual food crop species, as it has been occuring in other West African savanna regions (Koulibaly et al., 2010; Cabral and Costa, 2017).

Then, transition rulesets were developed for two more scenarios, targeting a decrease in the total area containing perennial vegetation. The LULC dynamics in these two scenarios have been simplified. The LULC dynamics in these two scenarios have been simplified to better replicate the expected results. One of the scenarios has been called Afforestation of Protected Areas (AFPA). In this scenario, transitions of perennials into cropland were considerably reduced in order to simulate the effective conservation of woodlands and their growth into forest formations, whereas the conversion rate of grasslands into croplands was kept at equivalent levels to those of the FLAF scenario, and neither croplands nor grasslands experienced changes into "non-cultivated or perennial" LULC classes to represent the maintenance of continuous cultivation for the satisfaction of pressing demands for annual crops' biomass. In the other scenario, widespread and unplanned cropland expansion was targeted. This scenario has been called Cropland Expansion (CEXP). In this scenario, conversion of non-cultivated vegetation into croplands was set the highest, whereas the opposite transition was halved in comparison to the FLAF scenario.

Table 3.1 LULC transitions expressed as percentages (%). During the period 2000-2013 observed by the US Geological Survey; and expected simulated transition rate during the first iteration (T_0-T_1) of the CA run in the FLAF, AFPA and CEXP scenarios.

			Simulated (this study)		
Origin LULC class	**Target LULC class**	**Observed**	**FLAF**	**AFPA**	**CEXP**
Crop	Non-crop or perennial	9.2	12.0	0	6.0
Crop	Grassland		2.0	0	3.0
Crop	Perennial		10.0	0	3.0
Non-crop or perennial	Cropland	11.6	13.8	8.7	25.9
Grassland	Cropland		16.0	16.5	35.0
Perennial	Cropland		12.2	3.0	20.0

The next step was to distribute the total transition probability values between cropland and non-cultivated (or perennial vegetation) among the different LULC classes of the baseline map of this study. Such distribution was made trying to meet two assumptions about future cropland LULC shares: maize would be the crop specie whose area would experience the highest relative increase, following past trends and the widespread promotion of which it is subject by researchers and international organizations; and rice would be the one whose area would experience the lowest relative increase, due to the limited available area for its profitable cultivation (Amadou et al. 2018).

Soil types were used as a conditioning rule. This prevents LULC transitions from occurring in any random location, which would result very quickly in a spatial distribution without any order. On the other hand, it will exaggerate the current spatial pattern of distribution, concentrating some LULC classes more than they currently are. The soil types map presented in Figure 2.2 (in Chapter 2.3) was used as an environmental layer to restrict where certain LULCC transitions could occur and, therefore maintain as much as possible the paradigm of crop species distribution in West African savannas. Soil types were aggregated in three categories: leptosols have been considered to be low fertility soils; lixisols and luvisols medium fertility soils; and fluvisols and gleysols have been described as hydromorphic soils.

In West African savanna agricultural regions, groundnuts typically occupying the least fertile soils, followed by millets and sorghum, as fertility increases maize becomes more likely to be cultivated and, finally, rice is most of the time given priority over the crops in valley-bottoms. The LULC and soil raster maps where crossed to calculate the proportion of each LULC class area that overlays with each soil type (Appendix 1) and *vice versa* (Appendix 2) in order to quantify and confirm that such pattern occurs in the study region.

Most pixels of every LULC class are located in low fertility areas because the soils classified as low fertile occupy the most extensive area of the study region. The opposite occurs for the hydromorphic soils, which occupy the smallest area. However, it can be clearly seen how soil fertility classes influence the pattern of LULC spatial distribution. Legumes and grasses, followed by cereals, are the LULC classes in which the dominance of poor fertility soils is higher, and perennials are LULC classes with the lowest predominance. On the other extreme, rice and perennial, followed by grasses, are the LULC classes in which the dominance of hydromorphic soils is higher, whereas cereals and legumes are those with lowest predominance on these soils. This distribution is expected across most (if not all) of other savanna landscapes with a similar set of crop species.

The value introduced as input for the GISCAME CA was calculated as expressed in Eq. 1:

$$Tv_{ij} = Te_{ij} * \frac{A_i}{A_s} \qquad \text{Eq. 1}$$

Where Tv_{ij} is the transition probability value to be introduced in the ruleset of cells of the origin LULC *i* to change into the target LULC *j*; Te_{ij} is the expected simulated transition rate during the first iteration; A_i is the total area covered by the origin LULC and A_s is the area covered by the origin LULC on the soil types in which LULCC is allowed for that specific transition.

3.2.3 Distribution of LULC transition probability values considering four different LULC classes

The total exchange between cultivated, non-cultivated and perennial LULC classes had to be distributed among the LULC classes of the baseline map. The detailed transition probability rulesets and their values can be consulted in Appendix 3 to 6. The rationale behind such distribution of transition probability values is as follows:

Farmland Agroforestry Scenario (FLAF):

The 16% transition probability of grassland into cropland during the first iteration was expected to be 5.5% for legumes and cereals, 3% for maize and 2% for rice. This was introduced by setting the transition probability of cereals and legumes to 6% in non-hydromorphic soils, maize to 8% in all but the least fertile soils and rice 27% in hydromorphic soils. The 12.2% transition rate of perennial vegetation into croplands was distributed among the different cropland LULC classes by assuming that cereals and legumes would further increase their area by adding 4% to each of the original perennial vegetation area, whereas maize would receive 3% and rice 1.5% additional area from the original perennial vegetation area. The same soil conditions that were defined for transitions from grasslands were also introduced to the transitions from perennial to crop LULC classes. This was estimated as 4.5% for the transitions into cereals and legumes, 7% into maize and 17% into rice. Transition probability of grassland into perennial was assumed to be 8%, restricted to those grassland cells with less than four perennial neighboring cells, to represent an active management of perennial growth and regeneration that targets widely open stands to allow for the cultivation of herbaceous crops. Transition probability values from crop LULC classes into grasslands were defined as 2% and into perennial vegetation as 10%, without any restriction. The transition rate of pixels of cropland origin into perennial origin was slightly higher than from grasslands to represent this active promotion of tree growth in farmland areas.

Afforestation of Protected Areas Scenario (AFPA):

From the first until the sixth iteration, the 16.5% transition probability of grassland into cropland was expected to be 6% for legumes and cereals, 2.5% for maize and 2% for rice. This was introduced by setting the transition probability of cereals and legumes to 6.5% in non-hydromorphic soils, maize also 6.5% but in all but the least fertile soils, and rice 27% in hydromorphic soils. The 3% transition rate of perennial vegetation into croplands was distributed among the different cropland LULC classes by assuming that maize, cereals and legumes area would further increase its total area by adding 9% to each of the original perennial vegetation area, whereas rice would receive 5% additional area from the original perennial vegetation area. The same soil conditions that were defined for transitions from grasslands were also introduced to the transitions from perennial to crop LULC classes. This was estimated as 10% for the transitions into cereals and legumes, 20% into maize and 7.5% into rice. No pixel was targeted to become grassland or perennial vegetation. This simplification allows conservation of a spatial distribution pattern of LULC classes very similar to that of the baseline, representing a scenario in which most of the existing perennial vegetation stands are preserved.

It was been assumed that, in this scenario, the pressure of human demands over wood biomass and fertile lands will be at some point so high that cropland expansion will accelerate. Therefore, LULC transition values were considerably increased during the seventh and the eighth iterations. The intention was that more than half (but less than two thirds) of grassland area would transition into cropland at each of these iterations. Transition probability of grassland into legumes and cereals was set as 33% each in non-hydromorphic soils, maize to 3% in all but the least fertile soils, and rice 7% in hydromorphic soils. Additionally, 3% of grasslands could transition into perennial vegetation. Transition probability of perennial vegetation into legumes and cereals was set as 20% each in non-hydromorphic soils, maize to 25% in all but the least fertile soils, and rice 12.5% in hydromorphic soils.

Transition probability values from crop LULC classes into grasslands were defined as 40% from legumes, 30% from cereals, 2% from maize and from rice; and into perennial vegetation as 20% from legumes and maize, 15% from cereals, and 10% from rice. Only legumes and cereal cells not located in the least fertile soils; and maize and rice cells not located in hydromorphic soils were allowed to change. It was assumed that the high amount of fertilizers applied to maize and rice would make more likely the development of perennial stands after abandonment of their cultivation than in fields previously cultivated with millet, sorghum or groundnut.

Cropland Expansion Scenario (CEXP):

The 35% transition probability of grassland into cropland during the first iteration was expected to be 14% for legumes, 13% for cereals, 6% for maize and 2% for rice. This was introduced by setting the transition probability of cereals and legumes to 15% in non-hydromorphic soils, maize also 15% but in all but the least fertile soils, and rice 27% in hydromorphic soils. The 20% transition rate of perennial vegetation into croplands was distributed among the different cropland LULC classes by assuming that cereals and legumes area would further increase its total area by adding each 8% of the original perennial vegetation area, whereas maize and rice would receive 2% additional area from the original perennial vegetation area. The same soil conditions that were defined for transitions from grasslands were also introduced to the transitions from perennial to crop LULC classes. This was estimated as 9% for the transitions into cereals and legumes, 5% into maize and 22% into rice. Transition probability values from crop LULC classes into non-cultivated vegetation were distributed equally between grasslands and perennial vegetation. This differs from the FLAF scenario, in which transition into perennial vegetation is higher; this represents that in the CEXP scenario the promotion of tree cover in farmlands is not as active as in the FLAF scenario. To achieve such a result, the transition value from grasslands was defined as a bit lower than that of perennial vegetation, because the transition from the former is placed first in the ruleset, and therefore, simulated transitions with the same value in the ruleset would be higher. Transitions from grasslands were defined as 5% from legumes, 4% from cereals and maize and 0.5% from rice, and into perennial vegetation as 5.5% from legumes, 5% from cereals, 3.5% from maize and 1% from rice, without any restrictions. In order to achieve widespread cropland expansion in this scenario in a simple way, there is no exchange between grasslands and perennial LULC classes. This simulated LULCC dynamic, although it is much more simple than the real one, may well be coherent with the scenario’s narrative. The fact that perennial vegetation can only grow after cultivation abandonment represents a situation in which tree regeneration is facilitated in some farming areas, while a multitude of uncontrolled fires are set to expand croplands, inhibiting the growth of perennial vegetation over grasslands. On the other hand, whenever there is clearance of perennial vegetation, only crop cultivation can occur afterwards, because pressing demand for crop biomass prioritizes the high soil fertility during the initial years after clearance.

3.3 Annual crop biomass growth simulation

3.3.1 Methodological overview

The West African savanna belt is dominated by rural economies. Agronomic research across the region has been prolific since many decades ago, at least in comparison with forestry and LULCC science, the other two disciplines addressed in this study. Hence, information on the performance of annual cropping systems is richer.

Traditionally, the performance of agricultural systems has mostly been measured as the weight of the edible biomass yield (Eriksson et al., 2018). Indeed, harvesting of this biomass compartment is usually the main driver of farmers' activity, and the rest of the plant is many times abandoned in the field, without receiving any management treatment for some specific purpose; or burnt to prevent the impact and propagation of late dry-season fires or to increase soil micro-nutrient content for the following growing season. However, such disregard of crop biomass cannot be generalized to the whole farming system of any West African rural economy. This managerial scheme can only be applied to fields far from the homestead, due in part to the high transportation costs, but it is not so common in those closer to the homestead. Rural economies produce, indeed, a much wider variety of biomass-based products which are essential to understand the functioning of the productive system (Bullock et al., 2017). Considering only traditional technologies of biomass use, annual crops already provide a wide array of products, such as raw materials for construction and tools' and feed. Livestock is an important component of the productive systems of Sudanian savanna landscapes. In a region where yields are influenced by a high inter-annual climate variability and post-harvest losses are high, domestic animals serve multiple-purposes (Giller et al., 2011), typical seen as a safety net to overcome punctual, but periodic, food crises. They can feed from plant resources not eaten by humans, and grown in non-cultivated grasslands, and the biomass provided by croplands is an important complementary feed resource. Finally, cropland biomass can be used as cooking fuel, widely used in regions where firewood is scarce; such is the case of this research's study region. Any consumptive use of biomass is problematic because it diminishes the proportion of nutrients that are recycled within the ecosystem and, consequently, imply a reduction of soil fertility unless external inputs are applied, compromising the maintenance of future yields (Brüll, 2015). Indeed, continuous cultivation combined with relatively small quantities of external inputs applied, is the main factor holding crop yields in tropical Africa generally at lower levels than in any other region of the world.

Therefore, to enhance discussions regarding the trade-offs of the different uses of biomass that can guide the sustainability of West African primary production, it is necessary to estimate the potential provision levels of the different goods that can be obtained from biomass. However, holistic assessments of the contribution of annual crop production to the diversity of biomass-based products used in rural economies are rare. Furthermore, the measuring unit “grain yield” is just a rough indicator of the capacity of farming systems to enhance food security. The food security status of many West African regions has barely improved over recent decades (Cudjoe et al., 2010; Abane, 2015; Schraven and Rademacher-Schulz, 2015; Tohinlo et al., 2016), while the adoption of newer crops is expanding, i.e. rice, maize and, more recently, soybean. Better information on the actual benefits that the consumption of different crops can provide is necessary in order to understand the actual impact of the adoption of such newer crops on the food security status of a region (Ickowitz et al., 2019). Over recent years, measurements of the yield of the specific nutrients provided by edible crops are used as a more accurate indicator of their capacity to meet human food requirements (DeFries et al., 2016), and more in-depth studies have been even carried out quantitatively by describing the diversity of the diets (as an indicator for their contribution to enable a healthy development) that can be conformed with the consumption of local food production (Wood, 2018). However, these assessments use data elaborated by public administrations, which are subjected to big inaccuracies due to factors inherent to any collection process of statistical data on small-holder farming systems (Reynolds et al., 2015). Moreover, such data is of little use as input for prospective, spatially-explicit, scenario analyses because it does not provide information on management.

In this study, such shortcomings are proposed to be overcome by simulating data with process-based crop models. Specifically, the APSIM 7.9 platform was used (McCown et al., 1995), in which plant growth is simulated through mechanistic relations with the soil and the atmosphere in a modular, one-dimensional, modeling environment. The choice of this platform was based on its emphasis on simulating soil resources dynamics, which makes it a particularly suitable platform for assessing the long-term performance (Gaydon et al., 2017). Furthermore, APSIM models have proved to perform well in West African savanna agro-ecologies regarding the growth of crops relevant to this study (Akponikpé, 2008; MacCarthy et al., 2010; Tachie-Obeng et al., 2013; Chen et al., 2016; Akinseye et al., 2017), with the exception of rice, without any published evidence to my knowledge. A synthesis of the model structure is provided in the next paragraph.

Jiménez Martínez and Fürst (2021) summarized the characteristics of the APSIM modeling framework as follows:

The water and soil modules are further developments of CERES (Ritchie, 1985). The calculation of evaporation is based on potential evapotranspiration (Priestly-Taylor or Penman-Monteith) and runoff on the USDA curve number. Both algorithms are modified by including the effect of vegetation cover, and in the case of runoff, the effect of tillage practice is also simulated; a three-pool system consisting of fresh, microbial and humic organic matter serves to simulate carbon and nitrogen cycles. Another independent module deals with the transformations of phosphorus in the soil. Crop modules specify the growth behavior of specific crops, with the possibility of choosing among an array of different cultivars. The crop modules communicate at daily time steps with the resource-supply modules, and it is possible to simulate both single- and multi-species cropping systems. Different crops planted in the same field do not have a direct effect on each other, but they do through their influence on the level of resource stocks/fluxes supplied by the radiation, water and nitrogen modules. Finally, a management module simulates the effects of farming practices on crop and resource-supply modules. This allows the examination of a diverse range of agricultural production challenges such as productivity trade-offs in intercropped fields, weed management, and examination of the performance novel cropping practices (Keating et al., 2003).

Environmental and crop phenological data is necessary to run cropping system simulations in APSIM. A tiered-approach was used to choose the input data, with description of the dominant soils and cropping systems of the region (van Ittersum et al., 2013; Vallet et al., 2016). In the following paragraphs a description of the data used is provided. Environmental data is divided into climate, soil and managerial data. A brief mention to the crop phenological data used has been provided together with the managerial data (as it is understood that the choice to cultivate a specific crop or cultivar is a managerial decision).

3.3.2 Input data

APSIM requires daily data on the following climate variables: incoming radiation, precipitation and minimal and maximum temperature. Wide spatial variability of total rainfall amounts and temporal distribution in specific years are common in interior West Africa. This is due to the characteristic cloud and rainfall types, which lends them a high spatial variability (Maranan et al., 2018). Such spatial variability at specific times does not follow a characteristic pattern that may result in climatic differences across the landscape (Sivakumar and Hatfield, 1990). Simply put, some parts of the landscape will receive more rainfall and/or better distributed in some years than other parts of the landscape; whereas in other years, the spatial distribution of rainfall may likely be inverse. The study region has a size too small for models to be able to account for spatial differences in meteorological variables. Due to the flat topography it is assumed that all of the locations within the region are affected by the same average meteorological conditions. Therefore, one single climate dataset is enough to simulate long-term crop yields across the study region because it does not contain climatic areas. Simulated data was downloaded from the National Aeronautics and Space Administration's (NASA) POWER database for the period 1997-2013. The selection of this period allows for the estimation of average yields accounting for the effects of continuous annual cultivation over a same piece of land. Data was selected using the coordinates of Bolgatanga 10.84°N 0.86°W. However, deviations of modeled climate data from the "average regional" real meteorological conditions across the study period can cause high errors in the estimation of yields via crop modeling (van Wart et al., 2013). This data has been used due to the lack of a long-term archive of complete climate data collected in the meteorological stations of the UER. Once the outputs of the crop simulation are obtained, they will be analyzed and compared with yield observations and other modeling exercises in order to validate and discuss the results.

The only natural factor considered in the simulations to introduce spatial performance differentials is the soil type. Relevant yield differences have been observed among fields receiving the same management treatment on different soils (Danso et al., 2018a; Idriss et al., 2018). Important advances have been achieved over the last years in the development and release of spatial soil properties databases, necessary to run process-based crop models. These spatial databases tend to display a gradient of fertility related to landscape position, with lower soil nutrient stocks towards the upslope. However, this gradient can be inverted in some landscapes (Danso et al., 2018b; Danso et al., 2018a). In particular, it not uncommon that the SOC in foot- and middle-slopes is lower than in the shoulder and the valley bottom (Danvi et al., 2017). Due to the complexity of mapping soil physico-chemical properties to the extent used in this research, and limitations in data storage and computational processing capacity, a vector map indicating soil types has been used as input for the spatial distribution of soil fertility.

Savanna soils are typically classified into three types according to their functionality in farming. This classification is defined in base to soil texture: gravelly or shallow soils, deeper sandy soils and hydromorphic soils with a higher clay content; and are related to landscape position: plateaus and crests, middle slopes, and valley bottoms, respectively (Falconnier et al., 2016). A soil types map obtained in 2008 from the Soil Research Institute of Ghana was used (Figure 2.2), and the originally present nine classes aggregated into three broad fertility groups: low fertile soils, relatively high fertile soils and hydromorphic soils. The resulting spatial distribution of soil fertility corresponds, if not exactly, fairly well with the expected landscape positions, which was difficult to map for this mostly flat landscape with the available elevation data. Low fertility soils have been considered to be all those areas covered by leptosols (hereafter, rank 1), as this definition refers to shallow soils developed over hard rock. Luvisols and lixisols, with a more developed profile (hereafter, rank 2) were considered with relative high fertility. The hydromorphic soil type (hereafter, rank 3) encompasses fluvisols and gleysols. Physico-chemical parameters (Appendix 7) of ranks 1 and 2 were taken from measurements on Regosols of a neighboring district (MacCarthy et al., 2010). Although regosols do not appear in the soil map of the study region, this was the best data that could be found so far, because those measurements were taken in a neighboring district and because regosols share common characteristics with lixisols, luvisols and plinthosols (Da Costa et al., 2015). The parameter values of rank 3 soils were obtained from a meta-analysis of Sudanian savanna flood plain soils (Buri et al., 1999). This soil parameterization agrees well with the SOC and C:N ratio of lowland soils in semi-arid/sub-humid transition zone of West Africa, as well as their lower available P than the uplands, as averaged by an alternative source (Niang et al., 2017). SOC concentrations fall within the range found in legacy data collected in the Sudanian savanna of Ghana (Owusu et al., 2020). The crop modules of rice and millet do not operate with the phosphorus module; therefore, the simulation output of these two crops is not limited by the amount of available soil phosphorus.

In this study, only the biomass growth of the core set of crops was simulated because these are the only ones provided in the thematic information of the base land use map. However, complementary crops are of great importance to fulfil healthy diets and provide cash income. This will be considered when interpreting scenario outcomes (in the discussion chapter), because it implies some limitations to assess landscape alternatives in base to food and nutrition security and criteria.

Following the information provided by regional agricultural statistics, literature review, and the given land use map thematic information, the cropping systems have been simplified to four types: millet-sorghum relay, legumes monocrop, maize monocrop and rain-fed rice monocrop. Nutritional, feed and fuel yields are simulated under different field management scenarios, simulated with the process-based crop model APSIM. The output will be used as input of the LULC scenarios to assess their impact on the future provision trends of potential biomass consumption benefits. This way, it is possible to compare the overall performance of alternative crop choices under equal growing conditions, and therefore assess the outcomes of alternative land use strategies.

Management operations of different cropping systems (see Appendix 8) were set following publicly available data and information of the study region or other Sudanian savanna areas. As expressed in Jiménez Martínez and Fürst (2021) in case that a variable could not be set through literature review, the suggested values of the West African APSIM manual were followed. The timing of management events was guided by Bamler (Bamler, 2015) and Boateng et al. (Boateng et al., 2016). It was assumed that the sowing of each crop is conducted after the first "good rains" since the beginning of its typical sowing period. A sowing window of about thirty days was established for each crop. The sowing event is simulated on the first day since the beginning of the sowing window in which 20 mm of rainfall have accumulated over the three previous days, and the soil water content is at least 50 mm in the case of millet, sorghum and maize, and 30 mm in the case of legumes. If such event never happens, sowing is done anyhow by the last day of the sowing window. Sowing depth was assumed to be 5 cm for all crops. In the case of rice, sowing date was established deterministically because it uses another modeling framework, ORYZA, in which sowing windows cannot be introduced.

An estimation of the manure produced within the region was conducted based on district-level livestock data (Shrestha and Alenyorege, 2008), and animal-level annual manure output (Leeuw and Reid, 1995; Sonaiya and Swan, 2004; Ly et al., 2011). The estimated total available manure was averaged over the total cropland area of the study region, resulting in 1,440 kg ha^{-1}. In rural contexts of the Sudanian savanna not all of the manure is collected. The application rates depend on the distance of the field from the livestock enclosure, and on the season, because during the growing season they may be kept far away from the farming areas (Callo-Concha et al., 2013). Collectable fecal matter of cattle varies depending on management, but it roughly oscillates between one and two thirds of total fecal output (Ayantunde et al., 2001). Therefore, the estimated available manure amount was halved up to 720 kg ha^{-1}, as a rough estimation of average manure application rates in croplands. Pigs and poultry are always reared close to the households, but their contribution to total manure production in the study region was negligible. Manure application is necessary to sustain the soil nutrient cycles. However, in the short-run, it does not have direct effect on yields unless it is applied at rates of several tons per hectare. Therefore, under the lack of a method to spatially allocate manure management, it was assumed that all the fields receive the same amount of manure, and because under that assumption, the average manure application rate is too low to have an effect on yields, different levels of manure application were not considered as a management factor.

3.3.3 Cropping field’ management scenarios

The default simulation of the APSIM model used in this study only simulates the interaction of crops with two nutrients: nitrogen (N) and phosphorus (P), hence the outputs assume that the soil stocks of other nutrients are available in quantities sufficient for not limiting crop growth. Management scenarios were set as described in Jiménez Martínez and Fürst (2021). The application of mineral fertilizer was included as a factor of five different rates: 0N-0P, 5N-2P, 20N-7P, 50N-17P and 100N-33P (units expressed as kg ha^{-1}). In the case of legumes, fertilizer rates were 5N-5P, 15N-15P and 30N-30P. Only three rates of fertilizer application were used for legumes because increased levels did not result in relevant crop yield increase. Note that the expressed amounts of fertilizer application refer to the amount of the element contained inside the fertilizer product, not the amount of the fertilizer product itself. Whenever mineral fertilizer is applied, the application consists of two splits: the first one the same day as sowing, and the second application 35 days afterwards. All of the phosphorus is applied at sowing, in combination with one third of the total nitrogen to be applied to the crop (in the case of legumes, half of the total nitrogen to be applied). During the second split, the remaining nitrogen fertilizer is applied. In the case of rice, three splits are applied: the first eleven days after sowing, the second twenty days after the first application, and the last split fifteen days after the previous application. During each consecutive split, the rate of nitrogen application in rice fields is incremented by doubling the rate of the previous split.

Additionally, two tillage practices were simulated. One simulates no-till with application of herbicides. In this case, no tillage event is simulated and no weeds grow within the simulated field. In the other case, conventional tillage and hand-weeding is practiced. Under this management, a weed population is simulated using the growth model of the sorghum module, which may grow during a sowing window starting 1st of April and ending 14th of October. The requirements for the weeds to grow are the same as those for sowing legumes, and weed emergence episodes may occur up to four times during the sowing window. Density of weeds was assumed to be 3.33 plants m^{-2}, with seeds located at 1.5 cm depth. In these simulations, a seed-bed is prepared 23 days before the start of the crop sowing window with disc tillage at a depth of 200 mm. During such event, all weed population is killed, organic residues incorporated into the soil, and the runoff curve number (CN) is reduced by 20, requiring 150 mm of cumulative rain to dissipate the impact of tillage on CN. Hand-weeding may occur up to three times during the crop growing period whenever weed biomass is higher than 750 kg ha^{-1}, or no later than 20 after (re-)emergence of the weeds, whichever comes first. It is assumed that most of the weed population is removed from the field (90%) and the remaining weeds are incorporated into the soil. In the no-tillage simulations, only 25% of the non-edible crop biomass is removed from the field. In the conventional tillage simulations, additionally, removal of all the non-edible biomass from the field was also simulated.

Finally, different sowing densities and cultivars were introduced as simulation factors. Among cultivars whose ontogenic behavior is parameterized in APSIM, the most widely adopted in (West) Africa were used. The exception is rice, for which only Asian *Oryza sativa* varieties are available. In this case, a variety named “local” by the APSIM platform was chosen.

Annual yields of each simulation were averaged over the entire simulated period in order to compare them with other data sources, as a way of validation and to better understand the uncertainty range. The average grain yield values under simulated low input management were assigned to their corresponding baseline assessment unit (LULC and soil class) location. Then, they were compared with district-level official agricultural data averaged between 2007 and 2013 in order to evaluate their suitability to define the baseline scenario. Records in the official agricultural data of the previous years were disregarded because by that time the area of the nowadays existing districts of Talensi and Nabdam was included within the Bolgatanga Municipal District. Assuming that whenever farmers have fertilizer, they tend to apply most or all of it to their maize and rice fields, it was assumed that in the baseline scenario, maize receives 5N-2P, which is close to the 8 kg N ha^{-1} reported in the Upper West Region of Ghana (Tachie-Obeng et al., 2013); and 20N-7P, which is close to the 25-33 kg N ha^{-1} are actually applied (Donkoh et al., 2013). It was assumed that no mineral fertilizer is applied to millet, sorghum and groundnut in the baseline scenario. The output of other management simulations was compared with field-scale observations in Sahelian, Sudanian or Guinean savanna agro-ecologies reported in scientific literature.

3.4 Woody biomass growth simulation

3.4.1 Wood growth dynamics in West African savannas of the Sudanian belt

Tropical savanna regions, due to their warm temperatures and relatively high annual rainfall, are naturally suitable for the development of woody vegetation stands. Indeed, within the rainfall range where our case study region is located, there is potential for the closure of woody canopy vegetation, but this rarely occurs due to recurrent disturbances (Sankaran et al., 2005; Liu et al., 2017) and the competition of herbaceous populations. Hydraulic lift by the roots of woody plants maintains a certain level of available water in the topsoil layers, allowing herbaceous populations to thrive after these disturbances and compete with the regeneration of woody stands, therefore maintaining the savanna state (Yu and D'Odorico, 2015). But disturbances and interactions with herbaceous populations do not necessarily limit the growing woody biomass. They indeed enhance it, unless the frequency of their action or their intensity is excessive. The relationship between growing biomass and the factors that shape its dynamics and amounts is non-linear (Hiernaux et al., 2009a; Hiernaux et al., 2009b). Hence, rainfall seasonality, its wide inter-annual variability and spatial patchiness, combined with the competition with grasses and the effects that herbivory, fire and woodcutting introduce into such interactions, result in open canopy landscapes with a mosaic of different tree densities and species composition.

Despite the fact that both the potential and the actual AGB across West Africa follows the rainfall gradient, the explanatory power of the relation between average annual stand growth and rainfall or spatially organized soil properties has been revealed to be very low (Picard et al., 2006; Breman, 2012; Veldhuis et al., 2016; Veldhuis et al., 2017). For example, in the Sahel most woodlands are composed of micro-phyllous nutrient-fixing species resulting in fast-growing stands, whereas in the wetter savanna regions the common woodland is formed by broad-leaved species, many of them do not fix nitrogen, the competition with grasses is higher and the higher rainfall leaches out more nutrient from the soil, which may result in a comparatively slower growth than many Sahelian stands. (Timberlake et al., 2010; Mbow et al., 2013). The usually faster growth of nitrogen-fixing savanna tree populations shall not be taken for granted, because grass competition for soil mineral nutrients can be very high and neutralize the effect of fixed nitrogen on tree growth. Moreover, in soils with poor content of available phosphorus, growth will be limited, regardless of the nitrogen available to tree populations (Cramer et al., 2010). The regeneration pace is more related with the variability in intra-annual rainfall distribution which largely defines the competitive outcomes between grasses and saplings, as well as the severity of the impacts of fire and livestock (Baker et al., 2003; Breman, 2012; February et al., 2013; Chidumayo, 2015; Singh et al., 2018). During dry years, recruitment of individuals into the adult stage is more likely to occur due to the absence of a layer of herbaceous biomass competing for resources (Cramer et al., 2010; February et al., 2013; Tomlinson et al., 2019). Moreover, herbaceous biomass can also limit the growth of adult trees in nutrient-rich savanna soils (Riginos, 2009). Clayey-hydromorphic soils can support more aboveground biomass (AGB) than sandy and loamy soils, but such potential can only be achieved with the exclusion of fire and herbivory (Moser-Nørgaard and Denich, 2011; Colgan et al., 2012; Holdo et al., 2012). Because this exclusion is rarely effective, it may explain why it is not infrequent that the regeneration and standing biomass of woody vegetation in valley-bottoms is lower than in plateaus and hills (Orthmann, 2005; Colgan et al., 2012; Assédé. et al., 2015).

Therefore, woody vegetation structure and productivity in Sudanian savannas is highly variable, particularly in young fallow lands, and ultimately determined by differing land use histories, current intensities of livestock husbandry and wood collection, and species composition (Gignoux et al., 2006; Fuwape, 2011; Breman, 2012). Most of the woody stands growing in savannas are not long-lived due to the interaction between fires, humans, wildlife, trees, grasses and periodic droughts, rarely exceeding 30 years (Swaine, 1992; Soto Flandez, 1995; N'Dri et al., 2014; Pellegrini et al., 2017). Due to repeated disturbances, the development phase of a savanna plant community may be difficult to determine, even in long-term research sites (Gignoux et al., 2006). Hence, it is not common to find stands that had been growing under favorable conditions over their lifespan, and from which estimations of potential maximum growth can be derived. Moreover, the economic interest of the colonial and the national states in savanna woodlands has been very low; existence of such land use histories is largely unknown. The lack of long-term, replicated studies, does not allow simulation of site-specific potentials of biomass provision.

The estimation of woody biomass provision dynamics would be of great utility in regional sustainable economic planning in West Africa, where wood biomass is the main fuel resource. Overharvesting and cropland expansion, coupled with severe impacts of grazing and fire, seriously reduce the capacity of the landscape to maintain the flow of biomass provision. Fuelwood value chains have, without any doubt, a high degree of resilience. Wherever wood resources become scant, extraction shifts are made to better stocked woodlands (Nketiah and Asante, 2018), allowing the regeneration of previously exploited stands. The natural functional dynamics of savanna vegetation enable this resilience: savanna trees usually regenerate well from sprouts, and they tend to accumulate biomass at a faster pace when this occurs. Moreover, grazing and fires may promote the development of woody stands by suppressing the competition of growing herbaceous biomass. However, at the country and agro-ecological region levels, the reduction of woody biomass resources has been evident over recent decades.

The decrease in tree cover in bush areas has been common across landscapes of the Volta Basin (Paré, 2008; Caillault et al., 2012). Drivers of deforestation and woodland degradation in savannas can be described as largely mosaic, unlike those operating in more densely forested biomes, which can be described as largely frontier drivers. Those drivers are executed by many different actors, from local to national and international, with different interests in the savanna resources, such as charcoal, precious lumber or fresh pasture and bush meat (facilitated by setting fires and thus, limiting the regeneration of woody vegetation) (Agyei et al., 2014).

In economic terms, there is evidence that forest degradation both in Ghana and Burkina Faso is in general profitable for rural households, because the products provided by forests are also provided by the non-forest environment, where additionally a more diversified range of income-generating activities can be performed. This has been associated with restrictive forest-use policies (Pouliot et al., 2012), although it can also be possible that forests in the savanna zone have no other main value than preserving landscape functions. Perhaps the lack of accessibility to forest products due to their remoteness or dis-services, such as wildfire threats, makes them undesirable for livelihood sustenance. The wider diversity of livelihoods of non-forest, tree-dispersed, lands, and their comparable productivity in comparison to forest lands may be also, to a high degree, a consequence of ecosystem functions and capacities, regardless of forest use rights. In many regions, such as the one targeted by this case study, woody biomass has become so scant that the main source of fuel has shifted to crop residues or animal dung, which has serious consequences for the sustainability of agricultural yields.

Hence, a key priority for land use planning to achieve the sustainability of rural economies is to maintain the flow of woody biomass provision. In order to ensure the sustainability of wood production, it is necessary to have a grounded knowledge of the growing resources, their growth dynamics and their biomass storage capacities. Such knowledge is based on inventoried data which, through systematic surveys consisting of repeated observations over replicated plots, can serve to anticipate the expected production of woody biomass in the future. However, such information is not available to inform regional planning processes in West African savannas. Spatial assessments of woody biomass provision are usually provided at landscape level (Devineau and Fournier, 1998; S.E.R.F, 2004; Fischer et al., 2011), and because repeated observations or replicated plots are not conducted, stand level growth dynamics remain largely unknown. Due to the wide variability of biomass growth and storage capacity of savanna woody stands, it is difficult to transfer such data to other areas within the same agro-ecological region without carrying high levels of uncertainty. Attempts to assess large-scale sustainable harvesting levels (at the agro-ecological region level) have also been conducted out of the synthesis of available topographic maps and remote-sensing images (Millington et al., 1994), but such assessments have not been replicated over time. Hence, the estimations provided are also static values, without representing the dynamics of biomass accumulation across the lifespan of woody stands. Static growth or yield data can be useful to estimate biomass stocks in a far future LULC scenario, but it cannot be coupled to dynamic LULC change assessments relevant to inform current regional economic policy.

3.4.2 Modeling the potential growth of an average (semi-)natural vegetation stand

Whereas the AGB of annual vegetation experiences turnover every year, the AGB of perennial vegetation persists and grows over the span of several years until it dies. Concerning landscape change simulation, this implies that the AGB value of cells containing perennial vegetation must vary over the passage of the simulated time. This can be done by supplying data of stand growth tables to the simulation (Frank et al., 2015). Simulation of woody stand growth has been necessary because forest inventories (including AGB data) of the study region are not available. Stand growth has been modelled empirically, after reviewing published AGB data on measurements of stands' AGB and growth of woody stands across the Sudanian savanna belt. Two criteria have been followed to select the data that was used as input for the empirical model: the similarity to the stand types and environmental conditions of the study region, and the suitability of the data to model potential growth, i.e.: the observed data was measured in stands which had not suffered severe disturbance impacts that could have hampered their growth.

Growth tables are summaries of the expected ontogenic growth of perennial vegetation stands tabulated by stand age. However, such growth varies considerably among stands, driven by characteristic combinations of climate, soil, species composition and land use history. Hence, there is a high degree of uncertainty in summarizing the expected growth of natural stands (Vanclay, 2001). Moreover, although some of the trees growing in parklands have been planted (Breman, 2012), they have never been the object of dense plantations and, hence, their growth performance under varying conditions remains largely unknown.

Acknowledging such a level of uncertainty, and until more data and better knowledge is available, this chapter explains the development of a standard growth table for mixed-species, uneven-aged, stands of the Sudanian savannas based on “common” or “medium” potentials observed across literature, assuming a higher degree of confidence in observations conducted in stands of the Volta basis. This standard growth table is made by applying a logistic model (Fekedulegn et al., 1999; Paine et al., 2012) to a meta-analysis of published data on the AGB of stands of known regeneration age in fairly well protected observation plots. The simulated growth table can be used as an estimation of the expected productivity values of regenerating woody stands subjected to low-cost management regimes, and protected with the aim of sustaining the availability of wood resources to local populations. Management practices described by (Soto Flandez, 1995) can be used as a guidance to achieve such productivity levels, which ultimately should be updated as site-specific observation campaigns are conducted.

The growth dynamic of any woody stand not subjected to strong disturbance impacts approximates the shape of a logistic curve (Fekedulegn et al., 1999; Paine et al., 2012). The pace of biomass production is slow during the very first years and becomes incrementally faster as vegetation increments its size, slowing down once a threshold is surpassed until the maturity stage is reached. This last stage is characterized by the maintenance of a relatively constant biomass production in equilibrium with biomass turnover due to mortality, and hence, the standing biomass becomes fairly constant (Breman, 2012).

This growth behavior can be simulated with very few input data: one observation during the early stages of growth and an estimation of the potential maximum standing AGB are enough to parameterize the model (Deklerck et al., 2019). In this study, a 4-parameter Gompertz equation (Eq. 2) was fitted to published data with the *nl* self-starter function of Stata.

$$\omega(t) = \beta_0 + \beta_1 * \exp(-\exp(-\beta_2 * (t - \beta_3))) \qquad \text{Eq. 2}$$

Where $\omega(t)$ is the AGB at time t, and β_0, β_1, β_2, and β_3, are the parameters to be estimated by the self-starter function.

As input data, we used observed AGB of coppiced natural vegetation stands of known age and effectively protected against disturbance during its lifespan (Table 3.2). This limited our input data for non-riparian forest to just four observations of stands aged between 5 and 14 years in Central Burkina Faso (Nygård et al., 2004). These stands are suitable for the simulation of the stands of the study region not only for having been fairly well protected during the observation period, but also because they grew on luvisols, the same soil type upon which most of the remaining woodlands of the study region grow. The age at which Sudanian savanna woodlands reach the maturity stage is unknown. Actually, it is difficult to predict because most of the woodland formations are very dynamic due to the continuous action of stressors. Thereby, the vast majority of the stands are relatively young, rarely over 30 years of growth age.

Hence, to allow the self-starter function freedom in the estimation of parameters without being restricted by a potentially premature asymptotic value, the (unknown) age at which maximum standing biomass is reached was set arbitrarily at a high value (200 years). Maximum standing biomass in Sudanian savannas is around 120 t ha^{-1}, attained only in riparian corridors (Chabi et al., 2016; Dimobe et al., 2019b). The extent of these corridors in the study region is very small. In order to keep the simulation process simple, the same growth table will be applied to all of the woody cells. Hence maximum AGB values of riparian forests have been excluded. Maximum observed standing biomass on dense, non-riparian woodlands ranges 60-100 t ha^{-1} (Orthmann, 2005; Chabi et al., 2016; Dimobe et al., 2019b). However, these observations have been taken either in regions with a land use history with much lower impact of disturbances or with slightly higher average rainfall and more homogeneous intra-annual distribution. The study region is highly populated, and there is no area where woody stands have been growing under low disturbance pressures (Nindel, 2017). There is no evidence that non-riparian woodlands in the White Volta basin reach those levels of AGB. It can be expected that this biological AGB potential can be achieved under the appropriate management regime. However, raising the asymptote would also increase the mean annual increment of young and early mature stands much higher than what is observed in protected stands of the White Volta basin. Thereby the asymptote was kept in the typical levels observed in non-riparian woodlands of the White Volta Basin. It has been observed that stands growing in areas affected by moderate disturbance pressures reach about 72 t ha$^{-1'}$(Balima et al., 2020). This is very close to the baseline map maximum value within the study region of 74 t ha^{-1}. Hence, this value has been chosen to define the growth asymptote. This does not mean that higher biomass is achievable. For example, it has been reported that there exists 82 t ha^{-1} in *Anogeissus leicarpa* stands of the Oti-Keran Forest Reserve of Northern Togo, but due to a lack of precise data on site qualities, maximum AGB had to be defined arbitrarily, and the value has been chosen based on common maximum AGB values found in literature and in the baseline AGB map. To force the logistic shape of the growth simulation curve, small biomass values within the first year of growth were added as input for the self-starter function.

Table 3.2 Input data of the empirical stand growth model for perennial vegetation

Age *years*	**Woody AGB** *t ha^{-1}*	**Source**
0.1-0.4*	0.5*	

5	7.3	Nygård et al., 2004
10	17.5	
14	22.4	
200-300*	74.1	Balima et al. (2020), Chabi et al. (2016), Dimobe et al. (2019b)

*initial biomass and old-growth stage age were arbitrarily set by the author

The baseline AGB map was used to create a baseline woody stand age map, by applying the inverse of the above-described logistic function to the values of AGB map. The plausibility that all the stands of the same age contain the same AGB is very low, but this approach is the only way to create a baseline scenario that allows simulation of stand growth while having an indicative value for the actual expected AGB of stands of a certain age.

The classes tree/woodland and mixed vegetation were aggregated into one single class that we will call “woody vegetation”, to refer to any pixel that contains some woody vegetation. This was done to ensure a seamless linkage between stand-level growth tables and the time-series of LULC maps. The class “mixed vegetation” refers to a mix of woody and herbaceous vegetation, hence representing a successional state of regenerating woody biomass which, with the passage of time, will become a fully grown tree or woodland. The accumulation of biomass growth over such a successional state is already implied in the growth tables, and hence there is no need to establish such class differentiation in the LULC map. The two woody LULC classes of the input LULC map were merged into one single class. The value of pixels of the biomass map overlaying non-woody pixels of the baseline LULC map were reclassified to zero.

3.4.3 Simulation of wood potential harvest

Finally, a heuristic method was developed to simulate wood harvesting events. Growing woody vegetation provides a continuous flow of biomass goods. Wood harvesting in savanna regions is done in various ways, such as pruning of isolated trees, thinning of growing stands or collection of fallen dead wood, the latter being the main resource harvested in community forests. Cutting of branches in community forests only occurs in areas where the stocks of dead wood are insufficient to meet the demands of local populations. Silvicultural management, if done appropriately, increases both AGB and timber stock recovery rates as compared to undisturbed forests (Gourlet-Fleury et al., 2013; Duah-Gyamfi et al., 2014; Mola-Yudego et al., 2016). However, systematic silvicultural management is rarely practiced in savanna woodlands of

Northern Ghana. There are no records of harvested wood, which is sourced by a multiplicity of individual actors, both local and extra-local, including the not uncommon illegal commercial lumbering activities. Trees are also exploited for forage supply by different methods, some of them reducing wood production drastically (Sanou, 2014). Furthermore, there are no long-term surveys of stand level biomass growth in northern Ghana, which would be necessary to understand the impact of harvesting practices on growth dynamics and maximize sustainable yield levels.

Systematic silvicultural management plans and actual practice in West African Sudanian savannas have being reported exclusively in francophone countries. Here, the management prescription consists of rotational coppicing. The landscape object of the silvicultural plan is divided into different areas, each of them subdivided into as many blocks as the length of the rotation (ranging between 10 and 20 years). Each of the blocks is harvested only once during the whole rotation period. Harvesting consists of logging half of the growing volume. The biggest and best-shaped trees are allowed to continue growing to serve as “nursery” trees, ensuring the maintenance of the soil seed bank until they are too old, then logged to provide high value timber (Diarra, 1999; S.E.R.F, 2004; Ouédraogo, 2006; Sawadogo, 2007; Sow, 2012). This management prescription is based on the assumption that by the end of the rotational period, every block recovers the totality of its initial AGB (PROFOR; Melin et al., 2016). Hence, the higher the initial standing biomass, the higher its estimated annual productivity is. Due to the lack of forest inventories in the study region, representing such management in simulation studies is very challenging. It would require creation of one specific growth table for each of the baseline biomass levels. Moreover, this type of silvicultural studies does not assess the productivity of new stands, growing over previously treeless land. Hence, it can hardly be linked to LULC change studies.

It is difficult to derive sustainable harvestable yields from stock growth because most of the studies on the dynamics of woody vegetation in savannas have overlooked the impact of tree harvest by humans (Tredennick and Hanan, 2015). This lack of appropriate data poses serious limitations to the simulation of harvesting episodes and its impact on growth. Hence, wood harvest in this modeling exercise will occur exclusively whenever a woody vegetation LULC changes into another LULC class at any location. This means that as long as a woody LULC class pixel does not change into another use, it will not provide any quantity of wood, and its growth will continue unaffected, following the dynamics shaped by the modelled logistic curve. In other words, the model simulates that wood is exclusively harvested by clear cutting of whole plots (represented by woody LULC cells). The spatial distribution of tree felling in savanna regions of Ghana is typically mosaic (Agyei et al., 2014), and therefore, the small pixel-size of the LULC data (25 m, i.e: 625m^2) eases the representation of those spatial patterns. Nonetheless, other wood harvest methods have not been simulated.

3.5 Projections of biomass demand

Following the systems ecology perspective of the cascade framework (La Notte et al., 2017), the generation of biomass from plants is an ecosystem service. To understand the benefits that can be derived from biomass consumption, more precise indicators can be used: the food for human consumption and its nutritional properties, the provision of feed for livestock and fuel. In this study, special attention has been placed on the capacity of regional yields to meet the key nutritional and cooking fuel requirements of the local population. The benefits derived from ecosystem services can be measured in the potential number of persons that can meet their nutritional requirements or fuel demand through consumption of the biomass produced within a certain area (Olander et al., 2018). First, the concentration of nutrients and fuel potential value of the different plant and biomass types and second, the average human demands for those qualities, were quantified. In the case of feed, only the provision side was assessed.

3.5.1 Quantification of the key consumptive qualities of biomass

Key nutrients assessed in nutritional adequacy studies are energy, iron, zinc, vitamin A and iodine (Ogutu et al., 2020). Other nutrients are also important, but these four form the core of most nutritional adequacy studies. In this study, only three nutritional indicators have been considered: calories (as an indicator of food security), and the micronutrients iron and zinc (as indicators of nutritional security). The assimilation of these two micronutrients is essential for the physical and mental development in children, and its deficiency leads to high mortality and illness rates. Iodine and vitamin A are also key micronutrients. However, their density in grains (unless they were bio-fortified) are negligible. Therefore, they have not been included in the assessment because the land use map used in this study does not contain thematic information on LULCs relevant for the provision of these micronutrients. Nutrient content data have been compiled from the West African food composition database (Stadlmayr, 2010). Nutrient Content (NC) is the amount of a nutrient per 100 g of dry matter of food: calories in the case of energy, and milligrams in the case of iron and zinc.

Regional provision of solid biomass fuel included the wood biomass and crop stalks. The use of food crop biomass residue must be considered in any land development strategy because the rate of biomass turnover plays an important role in ecosystem functioning. Traditionally, great parts of the biomass residues from food production were burnt in-field due to a number of causes. Over recent decades, crop residues have been increasingly used as cooking fuel to substitute wood in regions where the availability of or accessibility to the latter is diminishing. In the study region, for example, most of the households use crop residues as a fuel resource (GSS, 2013), whereas fuelwood is used by 37% of households and charcoal by 23%. Moreover, 30% of the households use crop residue as their main fuel resource (in Bongo district, almost 54%) (GSS, 2014b, 2014a). Crop residues are bulkier and less dense than wood, and therefore, require higher storage space for the same amount of fuel potential. However, they are easier to transport in small-amounts and require much shorter harvesting time because it does not imply displacement out of the households' working fields. Therefore, they are a very efficient way to provide fuel for the household economy. The energy available for fuel purposes in the region is expressed in this study in units of Net Calorific Value (NCV), also known as lower heating value. This unit refers to the amount of heat available after evaporation of all the moisture contained by the fuel material. NCV of crop residues were obtained from Duku et al. (2011), and NCV of wood biomass was estimated by averaging values of different tree and shrub species of the Sudanian savanna (Erakhrumen, 2009; Amoah and Cremer, 2017).

Livestock is also an essential component of rural savanna economies (Turner, 1995; Douxchamps et al., 2012; Descheemaeker et al., 2016), may improve the nutritional quality of diets (Nyantakyi-Frimpong et al., 2018) and given the ongoing rising demand of animal products (Elbehri, 2013; Smith et al., 2013), it is likely to continue to be an essential component of such economies for a long time. This means that crop choices are not only determined by their food, but also their feed provision potential. Regarding feed yields, only the supply side was included in this study. The study lacks data that could help to estimate the size of the regional livestock herds and their nutritional requirements, determined by their movements. Moreover, the quality of the feed necessary to satisfy certain demand of animal growth varies highly depending on its condition (fresh/dry). Crop residues are usually provided to livestock throughout the dry season, but these tend to have very low nutritional quality because the storage capacity is not sufficient. Therefore, feed quality varies widely among different locations within the Sudanian savanna zone (Amole and Ayantunde, 2016b). However, it is not always reported in the same units. Metabolizable energy (ME) is an indicator normally used to assess feed potentials.

Therefore, feed values in this study were expressed in metabolizable energy and collected from studies in Burkina Faso and Niger (Amole and Ayantunde, 2016a, 2016b). Ideally, both crude protein (CP) and metabolizable energy values should be reported, because the CP:ME ratio is a better indicator of feed quality (Lamers et al., 1994), but a regional average of the CP:ME ratio would be a poor indicator.

Market value was obtained from MoFA data (unpublished) and refers to the average market value (2007-2013) of each crop in the Bolgatanga market.

Grassland feed provision was included, assigning the same value to all cells, based on the median metabolizable energy of grasslands surveyed across the semi-arid regions of the Volta basin (Ferner et al., 2018).

In this study, perennial vegetation provides only woody biomass, due to shortcomings to simulate the evolution of the production of leaves, fruits and other biomass compartments over the ontogenic growth of undifferentiated species.

Table 3.3 Nutrient content, fuel, feed and market value of each LULC class and crop specie (Jiménez Martínez and Fürst, 2021).

	Nutrient content			**Fuel value**	**Feed value**	**Market value**
	calories	**Fe**	**Zn**	**NCV**	**ME**	
Crop	*cal kg $^{-1}$*	*mg kg $^{-1}$*	*mg kg $^{-1}$*	*MJ kg^{-1}*	*MJ kg^{-1}*	*\$ kg^{-1}*
Groundnut	2,370	43	19	-	7.26	0.963
Millet	1,440	59	11	15.5	5.24	0.582
Sorghum	1,530	36	6	17.0	5.57	0.394
Maize	1,350	14	5.5	15.5	7.88	0.314
Rice	1,340	8.5	5.5	15.6	6.20	0.909
Perennial	-	-	-	17.7	-	-
Grassland	-	-	-	-	11.03*	-

*Grassland ME values are expressed as GJ ha^{-1} year^{-1}.

3.5.2 Estimation of human nutritional and fuel demand

An assessment of the actual benefits that can be derived from agricultural biomass consumption was carried out to complement the analysis of grain yields. These benefits were expressed as nutritional yields of calories, iron and zinc; fuel yield; feed yield expressed and metabolizable energy for ruminants; and monetary value, expressed as the average value of grains in the Bolgatanga market between 2007 and 2013. The results were synthetized in spider graphs using normalized values of the simulated biomass production of each crop (and the corresponding biomass compartment for each variable) under equal management intensities and averaged over the baseline LULC map. Groundnut was excluded from the comparison because it performed better than the rest of crops for all variables (with the exception of fuel), and therefore, much of the representational power of the graphs would have been lost. Finally, due to lack of data, the calculation of the market value of land produce is incomplete, because it does not include the value of crop residues, although they are also often sold in markets.

The ecosystem good provided by food nutrients has been measured in Nutritional Yield (NY) units. This variable expresses the number of persons who would be able to obtain 100% of their Daily Recommended Intake (DRI) of a particular nutrient from a food item produced annually on one hectare (Eq. 3) (DeFries et al., 2016):

$$NY_{ij} = \frac{NC_{ij} \times 10}{DRI_j} \times \frac{y_i}{365} \qquad \text{Eq. 3}$$

Where NC is the Nutrient Content in crop *i* of nutrient *j*; DRI is the average Daily Recommended Intake of nutrient *j*; the value has to be multiplied by 10 because the NC value is expressed in content per 100 g of food; whereas *y* is the edible yield of the crop *i* expressed in kg ha^{-1} $year^{-1}$; and divided by 365 because DRI is a measure of daily intake.

Average caloric requirements were defined as Energy Minimum Requirements (EMI) and estimated at 2,227 calories per day (United Nations University et al., 2004) (Appendix 9). Average DRI of iron 16.26 mg per day (Appendix 10) and zinc 6.02 mg per day (Appendix 11) (World Health Organization and Food and Agriculture Organization of the United Nations, 2004) were obtained by weighting the DRI of the different age-sex population groups of the two districts that constitute the study region, under the assumption of cereal-based high-phytate diets, with insufficient ingestion of fruits, vegetables and animal products, implying low iron and zinc bioavailability (World Health Organization and Food and Agriculture Organization of the United Nations, 2004; Joy et al., 2014).

The estimation of the levels of regional biomass fuel demands is more complex and subjected to higher uncertainty. Whereas nutrient demands are fairly the same for every person (particularly for all persons of the same age-sex group), fuel demands are highly determined by several technological factors -such as the efficiency of biomass-to-energy conversion technologies, supply of energy from other resources different than biomass and the extent and quality of the electricity grid-, as well as the size of the household, the different types of energy end-uses (cooking, house heating, agro-processing and other industries…) performed in the study region and, to a lesser degree, the environmental factors of the space where the fuel is burnt (wind, ambient moisture and temperature, etc). Making assumptions about the future evolution of these factors in a specific region is much more complex than estimating nutritional demands. In this study, fuel yields will represent the number of persons that can satisfy their demand for cooking fuel assuming that all of the harvested wood and stalks are used exclusively for cooking purposes.

Net calorific values (NCV) are a poor indicator for the mass of fuel material necessary to meet a certain level of consumption demand. For the consumer of the fuel, what is relevant is how much heat is involved in generating a certain work at any given time. In the case of cooking tasks, for example, this means how much fuel mass is necessary to cook one meal. This can be better estimated by measuring “useful energy” (USE). This concept refers to a unit that measures the heat utilized for the purpose for which fuel is consumed, e.g. the heat transmitted to the pot/pan during the food-cooking process. The efficiency of the different cooking technologies (i.e. the proportion of the energy generated in combustion which actually serves the purpose for which combustion takes place) varies considerably between different cooking equipment and fuel resource types (e.g. the burning time of crop residue biomass is shorter than that of wood, and therefore, incurs in higher heat losses).

The adoption of technological innovations offers the opportunity to use energy from biomass more efficiently. Gasification or production of ethanol are suitable technologies to generate electricity or substitute biofuels, however, the adoption of these technologies in sub-Saharan Africa is still mostly confined to southern Africa (Mohammed et al., 2013), whereas in the rest of the continent it has not developed much further than the experimental stage.

An alternative cooking technology scenario can consist of the substitution of traditional fire cook stoves by domestic gasifiers. Microscale biomass gasification is a very promising technology in rural areas because a wide variety of feedstocks can be used in most gasifiers (Roth, 2014). The comparison of the regional energy efficiency of this technology with those of the traditional biomass-burning technologies is straightforward, because both involve the same operations (only transportation of crop residues to the household). The comparison with bigger-scale biomass-to-energy conversion facilities with the potential to provide electricity (Bakhiet, 2008; Field et al., 2016) or liquid biofuels (Ayamga et al., 2015), extends beyond the scope of this study, as it would require an analysis of the energy involved in the construction and maintenance of the facilities, as well as different transportation and operational costs. Most gasifying cook stoves are to be fed with biomass pellets, a processed product resulting from the densification of biomass by drying and pressing. However, gasifiers designed to burn unprocessed biomass do also exist, as well as gasifiers able to burn both pellets and unprocessed biomass. In this study, biomass fuel demand over time will be calculated under a scenario in which conventional flame cooking devices will continue to be used, as well as scenarios in which gasification stoves will be progressively adopted. For these latter scenarios, the energy input consumed for the conversion of all biomass harvested in the simulation into pellets will be discounted from total regional useful energy yield. This energy input has been assumed to be 0.365 of the output NCV (Kayo et al. 2014, pg 318).

Useful energy shall not be considered as a final measure of energy consumption. Gathering the required detail on final consumption separately for each type of end-use equipment within each consuming establishment would be extremely costly. However, illustrative examples of conversion efficiencies (the ratio between useful energy and net calorific value) can assist regional land use planning activities by providing a better estimate of the biomass quantities necessary to be harvested in a region in order to satisfy demand (Harris, 1991; O'Sullivan and Barnes, 2007). The conversion efficiencies of NCV into useful energy of unprocessed wood and crop residues burned in traditional and efficient cook stoves has been obtained from (O'Sullivan and Barnes, 2007), and those of gasifier cook stoves by averaging the efficiencies of the household-scale gasifiers available in Ghana according to the clean cook stove database (Table 3.4). Efficiencies of large gasifier stoves (such as those that can be used in schools, hospitals restaurants, etc.) can be higher (http://catalog.cleancookstoves.org/, last accessed on 16.12.2021), but they have not been considered in this study.

Table 3.4 Energy conversion efficiency of different solid biomass fuels and cook stoves

	Conversion efficiency *USE:NCV*
Pellets, Tier 4 gasifier stove	0.40
Fuelwood (15% moisture), efficient stoves	0.25
Fuelwood (15% moisture), traditional stoves	0.15
Crop residue (5% moisture)	0.12

Use of cooking fuel also depends on the foods to be cooked and, mainly, on the size of the households. Such differences can be considerable. In northern Nigeria, for example, it was estimated that the average annual fuelwood consumption per capita of bigger households was 144 kg year^{-1}, whereas in smaller households 1,200 kg year^{-1} (Cline-Cole et al., 1990). Data on average consumed useful energy is rarely available, but it can be estimated because data on average household firewood consumption is relatively abundant. It is usually gathered by measuring the wood biomass consumed by surveyed households per day. However, to my knowledge there is no available data on the average household amounts of crop residues used for fuel purposes. In this study, average charcoal and wood consumption by households in five districts of the Upper West Region of Ghana (UWR) has been used. In these districts, the use of firewood as a fuel resource is dominant, whereas the use of crop residues is low (GSS, 2013). Therefore, data on wood consumption can be used to make a good approximation of the total average useful energy consumption. With an average per capita consumption of wood of 193 kg year^{-1} and 69 kg year^{-1} of charcoal (Ayamga et al. 2015), the total useful energy per capita is 995 MJ year^{-1}. The calculation of the useful energy provided by charcoal was obtained by assuming a wood-to-charcoal kiln conversion efficiency of 25% (Energy Commission, 2006), charcoal NCV of 30 MJ kg and a cook stove conversion efficiency of 25% (O'Sullivan and Barnes, 2007). Furthermore, in the UWR the diets, cooking technologies and the environmental conditions of the cooking spaces are very similar to those of the UER. Therefore, this data can be transferred to estimate average useful energy used per capita in the study region.

3.5.3 Projections of population growth

Once a determination was made regarding the number of persons who can potentially meet their nutritional and fuel requirements by the consumption of a certain amount of biomass, three projections for population growth were simulated to understand the extent to which the regional biomass production can satisfy the nutritional requirements of the total regional population. The design of such projections presents the difficulty that the existing population data of the study region, currently formed by two districts, is available only in the census of the year 2010. Previously, the current districts of Talensi and Nabdam were part of Bolgatanga. Hence, the population living before 2010 in the geographical area of what nowadays is Bolgatanga Municipal district is unknown, and there exists no data of population growth rates within the study region. A look at the growth rates of the historical Bolgatanga District, as well as those of the other districts of the UER, helps to make estimates of the actual growth rates within the study region.

The population growth rates of the historical Bolgatanga District have experienced oscillations since they were first recorded in 1931. In 1948 it was 1.29%, and in 2010 they were 0.98% in Bongo District (separated from Bolgatanga in the census of 2000) and 0.78% in Bolgatanga District (which by then included the districts of Talensi and Nabdam, currently outside the study region). A peak of the growth rates was reached in 1984 (2.89%). With the exception of the intercensal period 1984-2000, the growth rates of the Bolgatanga District have always been lower than the average growth rate of the whole UER. During the last intercensal period (2000-2010), the growth rates of both Bongo and Bolgatanga were sensibly lower than any other district in the UER. Growth rates were highest in the districts of the western part of the region, followed by those of the eastern part. After this geographical pattern, another characteristic is that districts containing a major urban town experienced lower growth rates than their neighbors, i.e. in the West, Kasena Nankana experienced lower growth rates than Builsa; in the East, Bawku East experienced lower growth rates than Bawku West, and in the center, Bolgatanga experienced lower growth rates than Bongo (Figure 3.4). However, the annual growth rate of Bolgatanga town was significantly higher than the annual growth rate of any district, ranging between 2.7% and 3.3%, depending on the source. In conclusion, although there is certainly a concentration of population in the capital town, the less urbanized districts (Figure 3.5) have experienced a higher relative population growth than their neighbors. This empirical evidence strengthens the hypothesis that low population growth rate of the Bolgatanga District in relation to the other districts of the UER between 2000 and 2010 is not due (at least not only) to the inclusion of Talensi and Nabdam in the statistics, but to an actual low population growth rate at the district level within the borders of nowadays Bolgatanga Municipal.

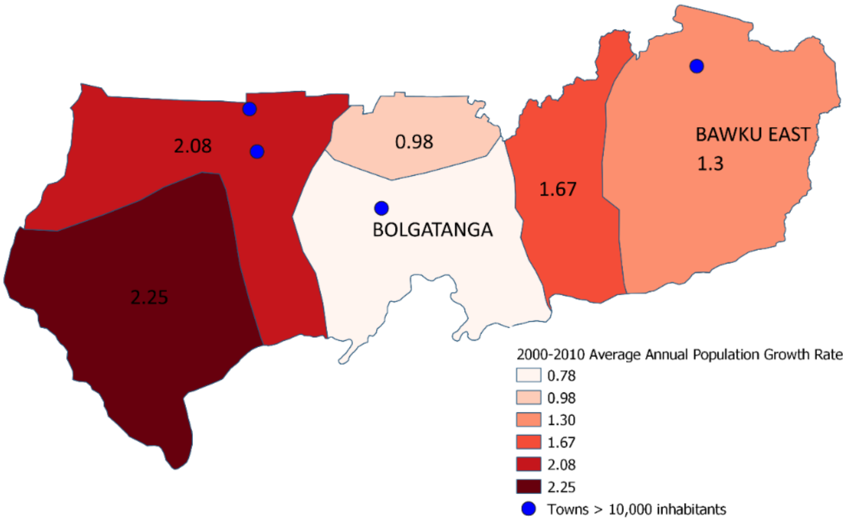


Figure 3.4 District-level annual population growth rate 2000-2010 in the UER of Ghana

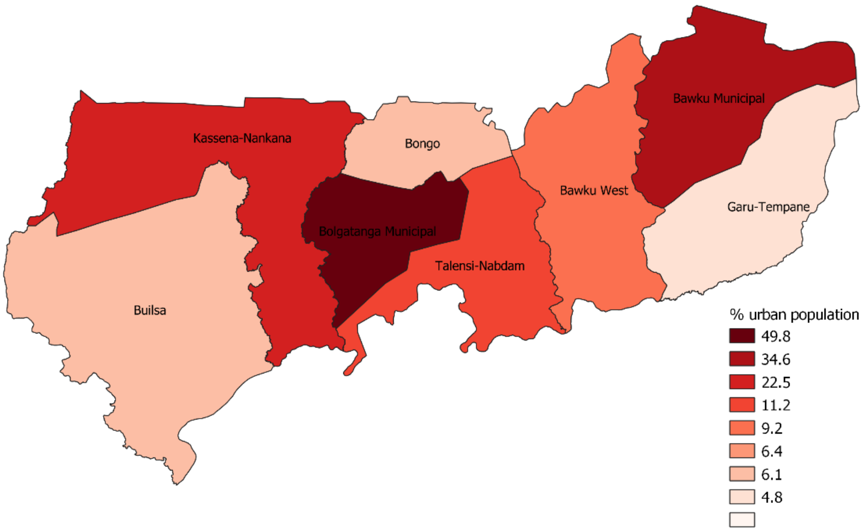


Figure 3.5 District level percentage of urban population 2010 of the UER of Ghana

Annual population growth rates experience a constant reduction in the three scenarios. Scenarios differ in the value of the baseline growth rate and the different pace at which growth rate is reduced. A synthesis of the two population projections at different points in time is presented below in Table 3.5.

Table 3.5 Population projections for the study region up to mid-21st century.

Population Growth Projection	**Year**	**2010**	**2015**	**2035**	**2055**
	Simulation Time step		**T_0**	**T_4**	**T_8**
Slow	*Annual growth rate (assumption)*	1.10%	1.00%	0.85%	0.60%
	Proportion of population in relation to 2010		1.10	1.26	1.37
Fast	*Annual growth rate (assumption)*	2.00%	1.80%	1.50%	0.95%
	Proportion of population in relation to 2010		1.11	1.66	2.38

Source: Author’s estimations based on GSS data.

By 2010, the sum of the population of the two districts was 216,095 (GSS, 2014b, 2014a). The annual population growth rate over the entire UER was 1.1% during the period 1984-2000 and 1.2% during 2000-2010 (GSS, 2013). Therefore, for the medium population growth scenario we assumed that growth rates have remained constant until today. We also assumed that the relative population growth over the study region by 2035 will be the same as the relative population growth over the entire UER, i.e. one third higher than the population of 2010 (Government of Ghana, 2015).

For the scenario of slowest growth, a slightly lower baseline growth than in the medium scenario and a faster decrease in annual growth rates was assumed. Given the significant investment in family planning (Government of Ghana, 2015), this is a plausible scenario.

Annual growth rates within the study region may become higher than those of other districts in the UER. This may happen, for example, due to comparably increasing livelihood opportunities due to the generation of economies of scale through increasing and more effective financial resources, allocated to the study region because of its consideration as a node for the planned Agricultural Growth Corridor (Government of Ghana, 2015). Therefore, for the projection of the fastest growth scenario, a baseline growth rate of 2% was arbitrarily set to be in the middle of the regional average (1.2%) and the growth rate of the urban population of the district of Bolgatanga (2.7%) (GSS, 2014b; Government of Ghana, 2015). Population doubled in the faster growth scenario by the 30th year of simulation (sixth LULCC iteration).

A detailed table showing values of the population growth scenarios resulting from the projections described in this chapter, as well as on the nutritional and biomass fuel demands at each time step (assuming non-changing consumption habits), is provided in Appendix 12.

3.6 Spatial and temporal upscaling of plot-level productivity data in regional scenarios

The outputs of the GISCAME LULCC, APSIM crop growth and woody vegetation growth simulations were imported to the R platform and processed with the packages *raster*, *rgdal*, *lulcc*. A map was created for each scenario and time step, with cell values equal to the different biomass types' productivities or potential benefits. In the case of total biomass and fuel provision, cell values were equal to the sum of croplands and woody vegetation, and in the case of feed provision, equal to the sum of croplands and grasslands. For the rest of the indicators, only croplands were considered.

3.6.1 Regional temporal dynamics modeling of yields

Simulated plot-level yield data was aggregated at the regional level. In the case of perennial vegetation production, simulated harvesting events coincide with the timing of LULCC time steps. Cumulative production calculated at each time step, a unit that is useful to estimate long-term supply levels necessary for regional land use planning by contributing to appropriately estimate land and industry investment requirements. Cumulative yield is calculated directly as the sum of the production in a time step plus the accumulated production of the previous ones. Nevertheless, LULCC and annual crops harvesting, in fact, occur every year. A simplified representation of the impact of such yearly changes on biomass provision dynamics and cumulative production was found by assuming that the total regional production between two time steps changes linearly.

Different paces of agricultural yield increase were simulated in order to obtain a temporally-explicit estimation of biomass provision potentials. Agricultural yields have increased in comparison to those of fifty years ago in most countries in the world due to technological improvements, in some cases even in spite of negative impacts from climate change, as it has been empirically revealed (Najafi et al., 2018).

As it was shown in Section 3.3, the yields of annual crops were simulated under five different levels of management intensification. Average regional yield increases occur gradually, because they require the purchase of inputs that cannot be purchased in the same quantities by all farmers, and because of changing farming techniques that are improved through experience and knowledge exchange. In this study it has been assumed that the gap between actual and potential agricultural yields will be progressively closed through the wider adoption of better cultivar and cultivar-mix choices, as well as the overall improvement of field management operations. Increasing management intensity is expected to have a higher impact on yield in most fields within the study region, at least in the case of crops moderately vulnerable to climate change; such is the case for sorghum (Adam et al., 2020; Müller et al., 2020), millet and groundnut. This process of sustainable intensification should also include, after a first step in which mineral fertilizer application is increased up to moderate levels, the return of plant biomass to the field in order to maintain its potential to sustain future production (Pieri, 1989; van Noordwijk et al., 2018). Precise application of fertilizer micro-doses can also highly contribute to increased yield while minimizing the fertilization costs (Aboyeji et al., 2019; Kugbe et al., 2019; Tsujimoto et al., 2019). Two scenarios of yield increase speed were created, in order to estimate long-term trends, by assigning the values of the APSIM outputs at different levels of management intensification to the LULC map of the last time step. Total regional yield was assumed to increase linearly between the baseline and the last time step (Table 3.5). For simplification purposes, it was assumed that in the baseline scenario mono-cropping is practiced, with the exception of the relay millet-sorghum, which is widespread in the study region. On the other hand, the yields assigned to the LULC in the last time step were assumed to be the ones providing the highest caloric yield for each combination of LULC category and management intensification level.

Table 3.6 Time step-wise assumptions of the management of cropland LULC classes in the baseline and last time step of the LULCC simulation for two yield increase (lower and higher) scenarios.

LULC class	**Baseline management (LULC map t_0)**		
	Fertilizer input	Soil fertility class	Cropping pattern
Cereals	0N-0P	All	Relay millet-sorghum
Groundnut	0N-0P	All	Groundnut monocrop
Maize	5N-2P	All	Maize monocrop
Rice	20N-7P	All	Rice monocrop

LULC class	**Lower yield increase scenario (LULC map t_8)**		
	Fertilizer input	Soil fertility class	Cropping pattern
Cereals	5N-2P	All	Relay millet-sorghum mixed with groundnut
Groundnut	15N-15P	All	Groundnut monocrop
Maize	20N-7P	All	Maize-groundnut mix
Rice	50N-17P	Low	Rice monocrop
		Medium	Rice-millet mix
		Hydromorphic	Rice-millet mix

LULC class	**Higher yield increase scenario (LULC map t_8)**		
	Fertilizer input	Soil fertility class	Cropping pattern
Cereals	50N-17P	All	Relay millet-sorghum mixed with groundnut
Groundnut	20N-7P	All	Maize-groundnut mix
Maize	100N-33P	All	Maize-groundnut mix
Rice	150N-50P	All	Rice monocrop

The intensification level of the different cropland LULC classes was different, taking into consideration that local cereals and groundnut receive much lower rates of fertilizer than maize and rice because of their lower response to such inputs. The profitability of fertilizer application in groundnut is usually lower than cereals, and lower in the local cereals than in maize and rice. The simulated levels of fertilizer application are well beyond the current profitable levels (Amapu et al., 2018; Dicko et al., 2018), but profitability may vary in the future. Furthermore, it shall be noted that the levels of fertilizers shown in Table 3.6 represent only the simulated rate of fertilizer used to define the APSIM simulations. Such fertilizer rates can be used only as indicative, and actual yields may vary highly due to the combination of different management factors including soil and water conservation practices (Danso et al., 2018b; Koo et al., 2018; Danso-Abbeam et al., 2019), adoption of better adapted cultivar mixtures, etc., which were not assessed in this study. Therefore, the outputs of the regional prospective biomass provision assessment must be interpreted as a potentiality which can be used to explore up to what degree the landscape can meet future local demands, provided that the appropriate on-site management technologies are adopted.

Finally, two scenarios for cooking technologies were included to assess the integrated landscape potential fuel yield dynamics (Table 3.6). Three cooking efficiencies (conversion of NCV into useful heat) have been considered: the traditional stove, with an efficiency of 12% for crop residues and 15% for firewood; the improved stove, which increases the efficiency of firewood up to 25%; and the 4-tier household biomass gasifier, with an efficiency of 40%. The share of cooking tasks that is performed with each type of technology (or any other with equivalent efficiency) is unknown. It has been assumed that in the baseline most households use the traditional stove and only a very small part of the cooking tasks is performed with biomass-conversion technologies of the highest efficiency. It has also been assumed that the adoption of more efficient biomass-conversion technologies will increase progressively in the future. In one scenario this process will be slower than in the other. The pace of the increase in more efficient cooking technologies has been defined as follows:

Table 3.7 Time step-wise assumptions for the proportion of cooking fuel biomass used in cooking technologies with different biomass-to-useful energy conversion efficiencies (low = 12% for crop stalks and 15% for wood; medium = 12% for crop stalks and 25% for wood; high = 40% for both types of biomass).

Scenario	SAEC			FAEC		
Cooking technology efficiency	Low	Medium	High	Low	Medium	High
Baseline	0.7	0.2	0.1	0.7	0.2	0.1
Time step 1	0.5	0.4	0.1	0.4	0.4	0.2
Time step 2	0.4	0.4	0.2	0.3	0.4	0.3
Time step 3	0.3	0.5	0.2	0.2	0.4	0.4
Time step 4	0.3	0.4	0.3	0.2	0.3	0.5
Time step 5	0.2	0.5	0.3	0.1	0.3	0.6
Time step 6	0.2	0.4	0.4	0.1	0.2	0.7
Time step 7	0.1	0.5	0.4	0.1	0.1	0.8
Time step 8	0.1	0.4	0.5	0.05	0.05	0.9

3.6.2 Under canopy herbaceous biomass production modeling

The coexistence of trees and crops in small-holder farming systems results in different performance outcomes depending on their spatial distribution pattern on the landscape scale. The impact of these large extent effects on long term production is difficult to model and quantify. The quantification of the outcomes of tree-crop interactions still faces many challenges because it depends on both tree and crop species- and variety-specific phenologies, and all the possible interactions that take place simultaneously have not yet been fully addressed. As a general statement, it can be said that parklands are more sustainable than annual crop monocultures because of the positive impacts that trees have on soil physical properties and biological decomposition, however this statement cannot be translated into specific operational recommendations. Canopy pruning is thought to be a good management option to achieve farm- and landscape-scale synergies of tree and crop production, but its effects are transient and they may reduce the soil nutrient pool (Bayala et al., 2015).

The effect of tree distribution on agricultural production was simulated in a purely spatial manner. Due to the unclear effects of savanna trees on soil carbon spatial distribution (Djagbletey et al., 2018), and a general lack of mechanistic understanding of the impacts of forests on watershed-scale ecosystem structure and function (Vose et al., 2011), the primary production outcomes resulting from the bio-chemical interactions between trees and crops was not simulated. It was assumed that herbaceous vegetation grows both around and under the canopy of open canopy plots, i.e. cells of woody LULC classes also provide annual vegetation biomass if they are surrounded by agricultural or grassland pixels. Wood production in locations occupied by woody cells is simulated as explained in Section 3.4. Additionally, crop and grass biomass is also assumed to be provided in these locations. The value of crop and grass biomass provision by woody LULC cells was defined in two steps. In the first one, the average biomass of all the neighboring cells is calculated (Eq. 4).

$$Y_0 = \frac{Y_1+Y_2+Y_3+Y_4+Y_5+Y_6+Y_7+Y_8}{8} \qquad \text{Eq. 4}$$

Where Y_0 is the herbaceous vegetation yield of the target perennial vegetation cell and Y_1….Y_8 is the herbaceous vegetation yield of its eight neighboring cells. Afterwards, this value is reduced in a magnitude related to the current standing woody AGB (Eq. 5) because the grain crops assessed in this study (with the exception of groundnut) perform C4 photosynthesis. Hence, shading considerably limits their potential yield. The correlation of AGB to canopy size and shade was not addressed in this study, as it can vary widely between different trees, even within the same species. It was assumed that the yield of annual vegetation growing under the canopy of the biggest trees (i.e. those that have reached the simulated maximum standing AGB) is one third of the yield in the open. This assumption was based on the observation that total biomass and grain yield of sorghum growing under the canopy of mature unpruned shea or dawadawa trees across different fertilizer and water supply treatments is roughly one third of the yield of sorghum growing under the canopy of pruned trees (Bazié et al., 2012). It was assumed that the magnitude of such negative impact lowers proportionally to the difference between the actual standing perennial AGB and the maximum potential standing perennial AGB.

$$Y = Y_0 - \frac{Y_0 \times 0.67 \times AGB}{AGB_{max}} \qquad \text{Eq. 5}$$

Where Y is the final herbaceous vegetation yield value of the target perennial vegetation cell after accounting for the effect of tree size, Y_0 is the herbaceous vegetation yield value of the target perennial vegetation cell before accounting for the effect of tree size, AGB is the current wood AGB value of the target cell, and AGB_{max} is its maximum potential wood AGB, as simulated with the ontogenic growth curve.

4 RESULTS

4.1 Quantification of simulated land use change

In this section, a synthesis of the quantitative areal changes under the three LULC change scenarios is presented. This synthesis is necessary to discuss the LULC change dynamics of the simulated scenarios in regard to those that have been observed in the past in other West African savanna regions or simulated by other scenario exercises.

Transition matrices resulting from the ruleset of transition probabilities are provided in Appendix 13 to 15. The share of the landscape occupied by croplands by the end of the simulated period falls within the range of expected shares across different parts of West Africa by the mid-21st century (Ahmed et al., 2016) (Table 4.1). The share of cropland area by the end of the simulation is also similar to another cropland expansion scenario designed for the central basin of the study region (Larbi et al., 2019). Grassland area diminished in all the scenarios, as well as its weight in comparison to perennial vegetation cover, following the past trends in the study region of pasture conversion into croplands (Forkuor, 2014). This trend has also been widely observed in many West African savanna landscapes over the past century, although additional plausible scenarios could simulate a reversing trend due to different reasons or a combination of them, such as diminishing agricultural activities or an extremely drying climate.

Although forest cover in the study region has decreased over recent decades (Codjoe, 2004; Laube et al., 2012), the FLAF scenarioi is a plausible scenario, because it can represent a continuation of the forest cover increase processes that has been experienced across the larger context of the whole UER (Ampim et al., 2021).

The expected diminishing rates of cropland expansion represent well some blueprint LULCC narratives of the West African Sahel (Lambin et al., 2014a) (Table 4.2), with the exception of the FLAF scenario, in which cropland expansion occurs very slowly at a fairly constant rate, and at the expense of grasslands. The area covered by perennial vegetation increased in the farmland agroforestry (FLAF) scenario has, however, decreased in the other two. This divergence was not expected. Instead, it was hoped that the afforestation of protected areas (AFPA) scenario had a woody cover similar to FLAF, but the challenges associated with achieving a target total area based on LULC transition probabilities made it difficult to adjust the final result in a way that corresponded to the designed narratives. In this way, the impact of afforestation on biomass provision and food security can be compared with that of the Cropland Expansion (CEXP) scenario, but the impact of perennial vegetation spatial distribution cannot be assessed because the two scenarios which differ in this regard also have very different total areas of tree cover.

Table 4.1 Percentage of the total regional area covered by each vegetated LULC class in three LULCC scenarios at time steps 2 (T_2), 4 (T_4) and 8 (T_8), representing 10, 20 and 40 years after the baseline (T_0), respectively.

		Cropland	**Grassland**	**Perennial vegetation**
Time step	**Years**	*% cover over total area of the study region*		
T_0	0	48.50	19.61	26.31
CROPLAND EXPANSION (CEXP)				
T_2	10	59.11	13.45	21.86
T_4	20	65.95	9.67	18.81
T_8	40	73.90	5.75	14.78
AFFORESTATION OF PROTECTED AREAS (AFPA)				
T_2	10	55.30	14.29	24.84
T_4	20	60.18	10.76	23.49
T_8	40	67.07	6.33	21.02
FARMLAND AGROFORESTRY (FLAF)				
T_2	10	49.54	14.47	29.70
T_4	20	50.66	11.94	30.57
T_8	40	53.04	9.09	30.19

In the FLAF scenario, the rate of tree cover area increase slows down over time, and it has even become negative during the last years of the simulated period. This can be expected because water and land resources for agricultural production become more scant if tree cover increases above a certain threshold (Ilstedt et al., 2016). Such simulation behavior occurs whenever the cellular automata are run without changing the values of the transition probabilities between different time steps. This implies that, as one LULC class increases its total area, the total area converted to another LULC in the next time step also increases, while LULC classes which experienced a contraction of its area in previous time steps will feed fewer cells into the woody LULC class.

Table 4.2 Average annual percentage area change of each vegetated LULC class calculated over 10-year (**T_0-T_2**, **T_2-T_4**, **T_4-T_6**, **T_6-T_8**) and 20-year (**T_0-T_4**, **T_4-T_8**) intervals; and percentage area changes by mid (**T_4**) and end (**T_8**) of the simulation in comparison to the baseline (**T_0**)

	Average annual % Δ						**% area over baseline (T_0) area**	
Timespan	**Over 10 years**				**Over 20 years**			
	T_0-T_2	**T_2-T_4**	**T_4-T_6**	**T_6-T_8**	**T_0-T_4**	**T_4-T_8**	**T_4**	**T_8**
CROPLAND EXPANSION (CEXP)								
Cereals	*2.13*	*1.30*	*0.89*	*0.49*	*1.85*	*0.71*	*37*	*57*
Legumes	*3.01*	*1.67*	*1.09*	*0.78*	*2.59*	*0.98*	*52*	*81*
Maize	*5.31*	*1.66*	*0.71*	*0.36*	*3.93*	*0.55*	*79*	*98*
Rice	*0.77*	*0.36*	*0.17*	*0.10*	*0.58*	*0.14*	*12*	*15*
All cropland	***2.19***	***1.16***	***0.72***	***0.45***	***1.80***	***0.60***	***36***	***52***
Grassland	***-3.14***	***-2.81***	***-2.62***	***-1.95***	***-2.53***	***-2.03***	***-51***	***-71***
Perennial vegetation	***-1.69***	***-1.40***	***-1.18***	***-1.09***	***-1.43***	***-1.07***	***-29***	***-44***
AFFORESTATION OF PROTECTED AREAS (AFPA)								
Cereals	*1.52*	*1.04*	*0.78*	*0.60*	*1.36*	*0.71*	*27*	*45*
Legumes	*2.05*	*1.35*	*0.98*	*0.73*	*1.84*	*0.89*	*37*	*61*
Maize	*2.44*	*1.20*	*0.77*	*0.58*	*1.97*	*0.70*	*39*	*59*
Rice	*0.54*	*0.23*	*0.11*	*0.06*	*0.39*	*0.09*	*8*	*10*
All cropland	***1.40***	***0.88***	***0.63***	***0.48***	***1.20***	***0.57***	***24***	***38***
Grassland	***-2.71***	***-2.47***	***-2.36***	***-2.30***	***-2.26***	***-2.06***	***-45***	***-68***
Perennial vegetation	***-0.56***	***-0.54***	***-0.54***	***-0.54***	***-0.54***	***-0.53***	***-11***	***-20***
FARMLAND AGROFORESTRY (FLAF)								
Cereals	*0.48*	*0.47*	*0.43*	*0.34*	*0.49*	*0.39*	*10*	*18*
Legumes	*1.27*	*0.98*	*0.75*	*0.59*	*1.19*	*0.69*	*24*	*41*
Maize	*2.46*	*1.71*	*1.25*	*0.98*	*2.29*	*1.17*	*46*	*80*
Rice	*-1.42*	*-1.36*	*-1.20*	*-1.01*	*-1.29*	*-1.04*	*-26*	*-41*
All cropland	***0.21***	***0.23***	***0.23***	***0.23***	***0.22***	***0.23***	***4***	***9***
Grassland	***-2.62***	***-1.75***	***-1.40***	***-1.15***	***-1.96***	***-1.19***	***-39***	***-54***
Perennial vegetation	***1.29***	***0.29***	***0.01***	***-0.13***	***0.81***	***-0.06***	***16***	***15***

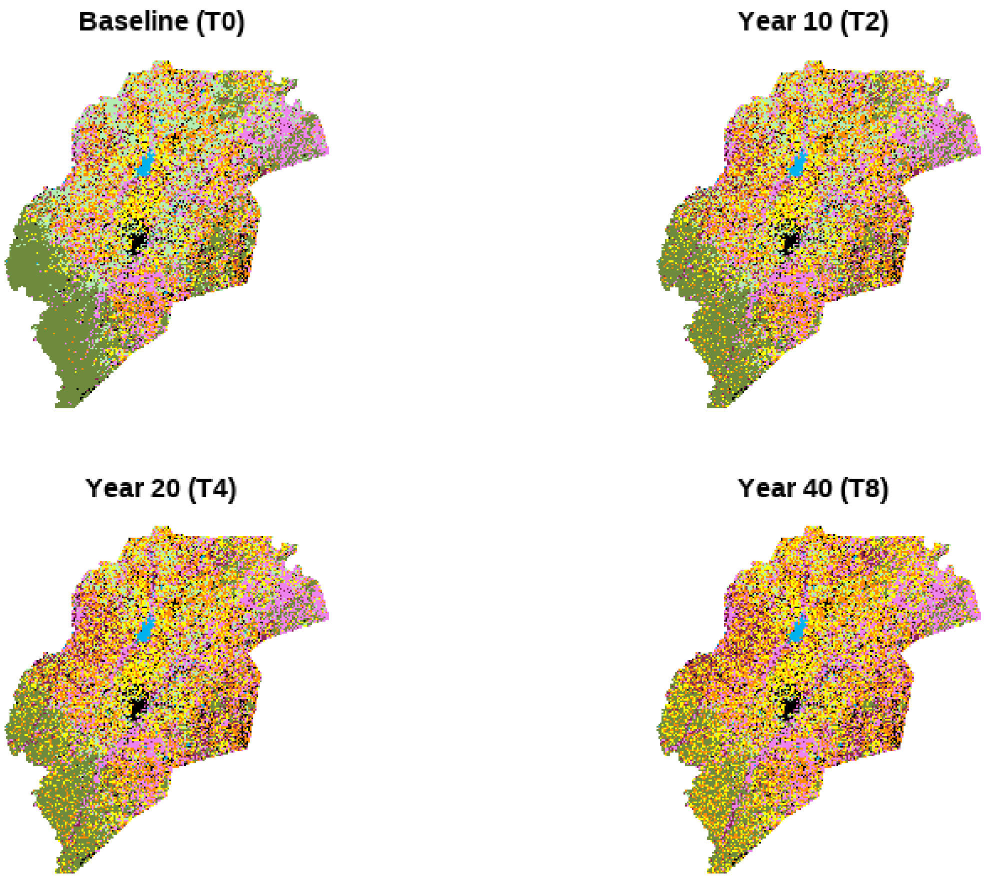
In the two scenarios which experience an absolute reduction of woody cover by the end of the simulation (CEXP and AFPA), such a decrease occurs continuously. In the CEXP scenario, the rate at which woody cover diminishes is the highest of the three scenarios, but it slows down over time, whereas in the AFPA scenario, it stays fairly constant. Although it indicates a certain degree of plausibility, such a continuous reduction of woody cover across the entire simulated timespan of forty years may not be considered the simulation with the most plausible dynamics of woody cover; this is because tree cover areas oscillate naturally, and such oscillations may well occur at time scales of only one or two decades (Adeyemi and Ibrahim, 2020).

Rice is the crop whose total area experiences the least amount of expansion in the CEXP and AFPA scenario, and its rate slows down over time, which is expected because it is the most demanding crop in relation to land conditions. Moreover, the available area for its profitable cultivation is particularly scarce (Amadou et al., 2018). However, in the FLAF scenario it is the only crop which experiences a decrease of total cultivated area.

Maize is the crop which experiences the highest increase in its cultivated area in the CEXP and FLAF scenarios. This behavior has been introduced to show its growing demand (Traoré et al., 2020) as well as the traditional and globally strong commitment of the industrial, scientific and policy communities to promoting its cultivation above other crops. However, in the CEXP and AFPA scenarios, the rate of increase in cultivated area for legumes is the highest after the second quarter of the simulation and, in the case of the AFPA scenario, its relative (and total) increase by the end of the simulated period is also higher than that of maize. This is also the result of imposing land quality restrictions on the probability of a LULC to transition into maize. However, it is also a very plausible outcome because maize is the main driver of cropland expansion into uncultivated savanna (Gebremariam, 2018), probably because of the higher additional yields attained by maize in the fertile soils of recently cleared land. Therefore, as the area of uncultivated savanna becomes scarce, the rate of maize expansion may decrease, while that of legumes may increase due to its adaptability to nutrient-poor soils. The share of total cropped area occupied by legumes increases in relation to that occupied by local cereals and rice in all three scenarios. This outcome is plausible due to the promotion over recent decades of legume cultivation by the scientific community.

The temporal evolution of the spatial LULC pattern distribution is shown in Figures 4.4, 4.5 and 4.6. The three designed LULCC scenarios were able to roughly maintain, throughout the different time steps, the targeted spatial distribution of LULC pattern. The spatial distribution of woody vegetation in all three scenarios was denser along the main water streams and in the southern part of the study region. In the AFPA scenario, moreover, woodlands expand their area, as well as they do other smaller woodland patches dispersed across the study region. Cropland patches also increased their size across the farming areas in the AFPA and CEXP scenario. In the latter, they also encroached into the woody areas of the southern part of the study region. In the FLAF scenario, contrary to the other two, patch size decreased markedly, and the spatial distribution of LULC becomes more similar between the different parts of the study region, with croplands encroaching into previously uncultivated areas and isolated or small patches of woody LULC cells evenly distributed throughout the region. Rice increased its dominance on lowland areas while retreating for the upland in the three scenarios.

CROPLAND EXPANSION (CEXP)



Land use/cover classes

■ Cereals (Millet/Sorghum)
■ Legumes (Groundnuts)
■ Maize
■ Perennial vegetation
■ Grassland
■ Rice
■ Built up
■ Water

Figure 4.1 CEXP scenario LULC maps at the baseline T2, T4 and T8 timesteps, representing 10, 20 and 40 years after the baseline (T_0), respectively.

AFFORESTATION OF PROTECTED AREAS (AFPA)

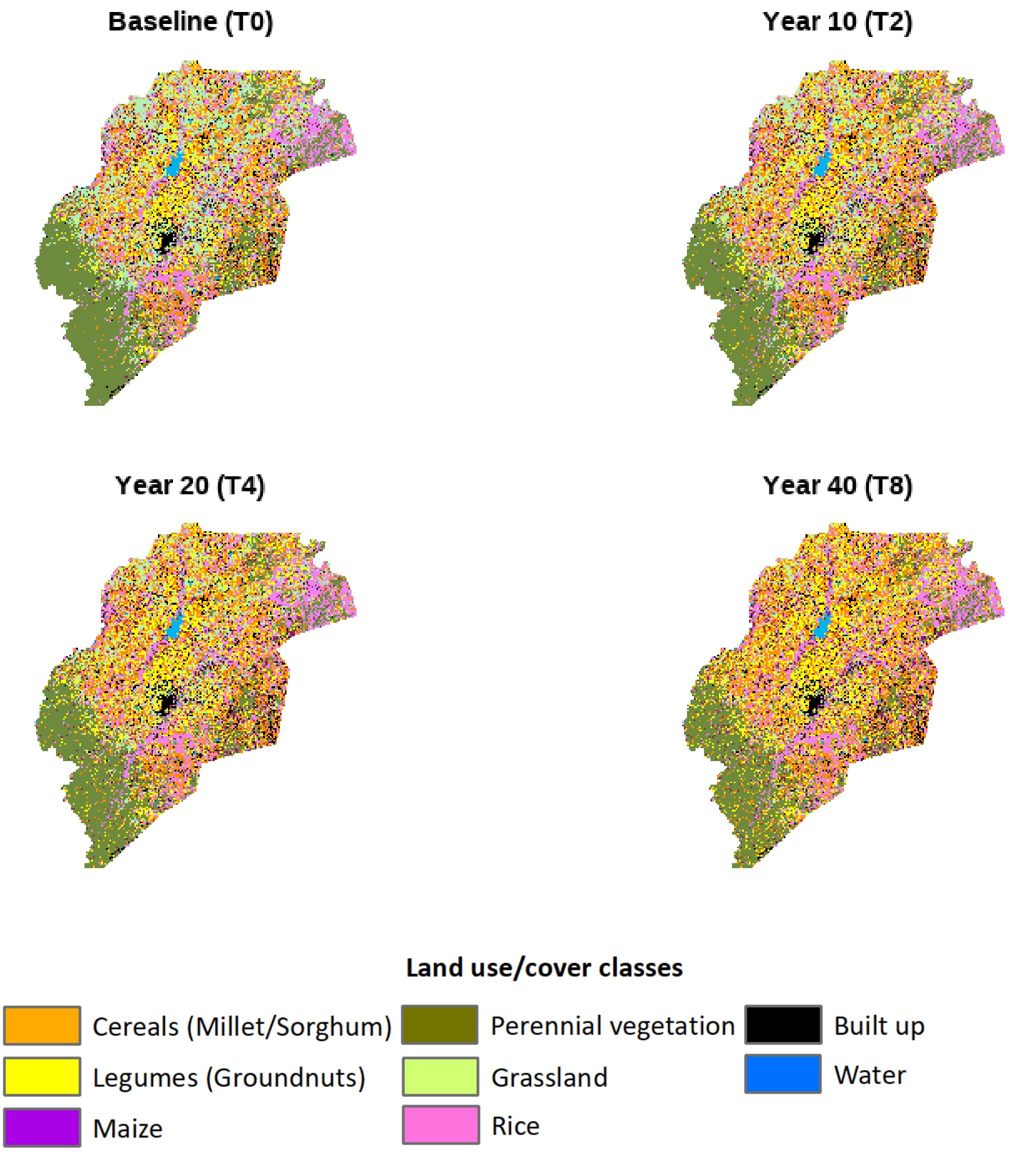


Figure 4.2 AFPA scenario LULC maps at the baseline T2, T4 and T8 time steps, representing 10, 20 and 40 years after the baseline (T_0), respectively.

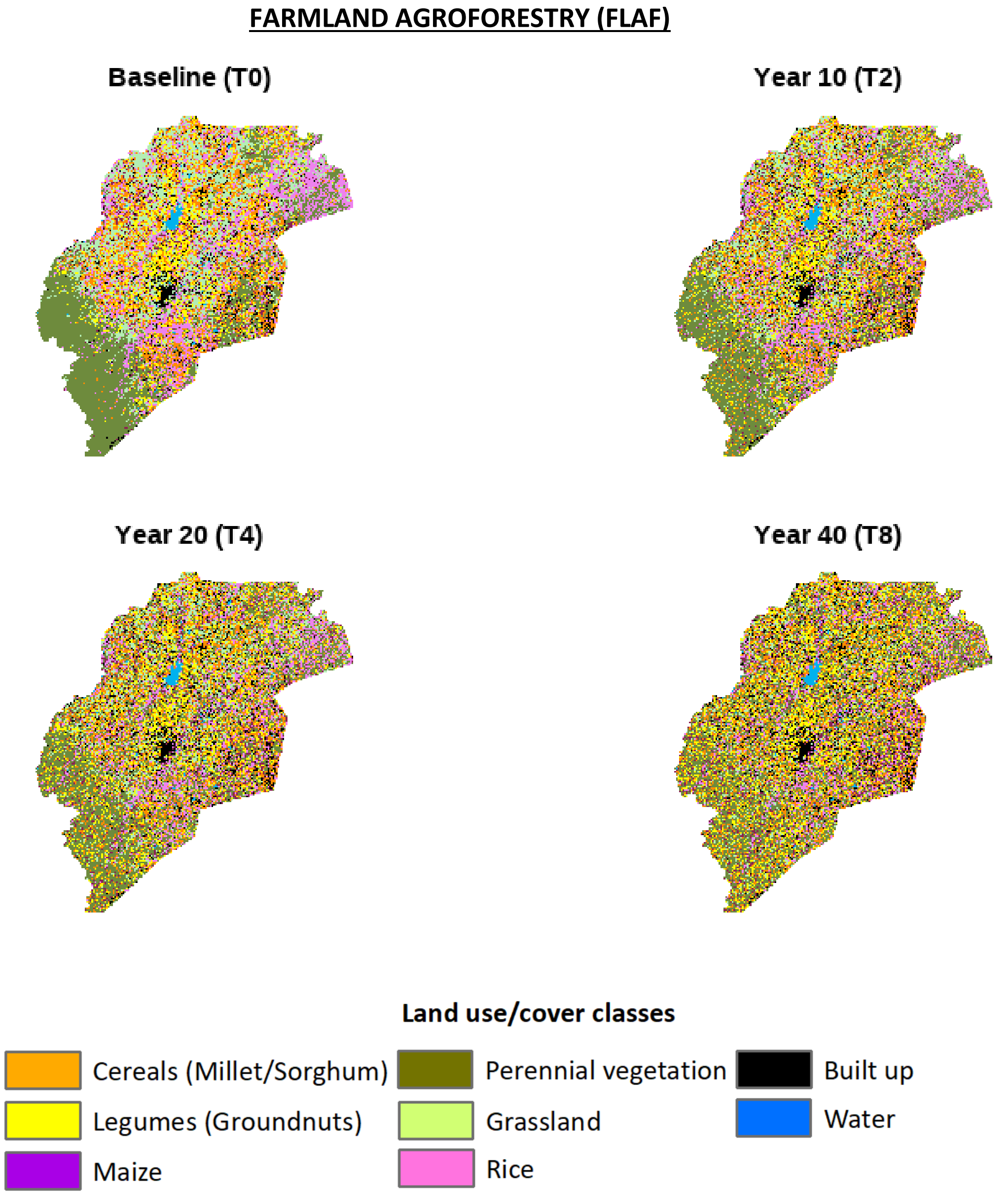


Figure 4.3 FLAF scenario LULC maps at the baseline T2, T4 and T8 time steps, representing 10, 20 and 40 years after the baseline (T_0), respectively.

4.2 Simulated yields of annual crop species

Yields of the different biomass compartments (grain, stem and leaf yields) of crop LULC classes used in this study for the computation of regional extent yields are synthetized in Appendix 16. The yields of all the factorial simulations (although only for monocrops) can be accessed in Jiménez Martínez and Fürst (2021).

4.2.1 Field-scale simulated yields

In what regards to field-scale yields, visual comparisons against data observed in other Sudanian savanna agro-ecologies of West Africa are presented in crop-specific graphics (Figures 4.1, 4.2, 4.3, 4.4 and 4.5). A common feature of the comparison of each crop is that minimum simulated yields are higher than minimum observed yields. Furthermore, in the case of millet and sorghum, maximum simulated yields are already achieved with nitrogen application levels of 50 kg ha^{-1}, and are clearly higher than observed yields with similar levels of mineral fertilizer intensity, which show that maximum yields are achieved by applying higher amounts of mineral fertilizer, around 100 kg N ha^{-1}.

Simulated millet yields range between 0.7 and 2.6 t ha^{-1} (Figure 4.4), falling within the range of observed yields reported in literature (Ba et al., 2000; Oluwasemire et al., 2002; Diangar et al., 2004; Zakaria, 2016; Traoré et al., 2017), with the exception of simulations without mineral fertilizer application, which are clearly higher than what has been previously reported (Bayala et al., 2002; NAAB et al., 2008; Sanou et al., 2012). No observed data was found for comparison under no or low input management on hydromorphic soils. At the micro-site level, yields of millet under low input management can be as high as 2.8 t ha^{-1}, but the variability of soil properties on the plot scale under this type of management results in overall low yields on a one-hectare basis (Stein et al., 1997).

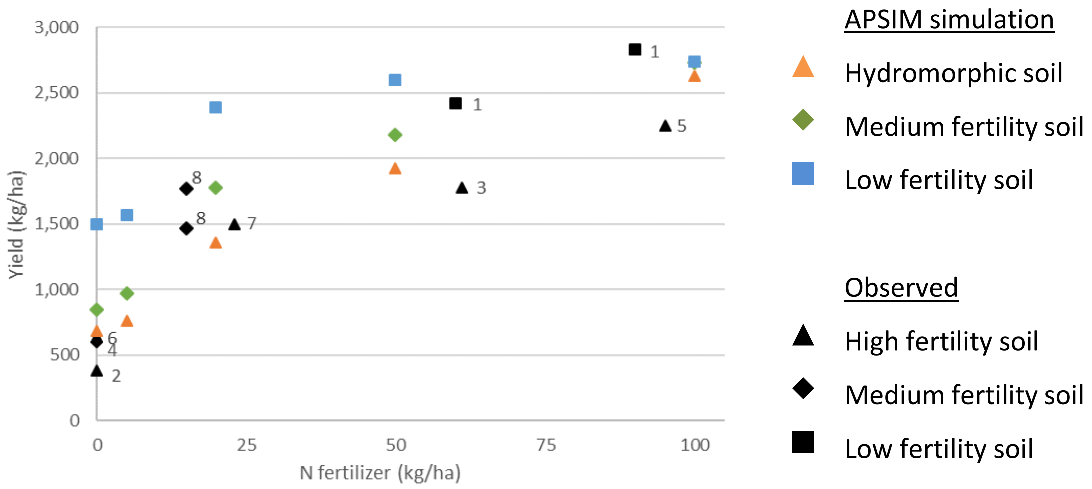


Figure 4.4 Millet simulated vs. published observed grain yields per fertilizer input level and soil fertility class. 1. Ba et al., 2000; 2. Bayala et al., 2002. 3. Diangar et al., 2004;

4. NAAB et al., 2008; 5. Oluwasemire et al., 2002; 6. Sanou et al., 2012; 7. Traore et al., 2017; 8. Zakaria, 2016.

The simulated sorghum, yielding in a range between 0.8 and 3.3 t ha^{-1} (Figure 4.5) has been the crop species that shows highest yield variability among the observations reported by the reviewed literatures. All the simulation outputs fall within the range of expected yields. Among all the simulated crops, sorghum is the one whose response to mineral fertilizer agrees the best with in-field observations (Barthès et al., 2015; Ouattara, 2015; Shuaibu et al., 2015). There is, however, evidence that sorghum yield can be as low as 0.17 t ha^{-1} (Kanton et al., 2000; Zougmoré et al., 2004).

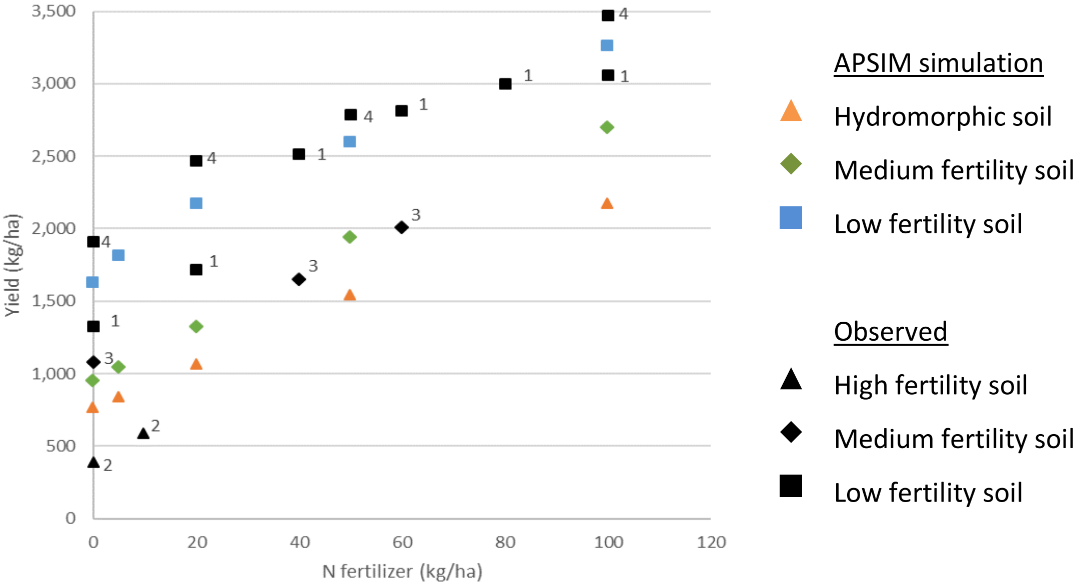


Figure 4.5 Sorghum simulated vs. published observed grain yields per fertilizer input level and soil fertility class. 1. Akinseye et al., 2020; 2. Barthès et al., 2015; 3. Ouattara, 2015; 4. Shuaibu et al., 2015.

Simulated maize yields, ranging between 0.6 and 4.3 t ha^{-1} (Figure 4.6), also fall within the range of experimental observations at different levels of inorganic nitrogen application (Findlay, 2001; Buah et al., 2010; Kugbe and Issahaku, 2015; Danso et al., 2018a). Yields simulated with 50 kg ha of mineral nitrogen are above those of the majority of reviewed articles (Igué et al., 2015; Akumaga et al., 2017; Srivastava et al., 2017). Maize yields without the application of fertilizers can be as low as 0.2 t ha^{-1} (Kugbe and Issahaku, 2015). A recent comprehensive review has shown that the biologically potential yields of maize, as high as 8 t ha^{-1}, have rarely been achieved under experimental field conditions in West Africa (Falconnier et al., 2020). The maximum maize output yield of the simulations matches the yield of the open-pollinated Obatanpa cultivar of 4.28 t ha^{-1}, obtained by high-yielding farmers in Ghana (Sallah et al., 2007) and is very similar to the yield of drought-tolerant varieties in Nigerian savannas (Beah et al., 2021).

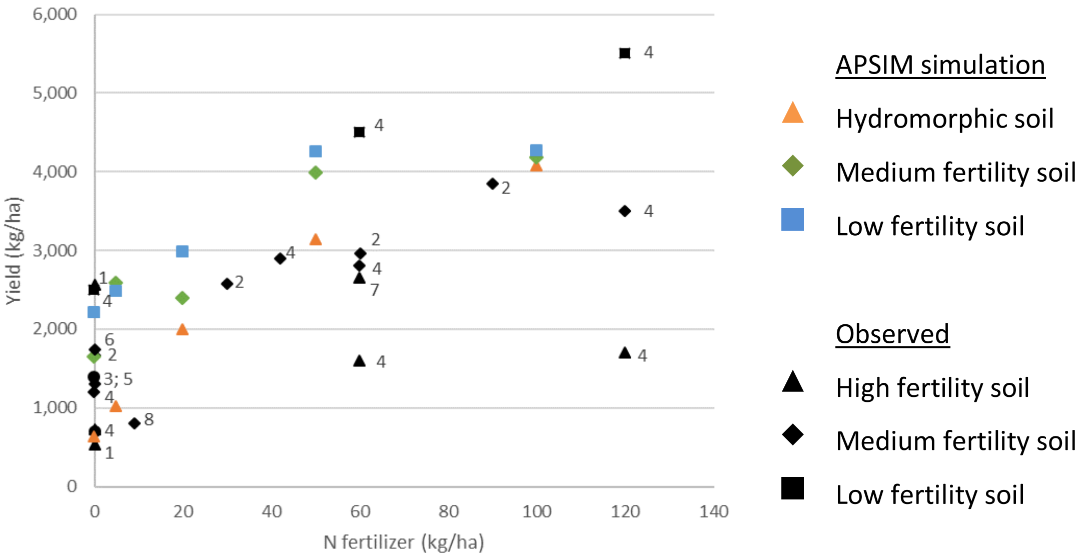


Figure 4.6 Maize simulated vs. published observed grain yields per fertilizer input level and soil fertility class. 1. Abaidoo et al., 2007; 2. Akumaga et al., 2017; 3. Buah et al., 2010; 4. Danso et al., 2018a; 5. Igué et al., 2015; 6. Kombiok et al., 2005; 7. Srivastava et al., 2017; 8. Yusuf et al., 2009.

The simulated rice yields range between 0.8 and 5 t ha^{-1} (Figure 4.7) falling within the range of experimental observations (Inusah et al., 2014; Niang et al., 2017; Tanaka et al., 2017), and are very similar to yields simulated with CERES (Oteng-Darko et al., 2012). The maximum simulated yields are in line with the output of high-yield farmers of the UER (Niang et al., 2017; Tanaka et al., 2017), and they show similar results compared to those obtained from other models, e.g.: DSSAT (Oteng-Darko et al., 2012). However, the response of simulated yields to fertilizer application at levels lower than 100 kg N ha^{-1} is higher than what has been observed in-field (Kone et al., 2011; Idriss et al., 2018). The rice yield potential in north-Sudanian climates of West Africa is higher than in the study region, and in the latter it is higher than in the Guinean savanna and humid zone, due to higher solar radiation, higher maximum and lower minimum temperatures, and particularly in the Sudanian savanna due to their optimal relative humidity (Niang et al., 2017). However, as the yield potential decreases following a north to south gradient, so do the challenges to achieve such yields, because the gradient of soil organic matter content follows the inverse spatial relationship, requiring higher fertilizing inputs.

Groundnut yields range between 0.7 and 2.9 t ha^{-1} (Figure 4.8) falling within the range of observed yields in experimental studies (NAAB et al., 2009b; NAAB et al., 2009a; Shiyam, 2010; Konlan et al., 2013; Narh et al., 2015), although higher yields can be obtained by adding higher quantities of mineral fertilizers in a balanced-mix (Iledun et al., 2016; Aboyeji et al., 2019). Groundnut yields in hydromorphic soils, or other humid environments, tend to be lower, even if organic matter content is high, than yields in slope and plateau positions.

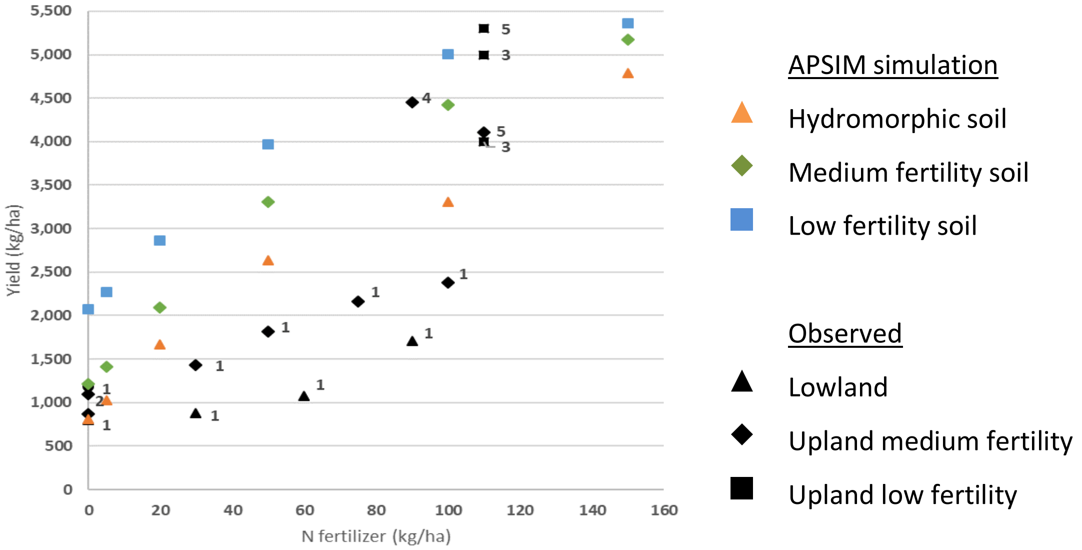


Figure 4.7 Rainfed rice simulated vs. published observed grain yields per fertilizer input level and soil fertility class. 1. Idriss et al., 2018; 2. Kone et al., 2011; 3. Niang et al., 2017; 4. Oteng-Darko et al., 2012; 5. Tanaka et al., 2017.

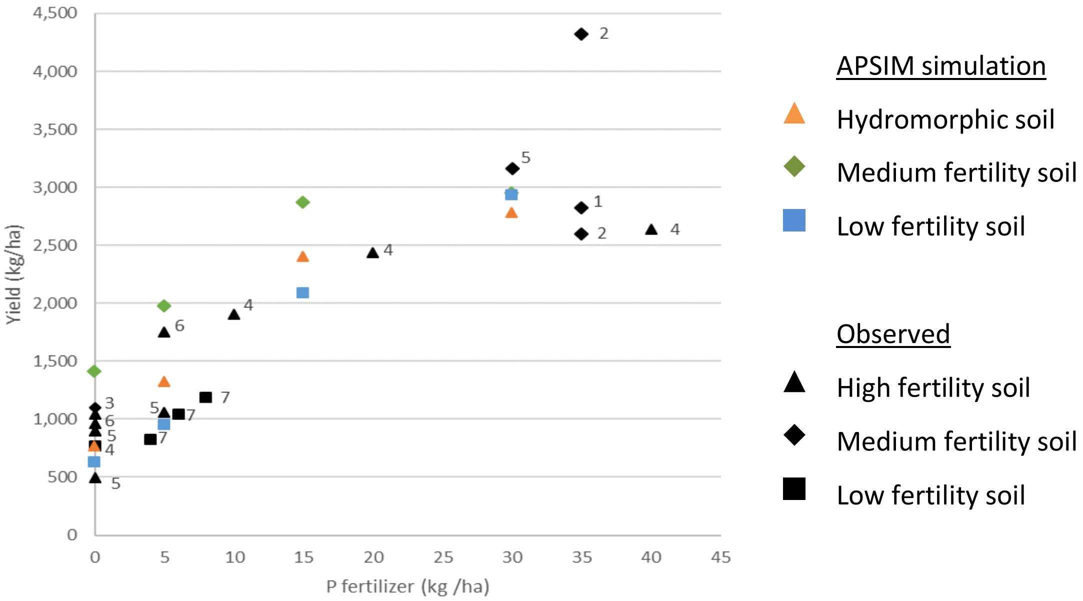


Figure 4.8 Groundnut simulated vs. published observed grain yields per fertilizer input level and soil fertility class. 1. Aboyeji et al., 2019; 2. Iledun et al., 2016; 3. Konlan et al., 2013; 4. Lombin et al., 1985; 5. NAAB et al., 2004; 6. NAAB et al., 2009b; 7. Shiyam, 2010.

The water cycle is not simulated with the same precision for all crop modules, which might be a source of uncertainty in the comparative yield performance among the five crops. Groundnut and sorghum seem to perform the best, judging by the fact that the average annual sum of evapotranspiration, runoff and drainage oscillates between 1,024 and 1,029 mm, very similar to the average annual precipitation of 1,024 mm. The average sum of the water components of millet is lower than the average annual precipitation, ranging 1,014-1,021 mm. In the case of the other two cereals, it is higher precipitation, ranging 1,033-1,084 mm in the case of maize, and particularly in the case of rice, which ranges 1,068-1,105, overestimating the volume of the annual water cycle by 80 mm.

4.2.2 Yields aggregated at the regional level

Average regional simulated yields in the baseline LULC map were compared with data from official agricultural statistics averaged between 2007 and 2013 (Table 4.3).

Table 4.3 Average regional crop yields over the period 1997-2013

Grain yield	**Unit**	**Millet**	**Sorghum**	**Maize**	**Rice**	**Groundnut**
Simulated (baseline)	*kg ha^{-1}*	817	1,030	1,551	2,030	1,092
Official statistics	*kg ha^{-1}*	854	1,055	1,665	2,389	891
Food Energy NY	*person ha^{-1}*	1.64	2.16	3.00	4.28	2.82
Food Iron NY	*person ha^{-1}*	8.49	6.40	3.93	3.42	12.31
Food Zinc NY	*person ha^{-1}*	4.28	2.88	4.17	5.98	12.16

Source Official Statistics: MoFA (unpublished)
Simulated APSIM yields were averaged over the baseline LULC map, assuming 0 kg N ha^{-1} input for millet, sorghum and groundnut; 5 kg N ha^{-1} for maize and 20 kg N ha^{-1} for rice.
Nutritional yields were obtained by applying the formula and the data shown in Section 3.5.

Average regional yields of sorghum, millet and maize correspond well between the simulations and the agricultural statistics.

Rice yields are slightly underestimated (85% of the agricultural statistics), which can likely be attributed to the inclusion of irrigated rice in the averaging of official agricultural statistics, which accounts for a relevant amount of the regional rice producing systems of the study region, whereas simulated yields only refer to rainfed yields. Indeed, the results of the simulations coincide with the average 2.45 t ha^{-1} obtained by rainfed rice farmers in the neighboring district of Navrongo (Tanaka et al., 2017).

Groundnut yields are slightly overestimated (122% in the agricultural statistics), for which this author does not have a clear explanation. The value provided by agricultural statistics coincide with the average 0.85 t ha^{-1} of the typical cultivars used in Ghana (Asibuo et al., 2008). It is known that groundnut cultivation is often undertaken in degraded soils with very poor fertility, but mapping of degraded soils was not conducted in this study. Hence, it is possible that the fertility of the soils where many of the groundnut fields are actually located within the study region is lower than the data used as input. Another reason for the high simulated groundnut yields might be the higher harvest losses that were incurred in the cultivation of this crop. Considerably high in-field yield losses are derived from their below-ground growing position, which implies more harvesting difficulties than above-ground grains. Frequently, groundnut fields are harvested beyond the physiological maturity stage of the crop, resulting in additional pod infestation and sprouting of nuts, besides many nuts being left unnoticed in the ground (Kombiok et al., 2012). Indeed, the experiments aimed at reducing the incidence of pests and diseases on groundnuts are particularly abundant, e.g.: (NAAB et al., 2009a; Narh et al., 2015;

Gaikpa et al., 2017), which may indicate that this factor is an important limitation to groundnut production, to a higher degree than other crops.

4.2.3 Multi-criteria biomass provision performance

The overall performance of annual crops depends on the levels of management at which they are compared. Figure 4.9 offers an example of three different levels of management. Groundnut has been excluded in this comparison because it over-performs cereals in most indicators, hampering the visualization of comparative performance of the different cereals. The complete results can be consulted in the supplementary material of Jiménez Martínez and Fürst (2021), including all the management levels simulated in this study and also including groundnut. The importance of millet is prominent, particularly at low levels of inputs. It is the crop providing the iron and fuel yields at all levels of fertilizer application, and it only has lower yields than maize and rice at high rates of fertilizer input. Millet also provides, across most treatments, the second largest feed yields, only surpassed by rice. Sorghum is also very important because it provides high caloric yields at low levels of fertilizer input. Its iron yield is higher than that of maize and rice, and its fuel yield it similar to that of maize at all levels of fertilizer input. Maize provides high caloric, fuel, and zinc yields, and its relative productivity increases at higher levels of fertilizer application. The production of rice is also of great importance because it provides the highest cash income and feed yields. With increasing fertilizer application, its caloric and zinc yields also become prominent.

As shown by the comparison, the optimal crop selection to cultivate in a field will depend on the end use of the biomass and, mainly, on the intensification levels. Only rice as a source of cash and feed outperforms the rest of the crops at any level of intensification. Otherwise, where no fertilizers are applied, millet and sorghum are a better option as a staple crop than maize. The high food-calorie provision of sorghum at no fertilizer application makes it a particularly important crop in this context. When a small amount of fertilizers is applied, maize already becomes the best option for food calories and fuel provision, and it outperforms millet in zinc provision as the amount of fertilizer increases to medium levels. Millet shows a balanced provision of benefits at all levels of fertilizer application, because it ranks highest in iron and fuel provision.

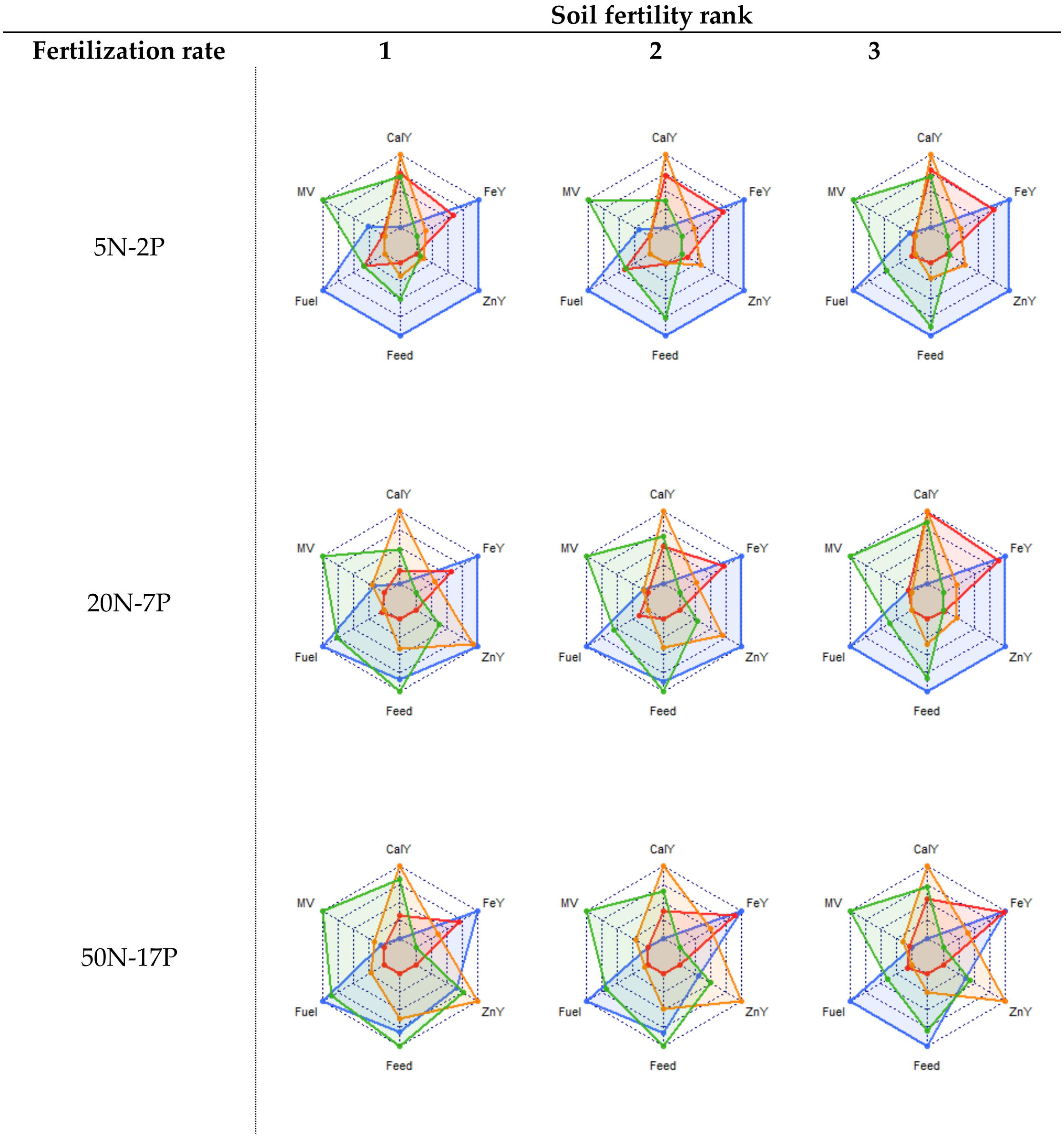


Figure 4.9 Multi-criteria assessment of annual monocrops performance. Millet (blue), sorghum (red), maize (yellow) and rice (green); in six different paddocks, defined by two factors: mineral fertilizer application rate (kg ha-1 of nitrogen and phosphorus) and soil fertility characteristics (1 = upland low fertility, 2 = upland medium fertility, 3 = hydromorphic soil). Caloric yield (CalY); iron yield (FeY); zinc yield (ZnY); metabolizable energy yield (feed), cooking fuel yield (fuel), monetary value (MV) (Jiménez Martínez and Fürst, 2021).

4.3 Simulated woody biomass provision

4.3.1 Stand-level woody biomass growth

The parameter values of the Gompertz equation resulting from using the data of Table 3.2 to fit Eq. 2 were used to simulate the plausible ontogenic growth of a (semi-)natural South Sudanian savanna stand, as presented in Table 4.4 and synthetized in Eq. 6.

Table 4.4 Outputs of the Gompertz model applied to woody stand AGB data

R-squared	0.9997	**Parameter estimates**			
		β_0	β_1	β_2	β_3
Coefficient		-1,316.786	1,391.037	0.0262292	-110.4924
SD (95%)			±0.3980	±0.0016	±6.9719

$$AGB(age) = -1{,}316.786 + 1{,}391.037 * \exp(-\exp(-0.0262292 * (age + 110.4924))) \qquad \text{Eq. 6}$$

The resulting modeled growth is displayed in a linear graph (Figure 4.10) and detailed as tabular data in Appendix 17. The Mean Annual Increments (MAI) and Current Annual Increments (CAI) fall within the range of observed values, although the availability of data for validation is scant. MAI in a stand within the same location where the input data was recorded, at an estimated age of 30 years, was 0.96 t ha^{-1} (Nouvellet, 1993), coinciding with the MAI of the simulated table. MAI in two community forests close to the study region, and aged 12 and 23 years, was 2.3 and 1.1 t ha^{-1} respectively (Dayamba et al., 2016), showing only slightly higher values than the modelled curve in the younger stand and lower in the older stand. MAI values of up to 2-3 t ha^{-1} in stands aged about 10 years have also been observed in (semi-)natural vegetation stands and woody fallows in Senegal (CIRAD-FORET - FRA, 1993; Kairé, 1999; Manlay et al., 2002). It must be noted that the input data correspond to observations in areas which had not been subjected to agricultural activities in the recent past before the start of stand growth.

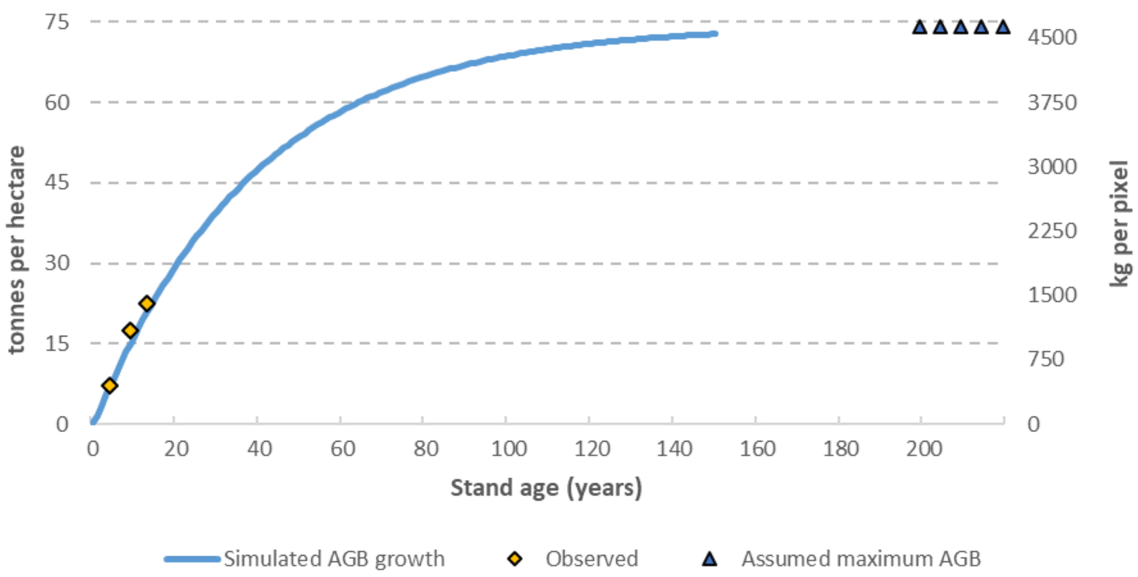


Figure 4.10 Growth curve of the simulated woody LULCC stands, expressed in tons per hectare (left axis); and kg per pixel (625 m^2) (right axis)

The growth of woody AGB in post-cultivation areas can be much lower, with an average MAI between 0.3-0.4 t ha^{-1} during the first 20 years (Yossi, 1996), in comparison with the simulated growth above 1.5 t ha^{-1} during the same age, and only comparable to the simulated growth at ages above 150 years. This slow observed growth can be the result of both poor soil nutrient content due to mining from crop cultivation and unrecorded collection of living wood material during the experimental period. As a proxy of CAI, measured annual woody AGB production in woodland savanna and dry forest mature stands (unknown age) of the forest-transition zone of Ghana ranged 0.9-2.31 t ha^{-1} (Moore et al., 2018), which is above the growth rate of mature stands simulated in this study. This difference might be the combined result of higher precipitation and, in particular, due to the fact that such a study was conducted in Kogyae, a Strict National Reserve, and the vegetation has probably been subjected to much lower disturbances than those in Sudanian savanna regions. The relationship between MAI and AGB by age in the simulated growth table coincide with in-field diachronic observations of Sudanian savanna woody stands (Bonkoungou and Framond, 1988): 25% of AGB at age 4 years, 14% at 7 years and 4% after 25 years, indicating that the results simulate well the growth dynamics of woodland stands of the mid-Volta Basin. In conclusion, despite the wide uncertainty regarding expected growth values in the study region, both the annual growth and its dynamic over the development of the hypothetical stand are plausible, and fall within the range defined by the highest and lowest growth values found across the reviewed literature. Therefore, it is assumed that before more and better quality data is available, the modelled growth is suitable to generate woody biomass values that can be integrated with LULCC simulations in order to facilitate decision-making processes in rural regional planning.

4.3.2 Baseline spatial distribution of woody biomass at the regional extent

The maps and histograms below show the distribution of AGB (Figure 4.11) and stand age (Figure 4.12) in the baseline scenario. The higher the biomass content of class, the lower the area it occupies. The most common stand level AGB is inferior to 10 t ha-1, even in the protected areas of the South and East in the study region. This is expected because the incidence of fire there is also very high (Nindel, 2017).

The spatial pattern of age distribution represents fairly well what is expected in the densely populated middle Volta basin. Woody stands rarely exceed 30 years of age (Soto Flandez, 1995) due to the combination of periodic drought, fire and excessive livestock impacts. In any case, we will always have to consider the uncertainties introduced by arbitrarily setting the, largely unknown, age of stand maturity and maximum AGB values. Such values indicate the potential AGB storage capacity of a site, but they are highly uncertain in savanna stands, which are subjected to more or less continuous pressures and repeated disturbances.

After conducting literature review, average AGB of (semi-)natural stands in the central part of the West African savannas is 20-30 Mg ha^{-1}, but values below 20 and 10 Mg ha^{-1} are also common (Affoue, 1995; Dayamba et al., 2016; Melin et al., 2016; Valbuena et al., 2016; Dimobe et al., 2018c; Dimobe et al., 2018a; Dimobe et al., 2019b). The average AGB of woody pixels in the baseline scenario is 15.43 t ha^{-1}. This value falls within the lower end of the range of values reported in literature, which can be expected because the study region has a particularly low AGB in comparison to other Sudanian savannas of central West Africa.

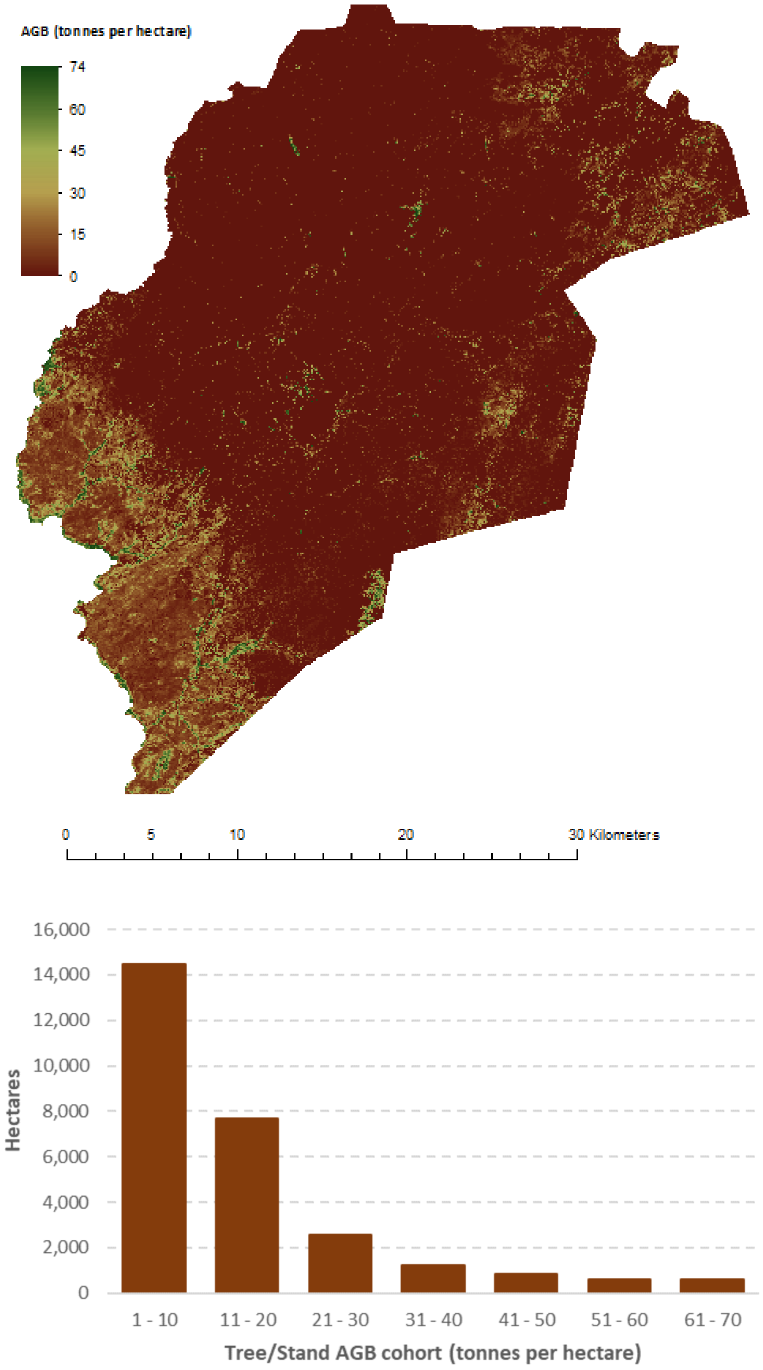


Figure 4.11 Area distribution per AGB range class in the baseline LULC map

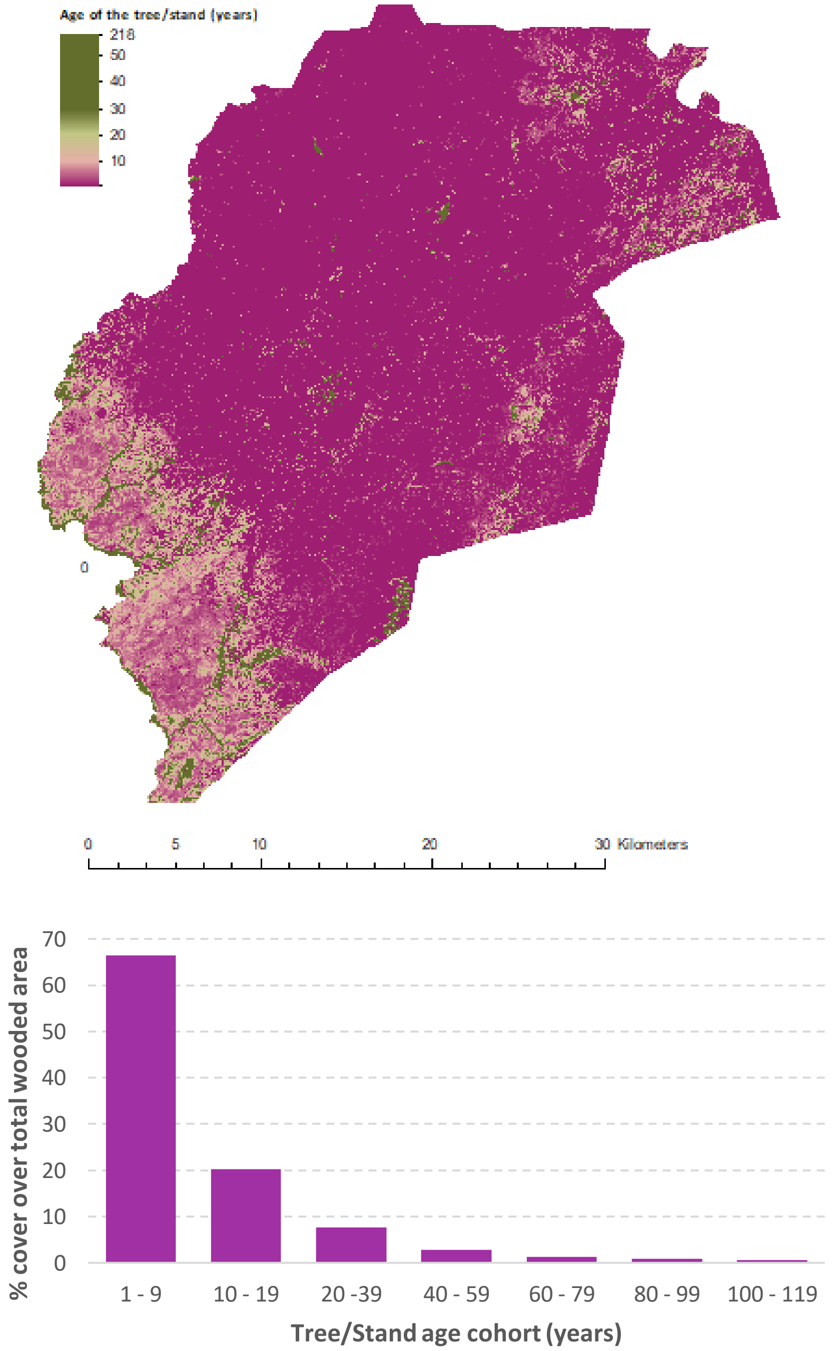


Figure 4.12 Area distribution per age range class in the baseline LULC map

Moreover, following the assumption that woody pixels represent the space that will be occupied by a fully-grown tree when it reaches maturity, the baseline scenario also fits the well described pattern of tree distribution in agricultural savanna landscapes, in which most of the largest trees are located in farmlands. This feature is captured in Figure 4.13, which shows that the weight of the growing AGB from trees of the largest size classes is higher for the aggregate of isolated trees pixels than for the aggregate of non-isolated tree pixels.

Figure 4.13 Percentage distribution of AGB classes in isolated and non-isolated woody pixels

4.3.3 Temporal dynamics of regional woody biomass distribution and yields

As it was described in the methodology, the proxy to assess woody harvest in this study is the AGB of pixels of a woody class that change to a non-woody class at any time step of the LULCC simulation. Hence, it is assumed that wood is only collected by total felling of whole trees, disregarding other harvesting methods such as collection of dead wood and pruning (Tredennick and Hanan, 2015). However, a comparison of the simulated wood harvest with the yields of woodlands in neighboring regions subjected to sustainable management plans can be used to discuss if the simulated harvest values are indicative of the expected sustainable yields.

Figure 4.14 shows the regional-scale dynamics of different indicators related to woody vegetation and its harvest. As shown in Table 4.5 and Figure 4.14a, average annual simulated harvest of woody covered areas range 0.80-1.6 t ha^{-1}, with an outlier maximum in the sixth time step of LULCC simulation of 2.66 t ha^{-1} in the FLAF scenario; 0.17-0.43 t ha^{-1} in the AFPA scenario, rising to 1.83 t ha^{-1} in the seventh and coming down slightly to 1.07 t ha^{-1} in the last time step of the simulation; in the CEXP scenario ranges 0.38-1.29 t ha^{-1}, rising up to 2.01 t ha^{-1} in the last time step of the simulation. Value variations across time are likely to be highly driven by the absence of any LULCC rule defining an age requisite for woody cells to change, therefore, it may randomly occur that "harvested" woody LULC cells at a certain time step have a considerably higher average AGB than in the rest of the time steps of the series. A longer time scope would be necessary to appropriately compare the sustainability of the wood yields of each scenario.

Table 4.5 Average annual woody biomass yield

	T_0 - T_1	T_1 - T_2	T_2 - T_3	T_3 - T_4	T_4 - T_5	T_5 – T_6	T_6 – T_7	T_7 – T_8
CEXP	0.55	1.10	1.22	1.29	1.28	0.38	0.38	2.01
AFPA	0.17	0.21	0.24	0.26	0.28	0.30	1.83	1.07
FLAF	0.80	1.01	1.19	1.31	1.42	1.49	1.56	1.60

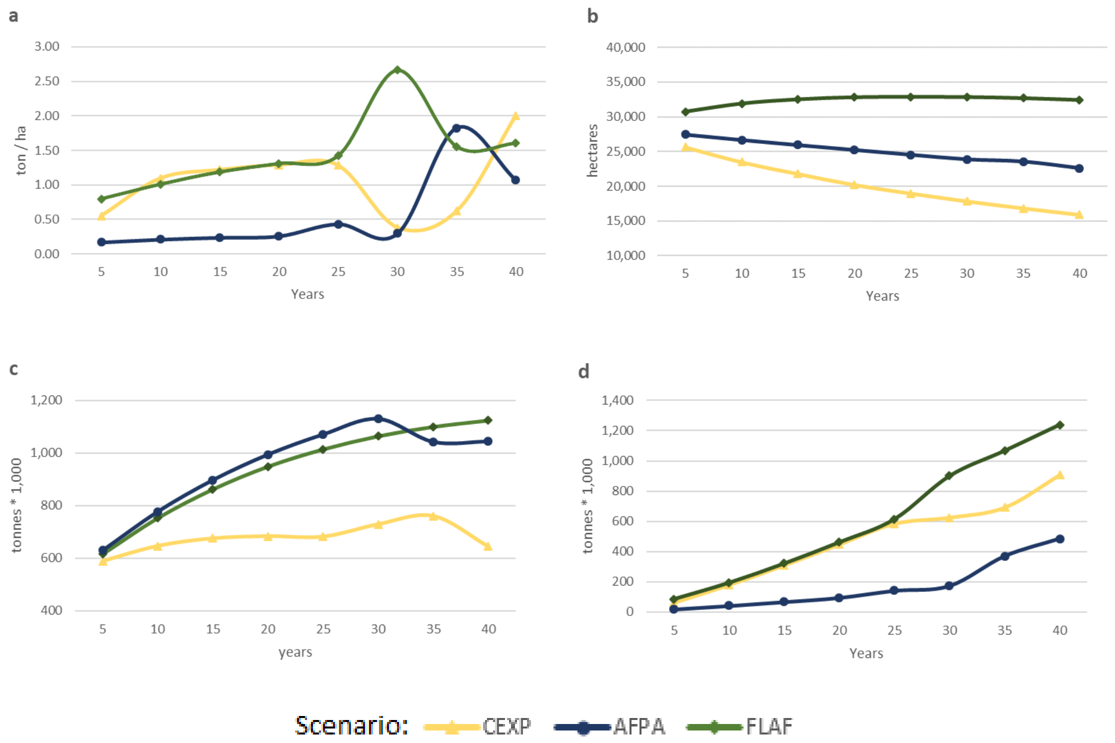


Figure 4.14 a: Average annual wood yield (t ha^{-1} $year^{-1}$). b: Area covered by woody vegetation (hectares). c: Total standing wood biomass (thousand tons). d: Cumulative wood yield (thousand tons).

The average yields of the three scenarios remain fairly constant until the twenty-fifth year of the simulation, which is due to the lack of age-based rules to forest conversion. Despite the pronounced loss of woody cover in the CEXP scenario, its projected annual yields are similar to those of the FLAF scenario during the first twenty-five years of simulation. This is due to similar rates of woody LULC transition into croplands and grasslands, with the difference being that the CEXP scenario experiences a net loss, whereas the FLAF scenario maintains, and even increases, its total wood area. Cumulative yields are the highest in FLAF and lowest in the AFPA scenario, which is expected due to the conservation of existing dense woodlands in the latter. The increase of the available wood resource in the AFPA scenario results in a relative closure of the cumulative yield gap during the last part of the simulation due to the high levels of biomass density accumulated in perennial vegetation classes during the first thirty years of this scenario. However, the high harvested amounts during this period result in the decrease of standing woody biomass below the levels of the FLAF scenario. The CEXP scenario contains much lower total standing biomass than the other scenarios during the whole simulated period.

However, it must be noted that the total woody stock increases the three scenarios. Even the cropland expansion scenario (CEXP) experiences a slight increase, during the simulated timespan. This output is the result of the lack of stand age data, which had to be simulated, and the management assumptions of the growth table. Simulated baseline age values most likely have underestimated the real world age of many stands because they were estimated as the inverse of the growth model, which assumes no negative disturbance impacts. However, in the real world, most of the savannas are affected by disturbances at different levels of severity. Therefore, their AGB remains low, even in old stands. Hence, whereas in the baseline map there are many cells with low AGB content which correspond to degraded low productivity stands in the real world, the simulation assumes that they are productive young stands. At the aggregated regional level, the output will be biased towards representing a net increase of total standing AGB. The GISCAME software has the possibility to restrict LULCC through transition rules based on certain mapped factors, for example, on age. However, such functionality was not been used due to the high uncertainty regarding woody stand age and management. Harvesting events are not registered because they are carried out by a multiplicity of stakeholders. Moreover, there is no information on the management prescriptions of state-managed woodlands.

4.4 Regional-level simulation of food, feed and fuel provision

4.4.1 Quantification of inputs and grain yield scenarios

The final output of this exploratory exercise is the spatial- and temporally explicit quantification of biomass provision (grains, crop stover, wood and total) as well as the potential benefits of its consumption (food nutritional yields, fuel calorific value and feed metabolizable energy). The provision by annual crops and perennial vegetation of the different biomass types and their benefits were simulated on a one-dimensional scale, and assigned on a cell-basis to each simulated LULC map. The maps of total fuel provision by cropland and perennial vegetation were summed up to obtain the total regional fuel yield. Additionally, it was assumed that some cultivation of annual crops occurs in the understory of trees. This feature was represented by simulating the provision of annual crop yields in locations covered by woody LULC classes. However, the effect of this feature on total regional yields was very small, ranging only 1-3% higher than if the cultivation of annual crops under trees were not considered.

In the following paragraphs, a selection of the array of outputs is presented: grain provision, nutritional yields, feed provision and fuel provision. These four example outputs are illustrative of the entire range of potential trade-offs derived from land and biomass use changes that can be analyzed in this study.

Regional total production and mean LULC class grain yield was assessed for the baseline and for the last time step of the simulation of each combination of LULCC and yield increase scenario (Table 4.6). Also the mineral nitrogen (N) and phosphorus (P) levels used as input for the APSIM simulations were included, both in regional total application and average rate of application in all croplands. By comparing simulated fertilizer input and grain production, a deeper insight into the implications of each scenario can be gained. Total regional production, and its difference between LULC scenarios, is determined by differences in the share of cropland area. Therefore, the difference between total regional production between CEXP (with the highest production) and AFPA is smaller than the difference between AFPA and FLAF (with the lowest production). The cropland area of the FLAF scenario is so small in comparison to the other two LULC scenarios, that even in the higher yield increase scenario, total production is smaller than with lower yield increase in the other two LULC scenarios. In the lower yield increase scenario, average grain yield by the end of the simulation is around 180% of the baseline, and in the higher yield increase scenario, about 230%.

Yield increase scenarios have a higher impact on total regional production than LULCC scenarios. Small differences in the average yields and fertilizer application rates can be found between scenarios due to the fertility of the areas where cropland expansion occurs and differences in the total area covered by each specific LULC class. In the lower yield increase scenario, mean rate of mineral fertilizer application by the end of the simulated period is roughly between 2.3 and 2.9 times higher than the mean rate in the baseline, whereas in the higher yield increase scenario, it is roughly between 8 and 10 times higher than in the baseline, both for nitrogen and phosphorus. However, total mineral fertilizer application across the region increases roughly, in the lower yield increase scenario, 4 times in the CEXP and AFPA LULC scenarios, and 2.5 times in the FLAF LULC scenario. In the highest yield increase scenario, the rate of mineral fertilizer application increases roughly between 14 and 15 times in the CEXP and AFPA LULC scenarios and roughly between 9 and 10 times in the FLAF scenario.

Table 4.6 Regional production, fertilizer input and area covered by cropland LULC classes at the beginning (baseline) and by the end of the simulation (40 in the future).

	Baseline	Yield increase scenario	LULC scenario 40 years in the future		
			CEXP scenario	**AFPA scenario**	**FLAF scenario**
Production (*tons*)	80,645	*Lower*	225,773	202,113	162,559
		Higher	293,001	265,843	202,073
Total fert. input (*N-P tons*)	383-135	*Lower*	1,471-586	1,365-541	984-371
		Higher	5,715-2,142	5,250-1,961	3,726-1,425
Mean grain yield (*t* ha^{-1})	1.55	*Lower*	2.84	2.80	2.85
		Higher	3.69	3.69	3.55
Mean fert. input rate (*kg N-P* ha^{-1})	≈ 7-3	*Lower*	≈ 19-7	≈ 19-8	≈ 16-7
		Higher	≈ 72-27	≈ 73-27	≈ 65-25
Regional share of cropland area	48%		74%	67%	53%

4.4.2 Nutritional yield scenarios

In contrast, nutritional yields may experience reductions because this unit is defined not only by the supply, but also by the demand side. The results are presented as times series of provision ranges, with limits representing the lower and higher scenarios of yield increase (Figure 4.15). Nutrient yields will increase if they are accompanied by grain production increases not necessarily higher than twice the current production in forty years, and population growth is slow or moderate. Food caloric yield is the lowest of the three nutritional indicators, and iron yield the highest, which agrees with another study conducted in the West African Sudanian savanna belt, in south-eastern Senegal (Wood, 2018). Differences in the pace at which population is growing are the main determinants of nutritional yields, more than agricultural productivity and even more than LULCC. In a fast population growth scenario, even if mean regional grain yields increase quickly, the nutritional yields will be lower than if population growth is slow and mean regional grain yields increase slowly. Fast population growth implies the stagnation, and even reduction, of nutritional yields, which can be particularly pronounced if cropland area is not expanded. Current regional iron yields are close to 2.5 times the local population, zinc yields 2 times the local population and food caloric yields below one (around 0.9), i.e. they are below the necessary supply levels to satisfy the caloric requirements of the local population. Iron yield may increase by up to 6 in the FLAF, and in the CEXP LULC scenarios by up to 8, if population growth is slow and grain yield increases are fast. Even if grain yield increases are slow, iron yields will also increase, almost up to 4 and 5, respectively. The difference between zinc and iron yields closes as grain yields and population growth increases. Food caloric yields are the least affected by grain yield increases. Food caloric yields can approach 2 in the FLAF LULC scenario, and surpass that level in the CEXP and AFPA LULC scenarios.

Assuming that the simulated average regional yield levels are achieved, the contribution of the regional agro-ecosystem to improve the nutritional adequacy of the local population will increase, regardless of the LULC change scenario. However, as climate change is likely to considerably limit the capacity to achieve such yield levels (Raes et al., 2021), the pace of population growth is also key. If regional population grows quickly, the contribution of the local agro-ecosystems to support the nutritional adequacy of its population will be very limited. Indeed, the likely future population growth pace will be faster than the fastest of the population growth projections used in this study. Shortly before the completion of this research, the Ghana Statistical Service published the first results of the 2021 Census, reporting the sum of the population of the Bongo, Bolgatanga Municipal and the newly created Bolgatanga East District (split from the former in 2018) as 298,942 inhabitants (GSS, 2021), considerably higher than 266,665 inhabitants projected for 2020 in the fastest scenario of this study.

In particular, iron yield levels may diminish if grain yields do not increase quickly, and caloric yields will also do if annual crop cultivation does not expand up to levels around 70% of the total regional area. Taking this into consideration, it is important to understand that regional LULC planning shall go hand in hand with interventions across the entire biomass value web.

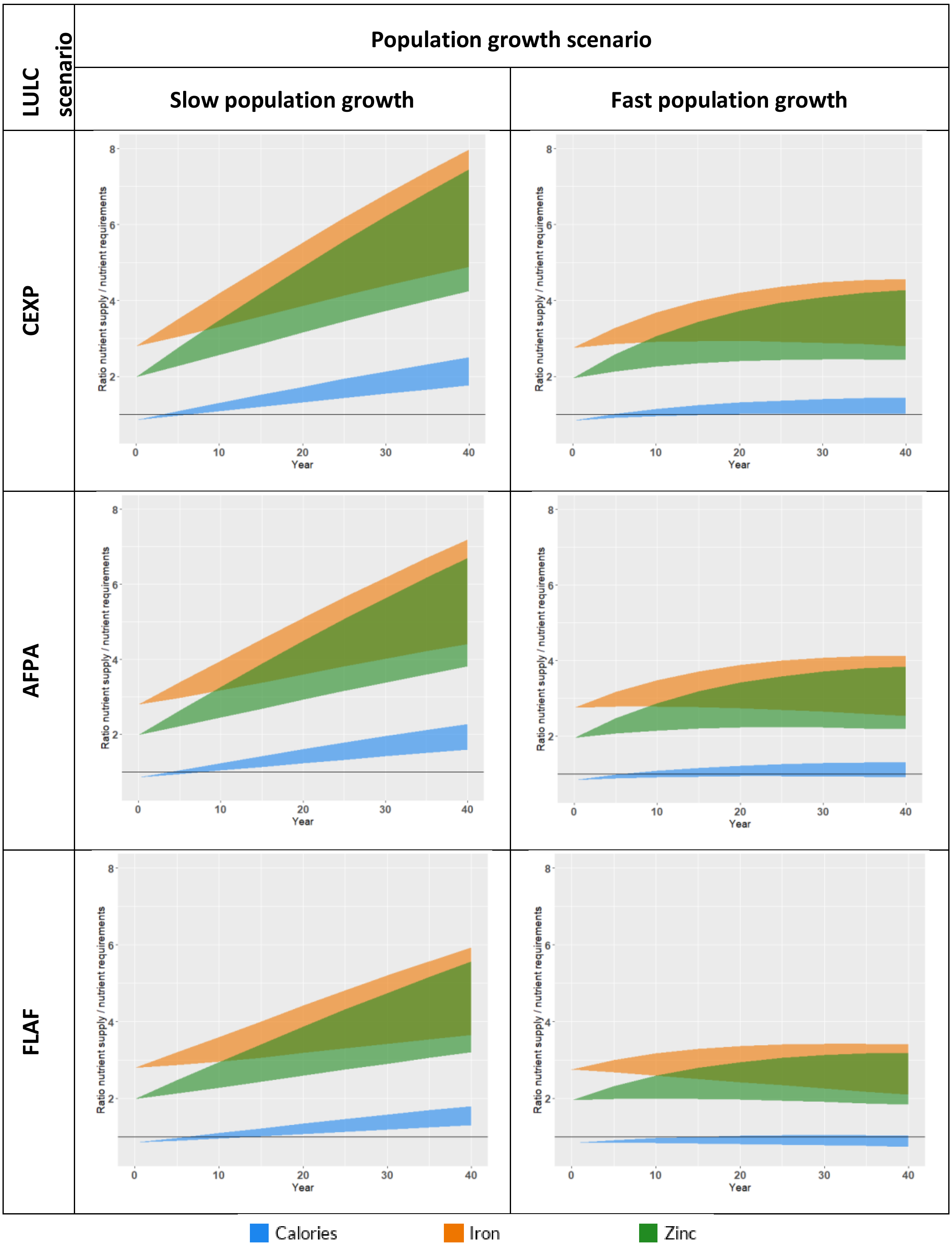


Figure 4.15 Regional-extent nutritional yield trends over 40 years for calories, iron and zinc under three LULCC, two yield increase and two population growth scenarios. The upper part of the polygons is nutrient yield in higher grain yield increase scenario, and the lower part a slower grain yield increase scenario.

4.4.3 Fuel and feed yield scenarios

The future trends of feed and fuel provision are different than those of edible grains. It has been assumed that the optimal pathway to maintain soil health and, hence the long-term stability of yields, is to increase the proportion of crop residues returned to the soil as mulch (Pieri, 1989; van Noordwijk et al., 2018). Hence, the scope for increasing biomass supply for fuel and feed purposes from food crops is rather limited. It has also been assumed that the spread of the adoption of soil mulching practices among farmers will be progressive, and therefore, the proportion of cropland biomass available for fuel and feed uses has been assumed to decrease linearly. Such an assumption results in a continuous and linear decrease in feed provision, with the exception of a slow adoption pace of mulching practices across the region combined with overall cropland expansion (Figure 4.16).

In the simulation of fuel provision trends, the calorific value of harvested wood biomass has been added to the calorific value of harvested annual crop stalks. The result is that the simulated fuel provision trends are more positive than those of feed provision (Figure 4.17). In the case of the two LULCC scenarios experiencing an increase in total cropland area, simulated fuel provision trends are clearly positive. In the AFPA scenario, fuel provision levels increase from 1.64 Terajoules in the baseline up to 2.3-2.7 Terajoules, depending on the intensity of annual crop biomass consumption, by the end of the simulated period. In the CEXP scenario, fuel provision levels by the end of the simulated period can double those of the baseline. In the FLAF scenario, experiencing woody vegetation cover increase, fuel provision levels remain stable in the scenario of low intensity of annual crop biomass consumption, meaning that the loss of biomass for fuel purposes due to mulching is totally compensated by the gains from harvestable woody biomass. Drastic but ephemeral oscillations of the fuel provision levels occur in the last time steps of the simulation in the three LULCC scenarios. This is the result of the combined effect of two simulation features: the unchanging value of LULC transition probability rules across time steps, which result in different total area changes between time steps; and the random allocation of the simulated logging events, which does not take into consideration tree age.

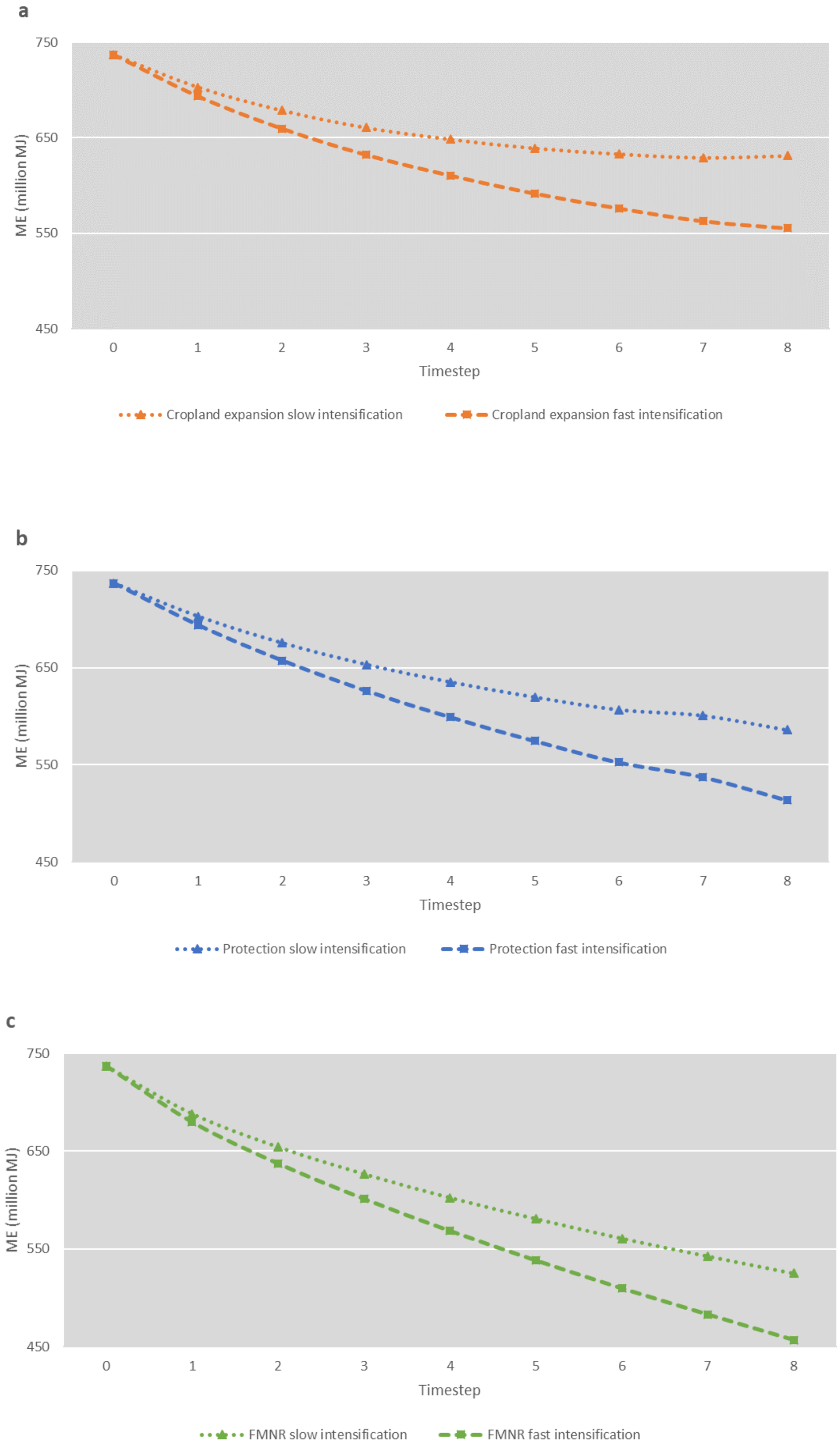


Figure 4.16 Regional-extent trends of feed provision from annual crop residue biomass over 40 years under three LULCC and two intensification scenarios. A: CEXP scenario; B: AFPA scenario; C: FLAF scenario.

Fuel potential provision, same as the other biomass-use indicators, is also highest in the CEXP scenario, followed by AFPA, and FLAF showcasing the lowest biomass provision levels.

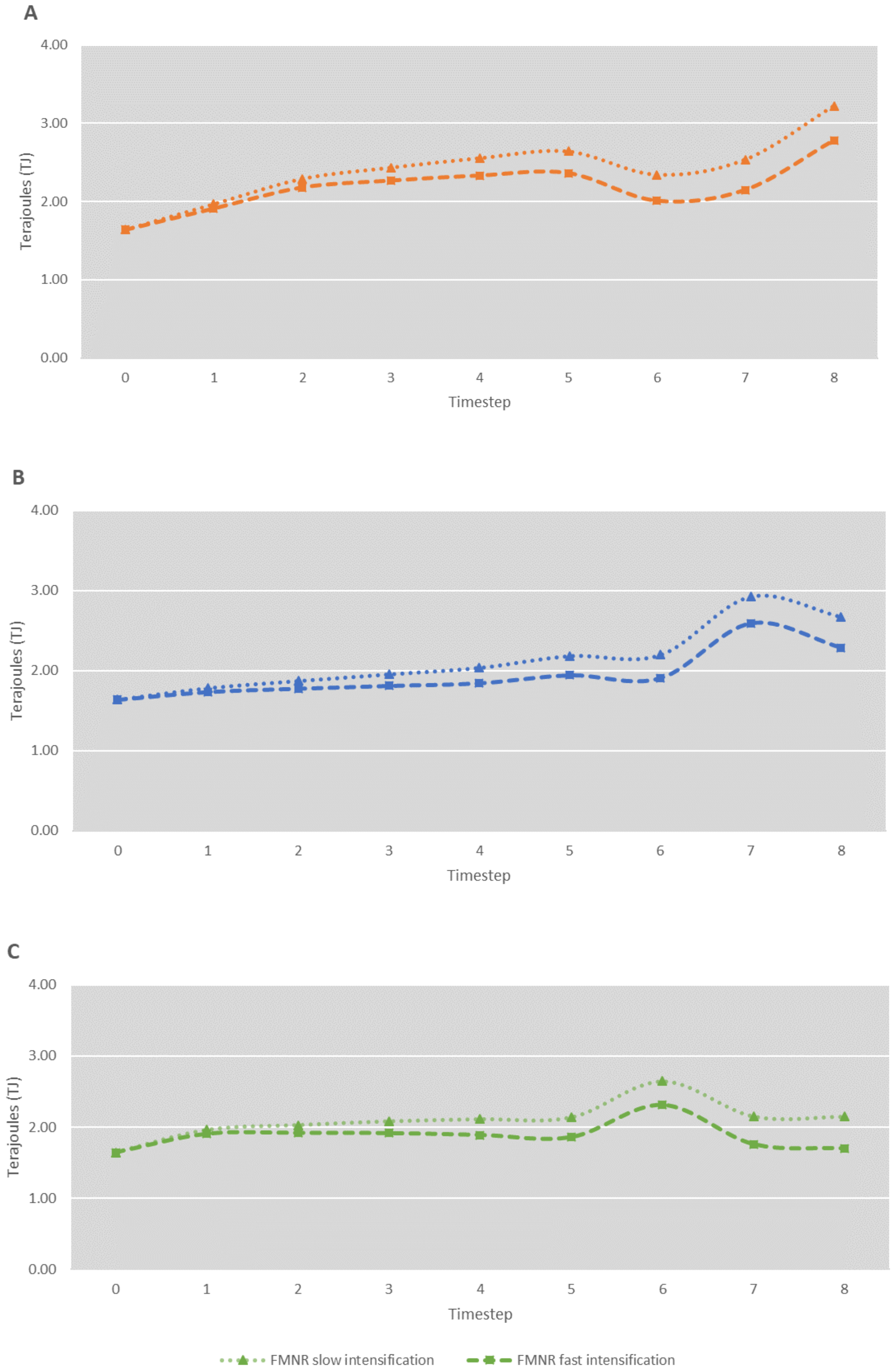


Figure 4.17 Regional-extent trends of the fuel value of biomass harvested from the landscape for fuel purposes biomass over 40 years. A: CEXP scenario; B: AFPA scenario; C: FLAF scenario.

The total supply of potential useful energy than can be used with different cooking devices from the wood and crop stalks harvested in the region is provided in Appendix 18 and 19. This is the same as it was done with the nutritional yields; fuel yield dynamics have been projected for each simulation scenario. Under the current levels of assumed biomass harvesting for fuel purposes, biomass demand for cooking is higher than the regional landscape's supply. Figure 4.18 shows the potential prospective dynamics of the match between supply and demand without considering any improvement in the average energy efficiency of cooking tasks. The regional supply would be higher than the demand only through the CEXP LULCC pathway, and this positive balance would likely reverse during some periods, leading to acute crises of wood shortage. Through the FLAF LULCC pathway, supply could be enough for the next few decades, but only at the expense of removing all biomass from cropping fields with the pervasive effects it would have for sustainable agricultural production. And even without considering these pervasive effects, the system shows limited capacity to sustain the pace of demand in the long-term, even under projections of slower population growth. Through the AFPA LULCC pathway, the match between supply of useful cooking energy and its demand would only improve after about thirty years in the future. In the case of faster population growth scenarios, and without an increase in the average regional cooking fuel efficiency, the balance between supply and demand would decrease regardless of the LULC scenario.

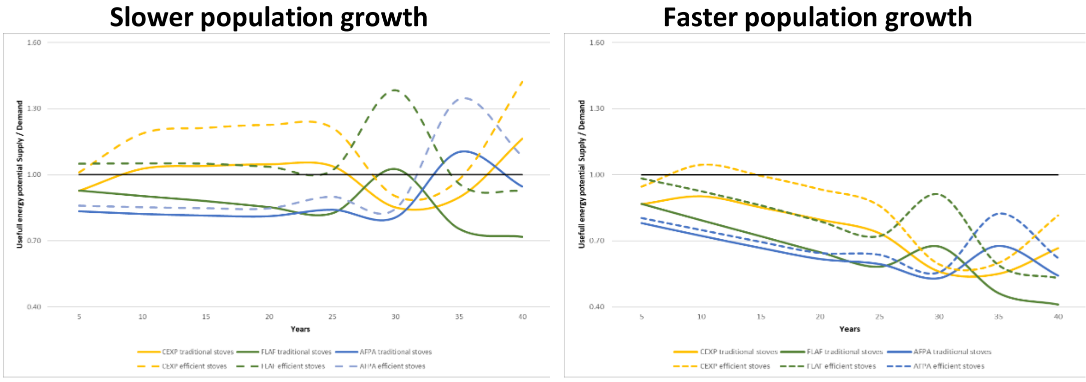


Figure 4.18 Projected cooking fuel yield dynamics (cooking useful energy supply *vs.* demand) without considering the spread of more efficient biomass-to-energy cooking technologies.

Given the limited capacity of the regional landscape to satisfy regional fuel demand with its own biomass production under business-as-usual scenarios of raw solid biomass as a source of cooking fuel, future supply dynamics of the potential useful cooking energy were estimated including two different scenarios of increased average biomass-to-cooking energy regional efficiencies. In this case (Table 4.19), the match between supply and demand will improve in the future.

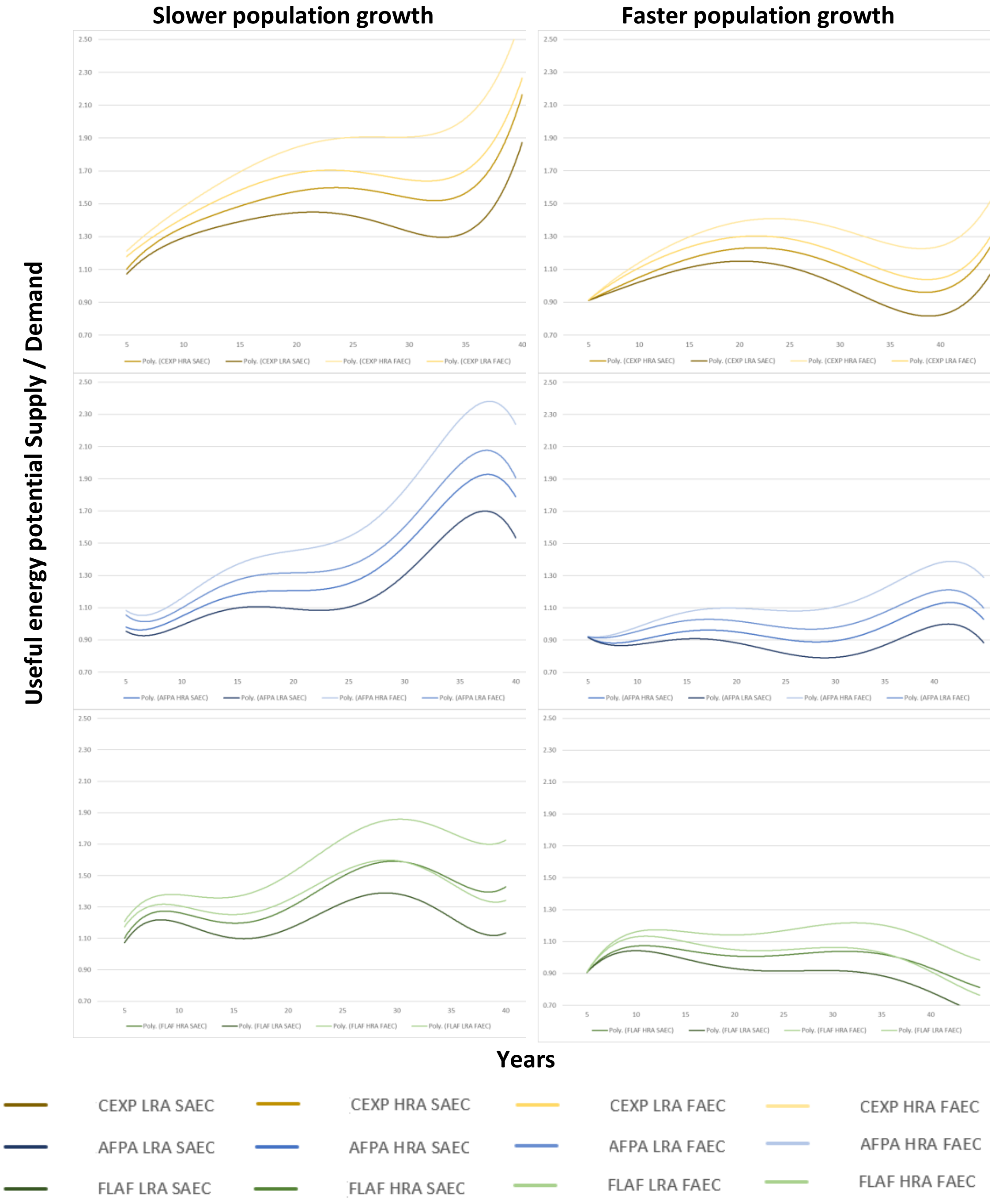


Figure 4.19 Projected cooking fuel yield dynamics (cooking useful energy supply *vs.* demand) considering two scenarios of spread of more efficient biomass-to-energy cooking technologies. HRA: High crop Residue Availability; LRA: Lowe crop Residue Availability; FAEC: Faster Adoption of Efficient Cooking technologies; SAEC: Slower Adoption of Efficient Cooking technologies.

Only the FLAF LULC scenario would imply a likely neutral or negative trend, and the AFPA LULC scenario a relative stable trend of such a match in the technological scenario with slower increase biomass-to-energy conversion efficiency improvement, and in both cases only in faster population growth scenarios. If population grows at a slower pace, the match between supply and demand would increase under the three LULC scenarios, which would provide opportunities to increase the inflow of revenues into the region as an exporter of biomass pellets, or even better, to develop and diversify its industrial sector with the increased availability of energy produced within the region. In any case, the likely future population growth pace will be faster than the fastest of the population growth projections used in this study. Shortly before the completion of this research, the Ghana Statistical Service published the first results of the 2021 Census, reporting the sum of the population of the Bongo, Bolgatanga Municipal and the newly created Bolgatanga East District (split from the former in 2018) as 298,942 inhabitants (GSS, 2021), considerably higher than 266,665 inhabitants projected for 2020 in the fastest scenario of this study.

In the three scenarios, croplands are the main source for both potential fuel and feed provision (Figure 4.20), always contributing around 70%, or even more, of the total provision of both indicators. Woody biomass only makes a continuously significant contribution to regional fuel production in the FLAF scenario, always above 20% and rising above 40% during the last part of the simulation. In the AFPA scenario, in which wood harvest is prevented, it is as low as 4-6% during the first 20 years. In the CEXP scenario the contribution of wood biomass to potential regional fuel is higher, around 20%, but it experiences drastic oscillations during the last part of the simulation. In scenarios of adoption of improved biomass-to-energy conversion technologies, the contribution of croplands' biomass to total fuel supply would be even bigger.

The contribution of grasslands to total feed provision follows the trend of its total area, hence diminishing continuously, from 30% to about 10%. Only in the FLAF scenario such a decrease is moderate, and therefore, the contribution of grassland biomass to potential regional feed provision does not become smaller than 24%.

The results of this study show that increasing yields substantially is necessary in order to maintain the levels of satisfaction of local demands, and cropland expansion is likely necessary as well. This agrees with other approaches conducted in other West African savanna regions, such as central Benin (Duku et al., 2018).

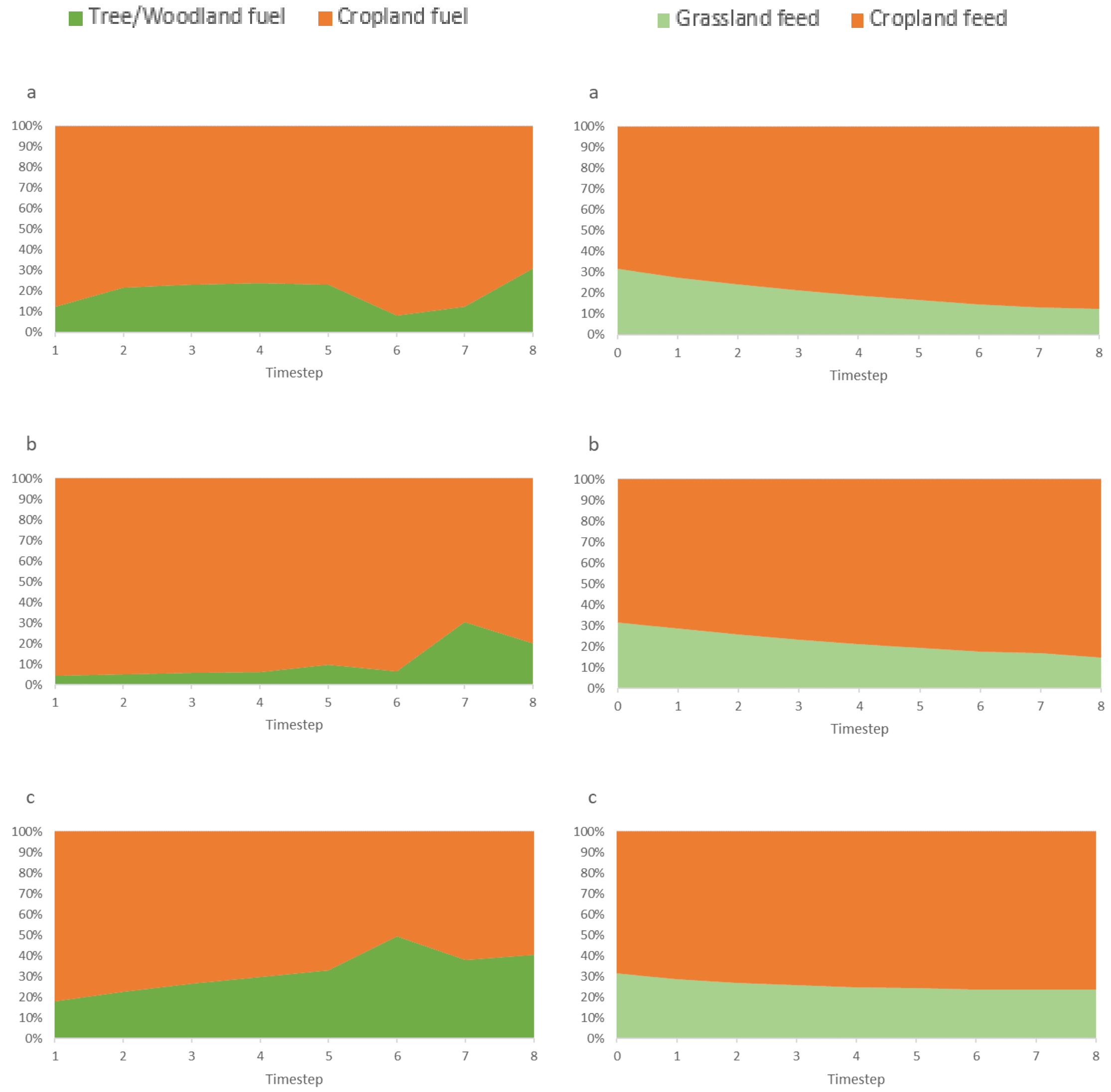


Figure 4.20 Contribution of wood and cropland biomass to potential regional fuel provision (left); and contribution of grasslands and croplands to potential regional feed provision (right) under three LULCC scenarios: a: CEXP; b: AFPA; c: FLAF.

5 DISCUSSION

5.1 Land use change scenarios

Land change simulation models must predict both the total area covered by each LULC class and the location of any change (Pontius and Millones, 2011), but there is always a trade-off between the accuracy to simulate the total quantity of each transition and its spatial distribution (Camacho Olmedo et al. 2015). LULCC models can be used to design scenarios and explore their impact. Those models in which the user has control over the simulated outputs can be of great value to participatory landscape approaches because they allow conversion of specific LULCC narratives about the future into spatial-temporal explicit data (Gounaridis et al., 2018). In this study, major LULC scenario traits were simulated satisfactorily according to the qualitative definition expressed in section 3.2 (in terms of spatial distribution of LULC pattern and temporal trends of the total area covered by each LULC).

5.1.1 Advantages and shortcomings of the methodology and data used in this study to simulate LULCC change

Once the set of probability values was established for each scenario, the cellular automata was run and, upon visual evaluation of the results, values were adjusted until the outcome of the LULC spatial distribution pattern resembled the qualitative definition of each scenario. In the baseline map, cultivated lands occupy 48% of the total area of the study region. Trend projection exercises estimate that the share of cropland area in some West African countries can reach up to about 70%, and even more (Ahmed et al., 2016). Although this data is not disaggregated at the regional or district level, that value has been used to define the cropland area by the end of the simulated period in the cropland expansion scenario. Given the lack of data in tropical Africa to simulate observed LULCC change at the district/landscape scale, it has been assumed that the arbitrary assignation of LULC transition probabilities does not underperform empirical inductive methods that measure changes over a time-series of historical data.

The approach of this study to simulate to LULC transitions, with a CA which is not informed by a time-series of LULC maps, has its shortcomings. This approach makes it easier to calculate the transition value based on the total area of the LULC of origin than on the demand for the target LULC. Regarding the clearance of woody vegetation stands, this is problematic in West African savannas, because these events are largely driven by cropland expansion.

The main difficulty in estimating transition probabilities is that these vary widely depending not only on the dynamics of the socio-ecological system itself, but also on technical issues such as the extent of the study region and the initial area covered by each LULC class. For example, when LULCC is analysed over the entire West African region, the rate of change of each LULC class may be lower than if the analysis had been done over smaller areas experiencing faster LULCC, such as novel agricultural frontiers. Cropland expansion annual rates have accelerated over recent decades over West Africa as a whole (Herrmann et al., 2020). These expansions have taken place mainly across regions which were previously not extensively cultivated, such as the Nigerian mid-belt and Southern Burkina Faso (Asenso Barnieh et al., 2020, Souverijns et al., 2020). In our scenarios, these rates of conversion remain fairly stable or diminished across the simulated period, and are lower than those experienced across the Sudanian belt during the first-thirteen years of the 21st century, even in the CEXP scenario. This might be expected because the study region has already been extensively cultivated for decades, and it has been assumed that if accelerated cropland expansion persists, it will occur across regions which are not yet so extensively cultivated, such as it could be in the recently created Savanna Region of Ghana, for example.

The precise share of each LULC class was not controlled, and therefore, the total areas covered by woody vegetation were very different between the two scenarios in which the impacts of different spatial distributions of woody cover were expected to be assessed (FLAF and AFPA scenarios). Furthermore, in the FLAF scenario, loss of total cropland area within traditionally farmland areas was compensated with an excessive cropland encroachment into woodland areas that resulted in a very homogenous landscape across the whole region. Such a scenario is probably undesirable because it may result in maladaptation outcomes (Luedeling and Neufeldt, 2012). This outcome is rather unlikely because it would mean the widespread encroachment of settlements within a forest protected area and the end of the riverine areas as the most forested parts of the landscape. Furthermore, despite maintaining intermediate levels of tree cover are necessary to optimize the flow of ecosystem services on landscape scales (Bayala et al., 2007; Ilstedt et al., 2016), the simulated increase of tree cover within farmlands in the FLAF scenario was more widespread than expected. Scenarios with similar levels of total woody cover and biomass but different configurations of woody vegetation patches and different tree densities would be interesting to explore production dynamics, but the shortcoming of the lack of control to simulate different patterns woody LULC distribution across the study region limits the scope of questions that can be addressed by this set of LULC scenarios.

In savanna ecosystems, the proportion of tree cover naturally fluctuates over time (Tredennick and Hanan, 2015; Adeyemi and Ibrahim, 2020). LULC area fluctuations were only slightly simulated by the FLAF scenario, whose woody vegetation cover increase during the first half of the simulated period was turned into a slight decrease during the second half. Actual cropland area fluctuations in rural savanna regions of West Africa occur on an inter-annual basis (Forkuor, 2014). The rate of cropland area change becomes slower as the simulated time steps are further from the initial ones. Such is the expected behavior of future cropland expansion rates (Lambin et al., 2014a). The ability to represent total LULC class area fluctuations in temporally-dynamic LULCC scenarios depends on the length of the simulated timespan. In the GISCAME platform, if the values of the transition probabilities are the same at each time step, the natural behaviour of the LULCC change simulation, along an infinite succession of time steps, is indeed that the total LULC areas fluctuate. But LULCC scenario analyses have a defined time scope. Hence, if the length of the periodicity of medium- to long-term LULC area fluctuations can be approached, transition probability values must be changed at different time steps. However, the temporal periodicity of these fluctuations is unknown and may vary among study regions and depend on the extent of the region studied. Given the lack of data, it has been assumed that either a continuous increase or continuous decrease of the total area of the different LULC classes are plausible outcomes within the simulated timespan. In the future, explorative LULCC scenario exercises focused on the landscape/district extent must incorporate data and models at different scales, because vegetation dynamics at the plot-level are inherently unpredictable, particularly in savanna ecosystems. Further integration of models and data on large landscape scales shall provide meaningful simulations of the heterogeneity of trees and woodlands distribution and pattern dynamics (Staver et al., 2019).

A common land change trend that is not uncommon to observe in the Volta basin is the increase of bare land area (Zoungrana et al., 2015). Such surfaces are bare due to extremely low soil fertility, i.e. low capacity to support biomass growth. This is a phenomenon that can be driven, for example, by the reduction of fallow periods, which impedes the reestablishment of soil functions due to the exhaustion of soil nutrients and erosion after several years of continuous cropping. The input LULC data does not include an individual category concerning bare surfaces. They are included in the category “unproductive”, which shares with artificial surfaces, due to a high degree of confusion (Forkuor, 2014). Hence urbanization and land degradation processes cannot be simulated because, although they involve two different LULC classes, they are categorized within the same LULC class in data used in this study. Such a land use classification has no serious implications for the scope of this study, because neither bare nor built-up lands produce biomass, but present shortcomings for the development of a more robust spatial-temporal assessment, because the most severe impacts of inadequate land management (degradation into bare land) cannot be represented.

5.1.2 Alternative methodologies to simulate landscape-scale LULCC change in African savannas

An alternative methodology to simulate LULCC scenarios, when no time-series of past LULC is available, is the maximum entropy approach, typically used in species distribution modeling. It is a data-driven inductive methodology, establishing statistical relationships between the locations where LULC classes occur and the value of environmental variables in that same location. The strength of this method is that it allows one to quantitatively pre-define the total area covered by each LULC class in each scenario/time step. So far, this methodology has been used to simulate soybean cropland expansion scenarios across the Brazilian Amazon, largely driven by large-scale agro-industrial development and the global food system (Frey et al., 2018). In such a context, cropland expansion can be evaluated with coarse grain resolution. However, the methodology presents important shortcomings to represent land use change narratives in West African savanna agro-ecologies. The spatial allocation of LULC among a variety of LULC classes becomes particularly challenging. A suitability score rank must be established for each LULC class at each location, resulting in “niche” patches for each LULC class at specific locations whose area expands or retracts depending on the targeted total area pre-defined value, but whose core will remain unchanged regardless of how many model runs are simulated. This presents particular shortcomings for the simulation of biomass accumulation within woody LULC classes, because in the core area vegetation will never disappear. Hence, the highly dynamic nature of woody cover in small-holder savanna regions cannot be represented. On the other hand, because the “niche” area of each LULC class expands or retracts with every successive time step, many (but always the same) cells in the map would experience changes between woody and non-woody cover at every iteration of LULCC simulation, which is a pace of change too fast even for the landscapes of the study region. Furthermore, the characteristic feature of savanna agricultural landscapes, with trees dispersed over the farmlands, tends to be lost.

Recent open access release of high-scale, continental extent, LULC products offer good prospects for the application of geographical LULCC models to time-series of observed LULC in Africa. The ESA-CCI S2 prototype land cover map with a 20m pixel size, based on Sentinel images (http://2016africalandcover20m.esrin.esa.int/), is expected to be updated periodically. Because its time scope is currently very short, it cannot be used to analyze past observed long-term trends and, consequently, it will be difficult for LULCC models to be able to represent narratives of long-term future LULC pattern changes. Furthermore, its accuracy to detect croplands (83%) (Alkhalil et al., 2020) is much lower than the map used in this study, with a cropland classification accuracy of 95% (Forkuor et al., 2015). In the last year, a time series of 30 m pixelsize LULC maps of Burkina Faso and Northern Ghana has been made available, based on Landsat images, covering the period 1988-2015 (https://zenodo.org/record/4013392#.YAxZxBYo-Ul). However, the accuracy of this product is 70% (Souverijns et al., 2020), even lower than the ESA-CCI S2. Nevertheless, its long timespan makes it suitable to simulate observed past LULC change interactions as a base to develop alternative future LULC change scenarios, which nowadays can be done, for example, with open access R packages such as *lulcc* (Moulds et al., 2015). Finally, it must be considered that the class cropland is not disaggregated into different crops species in either of these two datasets. Therefore, in order to replicate the methodology exposed in this study but using data of one of these products, a heuristic solution should be adopted to disaggregate the cropland class. This could consist of running the LULCC model on the original dataset, and assigning afterwards at each time step a crop specie suitability score to each cropland cell with the maximum entropy approach.

Finally, LULCC simulations based on past observed LULC transitions shall be informed through better knowledge of their drivers and modeling of their impact values. The lack of data and methods to translate the knowledge of drivers of land use change into algorithms, impedes simulation of spatial data that serves to explain the processes of land use change in the study region. Available or accessible information of land use plans is very limited in Ghana, particularly at the catchment scale (Aduah et al., 2019). Economic variables, such as land price, are important drivers of land use change, but data on its spatial variability is in most cases not available, especially in countries that lack a universal census of its lands, such as Ghana. Furthermore, demands for land-based products are determined by socio-economic factors such as market access, spatial distribution of income, consumer preferences and policies. These factors are constantly changing and their spatial representation at a landscape scale is highly problematic, particularly in the context of growing global markets. Making assumptions about the impact on LULCC of the interaction between the demand for land and the demand for the products and benefits are derived from it, subject to a high degree of uncertainty (Nkonya et al., 2012).

5.2 Annual cropping systems

Input data for the estimation of regional crop biomass production was produced within this study through process-based modeling. The advantages of this approach include its suitability for out- and up-scaling of results over large areas (Soltani et al., 2020). Common alternative options to attain the same result are farm surveys, which are costly and difficult to extrapolate to other regions or times, and agricultural statistics, which allow the researcher to save considerable time, but do not contain any description of field-scale management. By using process-based modeling, the conditions under which the crops grow are explicitly described, even when more than one crop is cultivated within the same field, allowing generation of data for hypothetical growing conditions and, hence, being more useful for scenario analyses. It also allows the researcher to simulate data on the performance of intercrops and intra-annual crop sequences, and hence evaluate the impact of promising alternative land uses, such as the addition of a green manure crop in the late rainy season. In this study, only current monocrops and intercrops where assessed, and the focus was put into the impact of increased addition of fertilizers, which is expected to be the only management operation with a significant impact on sustaining food security in densely populated regions (Palm et al., 2010), such as the one in this case study. However, fertilizers alone cannot raise yields to the necessary and expected levels. Additional actions must be taken such as improving soil quality, reducing transportation costs and using complementary agronomic inputs (Liverpool-Tasie et al. 2017).

The simulated data is also subjected to uncertainties inherent in model structure and the accuracy of input data. Output values shall just be understood as indicative of plausible biomass yields, not to be used to optimize the levels of input applications. Uncertainty in model prediction was not quantified in this study, but it was assessed by comparison with field measurements from published data (Figures from 4.7 to 4.11). Such prediction uncertainty can be substantial (around 25-30%). Outputs from model ensembles can provide more accurate results than one single model alone, especially when aiming to simulate the impact of future climate scenarios on crop yields (Falconnier et al., 2020).

Simulating the most accurate annual crop yields has not been a priority in this study, because the focus was on comparing the yields of annual and perennial vegetation, with higher differences between both types of vegetation than those that may arise from shortcomings inherent to simulation models. However, in the following paragraphs several factors will be discussed that are relevant to scenario impact analyses and that could be assessed given the state-of-the-art of process-based crop models but were not included in this research, due in great part to a lack of data. Regarding the way in which environmental factors are represented in process-based crop models (i.e. climate and available nutrients), some considerations must be acknowledged.

5.2.1 Description, spatial allocation and simulation of soil fertility

Regarding the soil physical-chemical properties, three soils were parameterized in APSIM and the yields distributed in the biomass-provision map according to soil types. However, soil type beyond clay content (distinction between hydromorphic and non-hydromorphic soils), may not be the best indicator of soil fertility, at least in relation to maize yields, and particularly in agro-forestry systems, which homogenize yields across different soil types (Sileshi et al., 2010). Soils of the same class within the same landscape can have different properties; such was evidenced between ferric and plinthic lixisols in the Northern Region of Ghana (Nartey et al., 1997), with a significant impact on biomass productivity; and yields obtained by applying the same management can vary widely between regions within the same agro-ecological zone (Saïdou et al., 2018), even if the measured soil properties and climate are very similar (Danso et al., 2018a). The standard configuration of APSIM only simulates the cycles of the main nutrients: carbon, nitrogen and phosphorus. This can be generalized to most crop models and observational assessment studies. However, crops growing in soils with poor health, such as those with an unbalanced micronutrient content, will not respond to fertilizer application (Aniah et al., 2013; Vanlauwe et al., 2014; Kihara et al., 2016; Vlek et al., 2017; Burke et al., 2019; Kugbe et al., 2019). Therefore, the lack of data on soil micronutrient availability and their integration in crop models pose a limitation to the simulation of spatial yield variability. Despite these limitations, it must be acknowledged that because crop models are based on experimental evidence, the simulated yields can potentially be achieved through the application of a certain amount of macronutrients as long as they are balanced with those of micronutrients, or in combination with other management treatments (Bationo et al., 2018; Koné et al., 2018; Asante et al., 2020). Management strategies, within the same region, shall be tailored to the different resource endowments of each farmer in order to improve farm output (Traore et al., 2017). Hence, appropriate targeting technologies shall focus on the farm and farming system level rather than on individual fields (Giller et al., 2011; Rattalino Edreira et al., 2018).

Moreover, the spatial variability of soil fertility in densely populated savanna agro-ecologies is much more complex than soil types, alone, can inform. For example, ongoing processes of degradation of the productive capacities of soils are not uncommon. Most of the non-cultivated areas of the Bongo District develop over leptosols, which are very vulnerable to being affected by sheet erosion (Fugger, 1999; Noulèkoun et al., 2017). However, the occurrence of erosion is not determined by soil type, but also by its combination with land use history and current management. Hence, it may occur with other soil types which are not so vulnerable *a priori*. Indicators of soil erosion and land degradation common in the study area are sealed and compacted soils, surface gravel, concretions and iron pans (Adu, 1972), but such factors have not been mapped. The productivity of soils with these characteristics is likely to be much lower than any of the productivities simulated with the three soil datasets used in this study. Further expansion of croplands is likely to occur over soils which are marginally suitable for agriculture.

Besides the lack of a map of degraded lands, uncertainty regarding soil fertility is increased by the limitations of the APSIM simulations themselves. The model estimates the mass of soil eroded over one year, but it does not automatically update the soil conditions for the next. Hence, although the long-term simulations may well represent the inter-annual dynamics of soil nutrient stocks, detrimental soil fertility conditions due to soil removal could only be taken into account if new soil profiles were created manually after every year of simulation. Due to time constraints and data storage capacity, this procedure was not conducted. Future automation of such a process could enhance the long-term predictive capacity of APSIM simulation runs. Moreover, soil depth is one of the most determining factors of biomass productivity, and at the same type, one of the indicators for which spatial estimations is subjected to higher uncertainties. It is also one of the most ignored fertility parameters, and continental yield estimates of Africa have usually assumed higher soil depths than what recent findings suggest (Guilpart et al., 2017). Hence, any land use planning interventions based on information provided by this study must be preceded by field observations and measurements if necessary, in order to ascertain the actual suitability of soils for the intended land use.

In conclusion, the simulated yield levels can indeed be achieved under the explicitly described quantities of macronutrient application, as long as management is complemented by additional operations, which must be informed by locally-specific studies and tailored to the socio-ecological specificities of the farming system.

5.2.2 Challenges to the integration of climate data in spatio-temporally explicit simulations of linked crop growth and LULCC

Regarding climatic factors, the input data was used to simulate both present and future achievable yields, but it only covers the historical period 1997-2013. Annual yields were averaged over the whole simulated period. Hence, they do not change over the run of simulated LULC change time steps, and typical processes of declining productivity in low-input agriculture are not represented. Significant yield reductions occur in low-input savanna agro-ecologies after the second or third year of continuous cultivation (Fugger, 1999; Tian et al., 2005; Adediran, 2014). The effect of this shortcoming on yield estimation inaccuracies is dampened by averaging over thirteen years of continuous cultivation. By doing so, the sensitivity of the pixel values to the distorting effect of the first high-yielding years is lower. Accounting for the effect of land use history on crop yields could be done by creating a dynamic spatial layer containing the value of the years that a cell has been cultivated with the same crop. However, the crop performance simulation run should in this case be as long as the time series of simulated LULC maps. In order to fully include the effects of crop and land use rotations on yield dynamics through this procedure, a huge number of crop rotations shall be simulated in APSIM, raising data storage needs beyond the capacities of any non-clustered computational system.

No climate change scenario data was used as a factor to estimate future yields because of the high amounts and size of the data generated by daily-time step APSIM outputs. The first decade of the 21st century was already 1°C warmer and with higher frequency of extreme temperatures and extreme rainfall events than the historical climate 1961-1990. Simulation models indicate that this implied an average yield reduction in millet and sorghum across West Africa between 5 and 20% (Sultan et al., 2019). Hence, alternative climate change scenarios must be included in the future to improve the informative value of this type of explorative scenario impact assessment.

However, it must be acknowledged that uncertainties associated with the simulation of yields with process-based models rises significantly when climate scenarios are considered. Process-based models are more accurate in simulating crop growth under current climates than under climate scenarios. Despite their name, they do not totally simulate all of the soil-plant-atmosphere interaction processes. They are sub-divided into modules whose algorithms describe empirical observations rather than real mechanistic processes. APSIM, for example, represents the impact of CO_2 fertilization by linearly increasing the transpiration efficiency, rather than by directly simulating the effect of CO_2 on radiation use efficiency (Guan et al., 2017). Therefore, because the experiments conducted to parameterize the model are limited, and replicating the growth conditions of future climate scenarios is costly and difficult, the impact of climate change on simulated yields can widely vary among modeling approaches (Tao et al., 2020). Modeling exercises which do not include the effect of CO_2 fertilization tend to show a more negative impact of future climate scenarios than approaches that include it (Zhao et al., 2017). Such assessments justify their simplified approach to the evidence that CO_2 concentrations explain only a minor component of yield variability (Ostberg et al., 2018) and particularly in regards to C4 plants (such as is the case of the main rainfed cereals of West Africa: millet, sorghum and maize), which are assumed to not significantly benefit from increased CO_2 fertilization (Traore et al., 2017). However, assuming no impacts of CO_2 on crop yields is not a plausible scenario, and therefore there is a need to reduce simulation uncertainties by improving model functions that simulate the responses to temperature and CO_2 concentration (Wang et al., 2017; Amouzou et al., 2019).

Nowadays, the only robust evidence on the impact of future climates on agricultural yields around the globe is that their variability will increase. Africa will be the continent where the yield of global crops (maize, rice wheat and soybean) will be most severely affected (Ostberg et al., 2018). In general, crop yields in East Africa are expected to be less severely, or even positively, affected by climate change due to more favorable temperatures. However, in West Africa the sign of the impact of climate change on crop yields is most likely to be negative for most crops and sub-regions. This impact will be the main cause of above-optimal maximum temperatures, whose impact may not even be offset in scenarios of increased rainfall and atmospheric CO_2 concentrations (Sultan et al., 2013; van Oort and Zwart, 2018). Impacts of climate change on crop yields are likely to be more severe in the South Sudanian belt than in Sahelian and Guinean regions, because in the former above-optimal temperatures are the main yield limiting factor; and more severe in its western section (Senegal, Mali) than in the central (Volta basin), due to more exacerbated warmer and drier trends, including lower frequency of rainfall events (Roudier et al., 2011; Sultan et al., 2013; Sultan et al., 2014; Guan et al., 2015, 2017).

The review of recent simulation studies does not allow one to draw many robust conclusions concerning the trend of future yields in the context of climate change in the Sudanian savanna belt (i.e. the expected yields considering the combined effect of changes in management and climate). The only concluding remark is that the levels of potential (not actual) cereal yields will be reduced (Berg et al., 2013; Sultan et al., 2013; Sultan et al., 2014), and maize yields will be more severely affected than those of millet and sorghum (MacCarthy et al., 2021; Stuch et al., 2021). There are also some studies which go beyond such a conclusion, in that they state that the negative impact of climate change on crop yield can only be offset by increased levels of fertilizer application and improved management, and only in the case of millet and sorghum yields (Guan et al., 2017; Traoré et al., 2017; Akumaga et al., 2018). Other climate change scenario studies estimate that millet yields may increase regardless of the carbon dioxide emission scenario (Traore et al., 2017), and may even be positively affected by a 1.5° climate warming scenario. However, an increase in average annual temperatures above that level will be prejudicial for all crops, and will diminish the yield returns of fertilizer application (Faye et al., 2018b).

Impact of climate change on C3 plants can be positive; such is the case with groundnut, cowpea, soybean, tomato and cotton. For example, groundnut yield in Senegal is expected to be positively affected by climate change (Faye et al., 2018a), probably due to its poorer performance under wetter conditions, as it was also shown by the outputs of the simulations conducted in this research. However, sound management practices have to be put into practice to prevent soil nutrient mining and sustain yields (Amouzou et al., 2018). Moreover, the stimulating effect of increased atmospheric CO_2 on photosynthesis is often lost or decreased in the long-term (AHMED et al., 1993). Not all C3 crops are likely to be positively affected by climate change, such is the case with rice in West Africa, which is expected to be impacted very severely by drier conditions and the concentration of extreme rainfall events (Oteng-Darko et al., 2012; van Oort and Zwart, 2018).

Transfer of climate change impact estimations extracted from simulation studies in agro-climatic regions of West Africa other than the Sudanian savanna should be conducted with caution (Sultan and Gaetani, 2016). For example, simulation studies in Southern Guinean savanna region, where above-optimal temperature stresses are not as common as in the Sudanian savanna region, predict that about +57% maize yield increases can be expected by 2030 under RCP 8.5 (Srivastava et al., 2018). An important remark is that maize is the cereal whose yields are predicted to be most severely affected by climate change in Sudanian savanna regions of the four cereal crops assessed in this study (Ali, 2018), because in most climate change scenarios there is higher weather variability (which millet and sorghum can better withstand) and increased CO_2 (from which rice benefits more).

A recently published crop modeling study suggests that the potential yields simulated in this manuscript are slightly higher than what future climates will impose. Indeed, the impacts of climate change will be negative, and if management does not improve, yield reductions are expected (Raes et al., 2021).

5.2.3 Shortcomings of the model to simulate the cropping systems of the study region, their management and inputs

Regarding the effect of cultivar selection on simulated crop yield, two considerations must be discussed: the availability of cultivar models that simulate well the performance of local cultivars, and the simplification of the cultivar diversity in the modeling platform. Cultivar parameters in APSIM are based on experimental observations. Their value can deviate from the actual behavior of such a cultivar in specific agro-ecologies not tested for model parameterization. Cultivar choice was guided by a tiered-approach. The first priority criterion to choose a cultivar was that its parameterization had been conducted in the study region or elsewhere in the mid-Volta basin; such was the case for maize. The second priority criterion was that the parameterization had been carried out elsewhere in West Africa; such was the case for sorghum and millet. Finally, if none of these two criteria was met, cultivars parameterized elsewhere in the tropics were used; such is the case with groundnut and rice. Therefore, it is possible that the crop growth response of the chosen cultivars does not simulate adequately the growth response to environmental conditions of the main cultivars used in the study region. Such response variability is expected to be large in the study region, as well as in many other small-holder farming systems, because of substantial genetic diversity found both between neighboring regions and within fields. Actually, such cultivar diversity, if it implies functional response diversity, may enhance yield stability and even outperform the average yield of fields sown with one single improved variety (Kahiluoto et al., 2014). There is a general hope that yields may experience an overall increase if improved seeds are more widely adopted, even under harsher climatic conditions (Oteng-Darko et al., 2012; Tachie-Obeng et al., 2013; Singh et al., 2017; Traoré et al., 2017; van Oort and Zwart, 2018). However, in a region where the climate displays high interannual variability, looking for a single optimal cultivar can be a wrong strategy for optimizing agricultural performance, even if its choice targets farm-specific needs. The APSIM platform offers the possibility to simulate the simultaneous sowing of different cultivars within the same field. Hence, it would be interesting to conduct in the future a comparative assessment of the performance of different cultivars and cultivar mixes. In this regard, additional studies are required to parameterize APSIM crop modules with the values that simulate the growth of a wider set of cultivars.

Finally, it has to be taken into account that simulating biomass provision potentials at regional extents with one-dimensional models is a very simplified approach which presents shortcomings in the context of the study region. The practice of process-based crop modeling development has been traditionally oriented to simulate mechanized agricultural systems in Europe and America that are largely insensitive to natural factors because of the high intensification and homogeneity of the landscapes where they grow, dominated by large extensions of monocrops (Luedeling et al., 2016). The model structure of process-based crop-models is still entirely one-dimensional, and hence it can only simulate the performance of low spatial segregation cropping mixtures (i.e. fully mixed, relay and rotations) ignoring the importance of the spatial heterogeneity on landscape scale (parklands, alley-cropping agroforestry, windbreaks, woodlots, etc.) (Malézieux et al., 2009). In this regard, landscape metric assessments have revealed that, when accounting for landscape pattern, the estimated value of ecosystem services may increase (Inkoom et al., 2018a). However, further research is necessary because there are no clear guidelines on how to quantify the impact of land use pattern on land productive capacities (Inkoom et al., 2018b).

5.3 Perennial vegetation

5.3.1 Limitations of growth tables to simulate biomass dynamics in African savannas

In this study, growth tables have been used to estimate the future dynamics of wood resources. Growth tables are a fundamental tool in forestry management. They are used to simulate the growth of forest stands, which can be approximated with a logistic model because it approaches zero once the tree layer canopy closes. Furthermore, if enough information about the impacts of management on a specific stand type has been collected, then a yield table can be elaborated, which serves to plan the amounts of biomass that can be harvested without diminishing the renewability pace of the resource. Growth and yield tables are conceived as representations of a characteristic and exclusive combination of site, stand type and management prescription.

Nevertheless, in savanna ecosystems even the canopy of the densest woody stands is open. Therefore, the dynamics of woody biomass accumulation in savanna stands are very different from those of forest stands. Even the concept of site quality, as it has been traditionally defined in forestry science, has little applicability to savanna ecosystems because most of the trees across savanna landscapes grow far from each other. Moreover, spatially explicit data of variables relevant to define site quality, stand type and management are not available. There is some knowledge regarding the rough spatial distribution of these spatial factors, but not at the level of detail necessary to guide the planning of wood harvesting. For example, although valley bottoms have higher biomass accumulation potential than their surroundings and the spatial distribution of tree density across the landscape typically increases from plateaus towards valley bottoms (explained by the gradient of soil water availability), in African savannas this pattern frequently reverses due to the outcomes of the interaction between livestock/herbivores, fires and grass competition (Assédé. et al., 2015; Colgan et al., 2012; Pellegrini et al., 2017).

Due to the expected wide range of uncertainty, forest stand growth tables have not been used yet, to my knowledge, to estimate future wood availability trends in savanna landscapes. Such an estimation has usually been conducted by calculating its relationship with landscape-scale canopy cover percentage. The problem is that such estimations are also very uncertain, because canopy cover is a poor indicator of aboveground-biomass.

A recent study conducted in a landscape of Southern Burkina Faso established the relationship between canopy cover and biomass. However, despite the proximity to the UER Ghana, the linear relationship of such a study estimated very high AGB values, above 100 t ha^{-1} (Karlson et al., 2015), to areas with high tree cover. It is possible that such an observed maximum AGB level is the result of the high abundance of eucalyptus and mango trees in the landscape where that study was conducted. Those values seem not to be plausible in the study region, where the area covered by those plantation trees is marginal, at least by the time when the baseline LULC data was obtained, and if the maximum values of the baseline AGB data (74 t ha^{-1}) are considered to be close estimations.

To our knowledge, there is only one published estimate of the relationship between tree cover (ranges) and woody biomass accumulation rates in West African savannas, and it was conducted in the humid savannas of Ivory Coast, dominated by palm species (Menaut and Cesar, 1979). It shows that, among open canopy woody formations, normalized differences in woody biomass increment are higher than the normalized differences in canopy cover. Therefore, the relationship between tree cover and AGB biomass growth in a real savanna system is not linear. In any case, this data was because canopy cover is aggregated into categories, and therefore it is not possible to draw a regression. Furthermore, observed values could be very different than in the study region because of the different species composition and average annual rainfall. In the decade of the 1990s, a study edited by the World Bank (Millington et al., 1994) provided estimations on the sustainable wood yields of African landscapes aggregated by large eco-zones (such as Guinean savanna and Sudanian savanna). Such estimations were based on land cover assessments of the standing woody vegetation and some data on site-level woody biomass yields. However, because the data is provided at the eco-zone level it does not capture the effect that tree cover changes may have on sustainable harvesting levels, and therefore cannot be used in district-scale LULCC scenario assessments.

The use of a forest growth table in combination with time-series of LULC maps has been chosen in this study, as a heuristic solution, because it enables simulation of the dynamics of the wood resources in a temporally continuous way. This characteristic of the growth table as a tool for explorative research has been considered to be key in order to better inform land use planning and economic cluster development processes.

In the FLAF and CEXP scenarios, the trend of growing woody biomass that is harvested from the landscape is abruptly modified at later steps of the simulation, and it comes back to the same levels of the previous steps by the end of it. This behavior is unexpected, because the rate at which tree/woodland cells changed into annual vegetation LULC classes did barely vary at each iteration of the LULCC simulation. This is likely the result of the level of the standing biomass of the particular tree/woodland cells that transitioned into another LULC class in those time steps. This should not occur “normally”, because all the cells of the same LULC class have the same probability of changing into another LULC class. Therefore, the distribution of the standing biomass of the different cells changing at each time step should normally be very similar. However, this does not mean that such behavior is the only plausible choice. In West African savannas, a multitude of stakeholders do harvest wood biomass in a wide variety of management forms, and there exists no register of harvesting events. Therefore, it could be possible that harvesting levels in some years are much higher or much lower than other years due to the specificities of the economic and governance context of those specific years. This “unexpected” behavior of the simulations is plausible, as are unexpected events and dynamics which may occur in the real world at any moment. A more linear behavior of the temporal dynamics of this variable could be simulated by adding standing biomass as an environmental layer that is updated at each iteration, and conditioning the transition of perennial vegetation cells of origin only to those within a certain range of standing biomass. The addition of standing biomass as a conditioning LULC transition rule can be useful to represent the biomass provision dynamics of alternative landscape management scenarios. Such a study will require a better understanding and quantification of the ontogenic growth of perennial vegetation in West African savanna regions.

5.3.2 Observed stand and landscape level woody biomass growth in other studies

The validation and uncertainty analysis can be approached by comparing the simulated values of two indicators with those published in literature: on one hand, the values of the modelled stand growth table can be compared with the few published data on woody stand regrowth dynamics in West African savannas; on the other hand, the values of the average regional woody LULC yield of each LULC scenario can be compared with published data on average productivity of West African savanna woodlands.

The average annual yields of the woody LULC class fall within the range of plausible yields of Sudanian savanna woodlands. In forestry, observed yields are commonly measured in units of volume. In order to make the comparison with the simulated biomass yields, a woody density of 0.65 t m^{-3} has been assumed, as averaged from literature and database reviews (Brown, 1997; Zanne et al., 2009; Carsan et al., 2014; Chabi et al., 2016). In the Nazinon forest, close to the study region, average annual allowable cuts are 0.5 t ha^{-1}, ranging 0.36-0.81 t ha^{-1} depending on the forest compartment (Diarra, 1999; Sawadogo, 2007; Sow, 2012). These allowable cuts fall within the lower end of other forests of Southern or Central Burkina Faso, which may range 0.64-0.86 t ha^{-1} (S.E.R.F, 2004; Ouédraogo, 2006). It must be taken into consideration that these management units, despite being formally designated as forests contain, in ecological terms, all the vegetation formations of savanna regions, from open forests to grass savanna. Hence, the allowable cuts are averaged over areas which contain parts without woody cover. On the contrary, in the land-cover based assessment of this, simulated harvest is averaged only over areas occupied by woody cover. If the simulated data is compared with the exploitable volume of dense woody formations, values do agree better. National level assessments in Burkina Faso establish allowable cuts of 0.94 t ha^{-1} in sparse forests, 1.58 t ha^{-1} in gallery forests and 1.85 t ha^{-1} in plantations (PROFOR). These values are similar to the average yield of the woody LULC class in FLAF scenario. This is plausible because this scenario assumes active management of trees and a net increase of tree cover. The average yield in the CEXP scenario also ranges around these values, assuming the collection of the woody vegetation cleared for cropland expansion. However, in some time steps of this scenario, yields are as low as 0.55 and 0.38 t ha^{-1}, suggesting the scarcity of the resource. However, no trend of progressive resource depletion is observed during the simulated timespan. Simulations with a longer time scope would probably show diminishing average yields of this scenario. Finally, in the AFPA scenario, average yields remain very low (between 0.17 and 0.30 t ha^{-1}) during most of the simulation, as was expected from the scenario definition, focused on enforcement of protected forest regulations and management oriented towards developing a high forest structure. In the last two time steps, average yields of the woody LULC class rise above 1 t ha^{-1}, and even up to 1.87 t ha^{-1} in one of them.

At the stand level, biomass accumulation of woody vegetation in West African savannas at the stand level is more variable, and can highly deviate from the growth table values simulated in this study, whose MAI diminished from 1.72 to 1.65, 1.48 and 1.07 t ha^{-1} $year^{-1}$ at the age of 5, 10, 20 and 50 years, respectively. In some stands of Southern Senegal growth during the first twenty years was much faster, with an MAI at the age of 4 years of 6 t ha^{-1} $year^{-1}$, attaining 30 t ha^{-1} as early as 9 years since the start of the stand development. Such differences are likely the result of different site qualities, species composition and management. Southern Senegal, despite sharing major climatic features with northern Ghana, is located thousands of miles away, and hence, specific growing conditions and species composition might be very different. On the other hand, it is also worth noting that these stands were harvested by local communities after the third to eighth year of regrowth, which might explain both the fast early growth, due to its promotion by thinning and stump re-sprouting, as well as its observed maximum attained biomass, which can be limited by the relatively simple functional diversity of the stands, formed mainly by fast-growing pioneer species. On the other hand, the maximum attainable AGB of these stands (43 t ha^{-1}) was much lower than the levels defined in this study (Kairé, 1999; Manlay et al., 2002). Because these stands had been use as firewood resources for a long time, it can be argued that, in the study region, stands with these growth characteristics are also common. Probably a good part of the cells classified as mixed-vegetation in the baseline LULC map are conformed by woody stands subjected to this type of management and never attain AGB levels much higher than 40 t ha^{-1}, whereas those of the class tree/forest are conformed mainly by trees of other species and with other uses, whose biomass is never or rarely harvested, and therefore, their AGB levels rise well above 40 t ha^{-1}, and as high as 74 t ha^{-1}. However, both classes were merged because no information was available to enable the spatially-explicit allocation of these two very different types of woody vegetation use and management.

Studies on biomass accumulation dynamics based on annual observations, such as the one mentioned above in Senegal, are missing in the mid-Volta basin. Results of AGB measurements conducted two years after coppicing in Southern Burkina Faso (18 t ha^{-1}) (Dayamba et al., 2016) might suggest that early-regrowth biomass accumulation rates above 5 t ha^{-1} $year^{-1}$ are also plausible in this region, but this is just my assumption, because the study does not explain whether the measured plot had been completely cleared during the coppicing event, or some stems had been excluded, as it is typically prescribed in managed forests of Burkina Faso.

On the other hand, lower biomass accumulation values have been also commonly observed. A meta-analysis which was used for many years as a blueprint for estimating productivities based on the rainfall belts of West Africa, shows that MAI values under 1 t ha^{-1} year^{-1} are the most common on stands aged between 20 and 60 years, and some may display MAI values as low as 0.5 t ha^{-1} year^{-1}, even on average fertility sites (Clément, 1982). However, because of the lack of continued control against disturbance events of the stands observed in that study, such values cannot be indicative of potential growth rates. In this study, the simulated MAI does not become lower than 1 t ha^{-1} until the 60th year of age.

5.3.3 Considerations regarding the inclusion of additional woody LULC classes, non-woody biomass and climate change in future landscape scale dynamic scenarios

Stand-specific data of local tree species growth is limited to very short timespans that cover only the young stages of stand development. Furthermore, they frequently do not include biomass data (volume instead) or monitoring of species' growth has not yet been conducted in semi-arid West Africa. *Faidherbia albida* alley cropping stands aged 6 years in cultivated agroforestry systems can potentially accumulate 2-4 t ha^{-1} year^{-1} of woody biomass (Okorio and Maghembe, 1994). However, planted in dense windbreak formation in Sahelian Niger growth of stands aged 5 years was much lower, 0.21 t ha^{-1} year^{-1}, and similar to those of *Acacia nilotica,* 0.15 t ha^{-1} year^{-1} (Lamers et al., 1994).

Therefore, given the lack of both stand-specific growth data and spatial data on the location of different types of stands, the values of the growth table used in this study must be understood as indicative outcomes assuming that the development of woody biomass is not severely affected by disturbances such as intense fires, unsustainable fodder supply management (e.g. excessive pollarding) or overharvesting. Additionally, management treatments may be necessary to achieve, or improve, the productivity values simulated in the growth table. Due to widespread impoverishment of soil seed banks, assisted regeneration is necessary by means of active sowing and seedling planting – also by physically protecting each individual stem during its early development stages, when they are highly vulnerable to fire, predation and grass competition. In the case of dense formations, stand-level functional diversity is necessary, with fast-growing pioneer species that drive a quick early biomass accumulation rate and, through the limitation of grass biomass, offer some protection against fire to the slower-growing plants, but often with higher maximum AGB potential, shade-tolerant, species. Regular thinning and non-severe fire impact also promotes growth rates (Soto Flandez, 1995). Specific management recommendations have to be evaluated on-site. For example, native species such as *Combretum nigricans, Lannea microcarpa* and *Detarium microcarpum* can grow well in highly degraded areas, and therefore be used to restore soil structure (Padonou et al., 2013; Padonou et al., 2015) and increase regional-extent biomass production.

Future developments of this approach must consider the inclusion of land uses which are not mapped, either because they could not be identified through the land categorization process, or because they do not exist in the study region, but are expected to provide benefits if adopted. This is one of the main strengths of assessing future land use scenarios in information regional planning processes. The GISCAME platform has a functionality that allows one to define new LULC classes, and due to the possibility of establishing transition rule values manually without relying on model-based simulations of observed past LULCC, these classes can be included in scenario assessments. Plantation LULC classes have not been included in this scenario assessment because of the lack of replicated studies to compare growth rate values, which actually tend to vary even more widely than (semi-)natural regeneration stands. Furthermore, it has been assumed that the contribution of plantation-based wood provision is negligible, at least in the baseline scenario, because they still occupy a very small extension of the study region.

Growth models of neem (*Azadirachta indica*) and teak (*Tectona grandis*) in Northern Ghana were developed during the decade of 1990s, but such studies have not been replicated. Peak MAI of *Azadirachta indica* can be achieved very early in good quality sites, before the age of 10 years, and range 8-15 m^3 ha^{-1} $year^{-1}$, whereas in poor quality sites peak MAI will be reached later and barely surpass 4 m^3 ha^{-1} $year^{-1}$ (Nanang, 1996). Peak MAI of *Tectona grandis* is reached at later stages. In very good quality sites above 14 m^3 ha^{-1} $year^{-1}$ at the age of 30 years, in medium quality sites above 9 m^3 ha^{-1} $year^{-1}$ at the age of 40 years and in poorer quality sites does not reach 4 m^3 ha^{-1} $year^{-1}$ at that same age (Nunifu and Murchison, 1999). Published data on eucalypt growth models based on observation in Northern Nigeria were published by the end of the decade of 1980s, with a peak MAI of 15 m^3 ha^{-1} $year^{-1}$ at the age of 9 years (Adegbehin et al., 1988), which translated into mass is about 10 t ha^{-1} $year^{-1}$. Efforts to reforest with exotic species such as *Eucalyptus* spp., *Tectona grandis* and *Azadirachta indica* at high establishment costs have not brought the desired outcome. Trees planted on inappropriate sites have rarely shown an annual volume increase of more than 2 m³ ha^{-1} compared with the anticipated 10 to 15 m³ ha^{-1} (Nouvellet, 1993; Soto Flandez, 1995). A recent field study estimated the AGB of a 30-year age eucalypt plantation in Southern Burkina Faso in 30 t AGB ha^{-1} (Dayamba et al., 2016). This would mean1 t ha^{-1} $year^{-1}$ MAI, equivalent to that of the simulated (semi-)natural vegetation growth.

In the case of mango, despite its economic importance, studies on the dynamics of woody biomass accumulation are very scant, as most studies conducted worldwide focus on fruit production and management on maximization of fruit yield. So far, the only study that, to my knowledge, could serve as an indicator for woody biomass accumulation in mango plantations has been conducted in India (Ganeshamurthy et al., 2016). Allometric relationships of mango trees of different ages growing in plantations of sub-humid Ghana have been modelled (Oguntunde et al., 2011), but without including a model to estimate AGB. I have used data of such allometric relations as input of pan-African mango allometric equations (Henry et al., 2011), but the modelled tree biomass growth seemed to be excessively fast and maximum AGB implausible.

Integration of plantation LULC types in scenario assessments would be of great value. A plausible future in the study region is one with a rapid increase in forest plantation area, which has been occurring recently in regions such as SW Burkina Faso, where their area has expanded exponentially during the 21st century simultaneous to cropland expansion (Knauer et al., 2017). Furthermore, precisely because the planted area is still small in the study region, it is expected that the eventual widespread adoption of plantations may have significant landscape-scale impacts which would be necessary to be assessed *ex ante*.

Inclusion of non-timber environmental products (NTEP) would also enhance the estimation of the contribution of perennial vegetation LULC classes to the human demands for biomass. Tree leaf production has the highest aggregated value among all the non-wood tree products provided by non-cultivated savannas (Vodouhe et al., 2016). Foraging of tree leaves has become more frequent over the last century due to the expansion of croplands over traditionally pastured grasslands. Estimations of NPP allocated to leaves in savanna woodlands exist (Moore et al., 2018), but not modelled across their ontogenic development. There are also available species-specific allometric models to estimate leaf production of individual trees, but feed value outputs cannot be easily generalized in available LULC maps. Furthermore, not all of the produced leaf biomass can be reached by livestock; Sanou (2014) proposes that around 15% of the total tree foliar biomass is accessible to livestock-, and foraging-behavior as well as the interaction of forage resource management with the health and growth rhythms of trees. Therefore, the interpretation of regional feed provision dynamics must take this gap into consideration.

Finally, the impact that climate change will have on savanna wood resources is difficult to ascertain (Bond and Midgley, 2012; Xu et al., 2018). It does not depend on the response of trees' physiology to climate change, but on the response to the changing competitive advantages between trees and grasses. Over recent decades, increased rainfall and CO_2 have driven an increase in tree cover in semi-arid regions, but this effect has been offset in high population density areas (Brandt et al., 2017), as is the case with the study region. Rainfall frequency is associated with higher tree cover in Sudanian savannas (D'Onofrio et al., 2019). This suggests that if rainfall is distributed more irregularly, as it is expected, tree cover may diminish even under more humid climate scenarios, particularly in regions experiencing land use expansion (Aleman et al., 2016). Moreover, long-term, pan-tropical ring-analysis data, suggests that future increases in CO_2, leading to a warmer climate, might hamper tropical tree growth due to deteriorating environmental conditions (Groenendijk et al., 2015). Increased aridity limits the fertilization effect of atmospheric CO_2, and thus, only trees with access to deep soil water sources would benefit from CO_2 enrichment. Some process-based studies predict an increase in tree biomass in savannas under warmer temperatures and higher concentration of atmospheric CO_2 because juvenile individuals will grow faster, reaching an adult stage quicker, hence allowing them to survive more effectively against periodic fires. Indeed, such an increase in landscape extent tree biomass may even be higher under fire suppression contexts (SCHEITER and Higgins, 2009; Saito et al., 2014). In conclusion, no climate change scenario has been included due to the high uncertainties faced by the state-of-the-art on modeling the impacts of the interactions between changing climate, management and site quality on woody vegetation growth.

5.4 Provision of biomass-based goods and their derived benefits

Ecosystems produce, through their functions, plant material (biomass) in different forms (grains, fruits, wood, leaves, etc.), which can provide a wide range of benefits to human well-being (better health, comfort, etc.) (La Notte et al., 2017). Benefits to human well-being cannot be quantified, but they can be estimated with indicators. The potential contribution of the agro-ecosystem to the availability of goods that enable the consumption of healthy diets was quantitatively estimated in terms of nutrient yields (calories, iron and zinc) of grain production. Fuel and feed provision was also estimated, but an actual quantitative assessment of how the different levels of provision can lead to a change in human well-being was not conducted due to the complexities of estimating the demand. The monetary benefits of biomass production activities are also of foremost importance for the well-being of producing households, but their estimation requires a complete analysis of the cost and benefits in which they (and even other actors across the value chain) occur. Biomass is also used as the material for tools, construction and many industrial products. Finally, the amount of CO_2 that ecosystems subtract from the atmosphere is another good from which important benefits are derived, such as climate change mitigation and healthier air to breath; whereas CO_2 stored in the soil contributes to the ecosystem service of biomass generation and, thereafter, reproduction of goods and human benefits. The following paragraphs discuss the results obtained from the analysis of nutritional yields and the insights that they offer towards an understanding of food and nutrition security problems. Next, a discussion follows on the obstacles faced during this study to estimate the provision of other biomass-based goods and how they can be overcome in the development of future integrated landscape scale/bio-economy assessment tools.

5.4.1 Sources of uncertainty and shortcomings regarding the up-scaled nutrient and fuel yields

Nutrient content values were gathered from a study that averaged values from an extensive survey across West African markets. However, the average nutrient contents of the crops grown in the study region can deviate from those used in this study, because they vary according to the interaction of cultivar characteristics and growing conditions (Shrestha et al., 2020). On the other hand, the development of nutrient rich varieties by the breeding industry is advancing considerably, and their nutritive profile may highly differ from those that are commonly cultivated.

The contribution of grains to dietary caloric requirements is lower than its contribution to iron and zinc requirements. However, the main nutritional problem in northern Ghana is malnutrition, with iron and zinc deficiencies being some of the most prevalent, rather than insufficient caloric intake (Chagomoka et al., 2015; Parish and Gelli, 2015). Hence, other factors related to the entire food system dynamics and their influence on diets may explain this situation. Farmers have low capacity to adequately store their agricultural output throughout the year and their post-harvest losses are usually very high, in the range of 40-80% (Lale and Yusuf, 2000). Most farmers in the region are net buyers of food. To avoid the economic loss incurred by post-harvest grain losses, they frequently sell a large share of their produce soon after harvesting, a period of the year when prices are low. Therefore, they need to buy food later in the year, when prices are high (Millar and Yeboah, 2006; Abdoulaye et al., 2012; Hjelm and Dasori, 2012). The impact that this simple and general mechanism of the food system, which can be applied to any crop, has on the diets of farmers, is accentuated by the fact that the most nutrient-rich products are quite perishable, such as vegetables and fruits. Hence they are mostly sold rather than consumed, and the gains are spent throughout the year in protein-rich but nutritionally poor yam-products and cassava, to ensure the necessary caloric intake (Alderman and Higgins, 1992; Nykänen et al., 2018; Noma, 2020). In this study, besides groundnuts, only cereal grain yields were simulated. Little information was provided on the nutritional diversity that can be derived from alternative LULC strategies because all cereal crops have a similar nutritional profile. Vegetables, fruits, tubers and a wide variety of legumes were not included as LULC classes. Studies assessing the capacity of particular agro-ecosystems to support nutritional diversity have so far been supported by in-field data collection (Remans et al., 2011; Wood, 2018).

The energy input required to produce pellets was assumed to be 36.5% of the NCV output. However, such energy inputs vary widely depending on the machine used, the different vegetation types, species and biomass parts comprising the blend, as well as the size of the particles composing the pellets (Miao et al. 2013; Puig-Arnavat et al. 2016). The energy input to produce pellets made of wheat straw is as low as 5% (Roth, 2014). Additional pre-treatments, such as biomass torrefaction, can also increase the overall energy efficiency of the system (Manouchehrinejad and Mani, 2019; Porsö et al. 2018, Sarker et al. 2021). These factors introduce additional sources of uncertainty into the estimation of the landscape-scale efficiency of converting biomass into useful heat in different scenarios of technology adoption.

5.4.2 Biomass-derived benefits not considered in this study: monetary returns, timber, and carbon sequestration

Regarding the financial benefit derived from agricultural production, the indicator used in this study was the town market value, which is a rather vague indicator. Indeed, market value is a very incomplete estimation of the economic benefits of agricultural LULC choices because it only quantifies the gross revenues of produce sales, without accounting for the monetary costs of inputs or the workload involved in crop production. A thorough assessment of the net benefits of producing each crop under different management operations and levels of inputs applied would be necessary. If, instead of management types being chosen according to the maximization of caloric production, they had been chosen according to net economic returns, the results of this study would have been different. Indeed, the levels of fertilizer application recommended to maximize farm economic returns are in general lower than those formulated to maximize grain yield (Amapu et al., 2018; Dicko et al., 2018).

Case studies show evidence on the comparative economic returns of alternative crop choices. A study shows that in the Vea catchment the net revenues of maize production per unit of cash invested are lower than those of sorghum, and in the cotton-producing areas of Burkina Faso and Benin lower than those of cotton (Danso et al., 2018b). In a study conducted in a region of Northern Nigeria, the net economic returns of maize- and millet-based cropping systems were similar, and whenever the former was slightly superior it involved higher costs, and therefore higher financial risks (Onuk et al., 2015). But a comprehensive assessment of the net economic returns of all the crops cultivated in the region is missing. Furthermore, such results are difficult to generalize due to the interactions between supply, market and policy dynamics which influence net economic return variations in both time and space Hence, the estimation of financial benefits in prospective LULC scenario assessments requires not only more complete datasets, but also the necessity to be informed by sound dynamic economic models able to address these complexities. Such integration of economic models in assessment of LULC scenarios performance would help to quantify the trade-offs between economic returns and impacts in ecosystem services at a certain point in time, but it could also be used to generate assumptions on emerging properties of the LULC system that may drive future LULCC. Finally, whereas this study only used the market value of edible grains, it must be acknowledged that some crop residues and by-products are also sold in markets (Ayantunde et al., 2014; Konlan et al., 2018), especially in the UER and especially groundnut residues and cereal stalks (Karbo and Agyare, 2002), which may help to better understand farmers' choices for crops which provide lower grain but higher stover yields. Availability of such data would be necessary for a complete cost-benefit analysis of the different land uses.

The vast majority of raw material biomass and sequestered carbon can be estimated by assessing only the dynamics of woody LULC classes. However, the provision of none of them was estimated in this study. Carbon sequestered in growing woody biomass under each LULC change scenario was quantified by halving the standing AGB, but this is an incomplete measure of the carbon sequestered on the landscape scale, as well as a poor indicator to inform climate change mitigation strategies. Studies aimed at such purposes must account for the CO_2 sequestered throughout the whole life cycle of wood products. Indeed, the carbon stored in timber and other wood products not destined for combustion can be higher than the CO_2 sequestered in the unharvested landscape (Oliver et al., 2014; Moriarty and Honnery, 2016). On the other hand, it may be argued that quantification of carbon storage at the regional level under alternative scenarios may not be relevant, at least for climate mitigation goals because the potential to reduce global CO_2 levels via afforestation or conversion of African savannas into bioenergy crops in Africa is very small (Searchinger et al., 2015; Grainger et al., 2019).

Concerning the quantification of the proportion of regional wood production that can potentially be destined to construction or industrial uses, it would be of great value to maximize the economic returns of woodland management. Potential uses are determined by the diameter and shape of each wood section. A standard threshold to classify merchantable stems is > 7 cm (Chidumayo, 1990; Bellefontaine, 2000; Pretzsch, 2009; Frank et al., 2015). The size of branches and trunks collected for firewood rarely exceeds 12 cm in diameter, and they are never bigger than 25 cm. Stems up to 40 cm in diameter are allocated to charcoal production. Wood with industrial use usually has a minimum diameter larger than 40 cm and it is usually not exploitable at least until the 40th year of age in (semi-)natural regeneration stands. In areas were the resource is very scarce, fuelwood is exclusively harvested from deadwood or loping of branches (Renes, 1991; Affoue, 1995; Kairé, 1999; S.E.R.F, 2004; SHACKLETON and Clarke, 2007; Sotelo Montes et al., 2012; Tredennick and Hanan, 2015). However, data at the level of detail required to conduct such analysis is very scarce, and size classes established to communicate it vary among studies. Beyond that, there are also conceptual inconsistencies among the literature reviewed: some studies understand trunk as all of the main stem, whereas others use the concept to refer only to that part of the main stem up to the height of the first major branch (Kachamba and Eid, 2016). The proportion of wood usable by the timber industry (i.e. straight wood sections) can be much lower because West African savanna trees are frequently multi-stemmed or develop primarily horizontal growth consisting of several big branches that start to appear at low stem-heights. Moreover, the shape of savanna trees is highly variable and it is difficult to arrive at conclusions regarding average pole/branch volume ratios (Muiambo, 2016). Pole/branch ratios decrease over the ontogenic cycle of the most common trees. In the case of *Vitellaria paradoxa* the proportion of stem biomass over total AGB decreases from 44% on trees of 7 cm DBH to 18% on trees of 32 cm DBH (Dimobe et al., 2019a); and in the case of *Terminalia laxiflora*, from 33% to 18% (Dimobe et al., 2018b). In plantations established with the purpose of commercial timber production, for example, those dominated by *Tectona grandis*, the proportion of the total wood resource that can be used for timber is much higher, ranging about

53-83% (JAFTA, 1999). Because the time scope of the simulations was no longer than 40 years and because data on the actual age of woody cells was not available, the availability of wood with industrial uses was not estimated in this study.

5.5 Integration of models and data in spatial-temporal scenarios of biomass provision

Linkage of plant growth and LULCC simulation models, by using LULC class as an indicator for the type and rate of biomass growth (or any other ecosystem service), is of great value in regional economic planning processes because it allows one to explore the impacts of alternative scenarios through the quantification and visualization of any variable of interest. Shortcomings regarding the field-scale simulation of biomass growth were discussed in the previous chapters. The next paragraphs address the shortcomings of the regional level simulated outputs derived from the upscaling process. These have been sorted into three categories: the method used for the temporal interpolation of each time step output, the diversity of the array of LULC types for which plant growth was simulated, and the simulation of the impact of landscape-scale processes on field-scale productivity.

5.5.1 Temporal interpolation of cropland biomass provision at the regional level

The final outputs of the approach proposed in this research are maps of simulated LULC (and associated biomass-products provision) at specific points in time. In the case of annual crops, field-scale growth under different management intensities was simulated. The output of field-scale simulations with a defined management was supplied to the LULC map of a specific time step of the LULC time-series. It was assumed that all LULC cells of the same map were subjected to the same management. Therefore, the methodology used in this study can serve to estimate regional level temporal dynamics of any ecosystem service of interest, but not to describe expected changes in the spatial variability of ecosystem functions and biomass provision.

Additionally, it was assumed that field-scale intensification and productivity would increase continuously in the future. Therefore, the further into the future that a LULC map represents, the higher is the intensification of the field-scale production simulation that was linked to it. In order to simulate the temporal dynamics of the expected biomass provision benefits in a temporally continuous way, it is necessary to interpolate the regional level biomass provision outputs between contiguous LULC maps representing time steps for which management is defined. Nevertheless, the future pace of intensification is very uncertain because it depends on many decisions operating from large to individual levels. The heuristic solution consisted of defining only the baseline and the end of the simulation management. Then, regional-extent biomass provision trends were drawn by linearly interpolating the biomass levels provided at the initial and final map of the LULCC time-series. Two management intensification scenarios were quantified, associating more productive field-scale outputs to the end of the LULC change simulation LULC map in the scenarios in which intensification occurs higher and faster.

Field-scale yield gaps were assumed to progressively close with the pass of the time. Such a trend is plausible assuming that appropriate local- and farm-specific management improvements are achieved. Yield levels were mainly driven by the quantity of mineral fertilizers applied. The average quantity of fertilizers and their distribution applied in Ghana has varied over time due to changing contexts. A shortcoming of the ability of this approach to simulate regional level ecosystem service provision under different land use change pathways is that, although management changes have relevant impacts on the maintenance of soil fertility (Fujisaki et al., 2018), they cannot be simulated in APSIM in a temporally-explicit way. It can simulate long-term dynamics of changes in soil pools, but each APSIM run simulates one single management treatment, regardless of the length of the simulation. Hence, the outcomes of the simulation must be understood as plausible yields, which can be achieved by the combination of increased fertilizer application (at field-specific rates) and by the general improvement of management including additional inputs and farming operations.

5.5.2 Representation of landscape-scale processes and their impact on pixel-level values

In order to properly simulate long-term trends of biomass provision, water and nutrient flows across the landscape shall also be simulated in a spatially-explicit way, so that the reproductive cycles of biomass are properly represented. However, both data and modeling approaches were insufficient for a long time. Experiments face challenges to set spatio-temporal system boundaries in a way that lateral flows can be properly quantified and the link between soil nutrient stocks and balances is properly established. Furthermore, its spatial modeling also faces the complexity of non-linearity, spatial variability, resolution and extent, which entail challenges for up- and out-scaling of findings. In general, most nutrient balance monitoring studies have been evaluated over short periods and, in Africa, have been mostly conducted in the Eastern part of the continent (Cobo et al., 2010). The transfer of the findings provided by studies conducted in East Africa to analyses focused on West African regions may imply substantial deviations of the actual nutrient cycles in this part of the continent, because the geology and soils of the Rift Valley, rejuvenated by volcanism, may display different functional responses than those of the old and heavily-weathered West African cratons.

The impacts on the water cycle associated with land conversion operate at larger extents than those of the study region (Vrebos et al., 2015; Abungba et al., 2020). Expansion of the area covered by woody vegetation, for example, would imply a widening of the growing period, and the likely increase in ecosystem productivity, but it would be associated to disturbance of the water and energy balance (Workie and Debella, 2018). Hence higher uncertainties would be introduced in the prediction of the spatial-temporal distribution of land productive capacities. It is well known that tree cover increase tends to lead to a reduction in runoff, mean annual stream and peak discharge, while it increases the volume of base flow (minimum annual flow) water, but an estimation of the magnitude of the impacts has not been addressed in this study. Review-based research in East Africa found weak correlations between tree cover change and water flow change (Guzha et al., 2018). Cropping plans, labor force, processing and storage capacities would therefore not be ready to take advantage of highly productive years/decades, whereas the increase stand-level woody growth might be too small to have an actual positive impact on regional economies. Assessing the interactions between the spatial pattern of vegetation distribution, ecosystem functions and plant growth rates is necessary for a better simulation of biomass provision dynamics. Integration of hydrological models should contribute considerably to this purpose. However, the spatial-temporal patterns of water use by perennial vegetation are very complex and research focused on the interactions between water, soil and vegetation (Hasegawa et al., 2006; Ferrio et al., 2020) has still not addressed the quantification of the impacts that trees and woody vegetation stands have on water flows throughout their whole ontogeny cycle.

Additionally, although land use patterns have certain impacts on field-level biomass production, there is a need to better understand such relationships. In this assessment, the two land uses with the higher cropland area (CEXP and AFPA), had significantly higher levels of biomass-based goods than the scenario with a much smaller share of cropland area (FLAF). In this latter scenario, land use pattern was much more heterogeneous, which has a higher potential to reduce the impact of agricultural pests and diseases. Further research on the integration of landscape metrics with ecosystem models is necessary to quantify such effects (Inkoom et al., 2018a; Inkoom et al., 2018b).

5.5.3 Considerations regarding the potential inclusion of irrigated- and pasture-lands in future landscape scale dynamic scenarios

The land use system simulated in this study is a simplification of actual savanna agro-ecologies. Free-ranging livestock plays an important role in vegetation structure and biomass growth in savannas. However, its ranging and foraging patterns are variables very difficult to simulate spatially at the regional scale. Grassland biomass varies widely between years and regions (Fournier, 1991) and cannot be approached only with data derived from remote-sensing products. Reports show that wherever fallow periods are shortened to less than three years, or not even practiced, such as in the study region, grassland biomass production is very low (Devineau and Fournier, 1998; Bliefernicht et al., 2018). Forage provision dynamics are intra-annual and linked to grazing frequency and intensity, as well as to vegetation structure, fires and species composition (Savadogo et al., 2008; Hiernaux et al., 2009a; Guuroh et al., 2018). It was assumed that feed provision was the same in all grasslands, irrespective of their location. This was the most straightforward approach because trade-offs exist between fodder quantity and quality, and median feed yield values have been already calculated based on extensive survey across the broader region in which this case study is located (Ferner et al., 2018). However, increasing grassland biomass production is feasible through active planting and management of herbaceous fallows (Some et al., 2007; Yameogo et al., 2011). Perennial grasses typical of the study region have also great potential as a fuel source (Samson et al., 2005), which can be an alternative on sites where tree plantations are not suitable. Grasslands also play a major role in landscape scale hydrological and nutrient cycles, contributing to the maintenance of the conditions that enable biomass reproduction on the landscape scale (O'Mara, 2012).

Irrigated land use has also been excluded despite the fact that the APSIM platform is able to simulate the performance of irrigated croplands. A tentative approach was conducted by including LULC classes defined by the crops cultivated during the rainy and the dry season. However, it increased significantly the number of LULC classes, and therefore, the computational and data storage needs required to simulate LULC change. Moreover, the main irrigated crop in the study region, besides rice, is tomato, whose national production is situated mostly in the UER, as well as other vegetables. But so far there are no vegetable growth models available in the APSIM platform. Simulation of tomato growth is possible with other process-based modeling platforms, such as DSSAT and AquaCrop, but the use of different modeling platforms to simulate some crops would introduce an additional factor of uncertainty into the comparative LULC performance assessment. Including tomato into the simulated cropland portfolio would ease the analysis of trade-offs related with the provision of vitamins. On the other hand, including irrigated rice production would have increased the total caloric provision of the three scenarios. However, the vast majority of the agricultural production in the region is rainfed. Therefore, the main value of including simulations of irrigated crop production would be, rather than providing more relevant estimations of total biomass provision, to assess the impact of alternative irrigation development scenarios on trade-offs emerging from the reallocation of water resources. In this case, a bigger extent assessment (for example, the Ghanaian part of the White Volta basin) would be more appropriate than the catchment/district extent of this study. Furthermore, although the UER holds about 44% of total national irrigation development potential, this is almost entirely located outside the study districts, and no expansion of irrigation infrastructure is planned within them, nor in Burkina Faso, upstream of the catchments of the studied districts (Choudary et al., 2015; Mul et al., 2015; Abugre, 2016). In any case, current land use plans can be subjected to reappraisal as the scientific evidence-base increases. In this regard, recent studies in the modeling of irrigation systems (Sekyi-Annan, 2019) offer great opportunities for the future improvement of landscape scale biomass provision simulations in the study region.

Finally, it must be remembered that expectations on the levels of production (achievable by adoption of best technologies or most suitable landscapes) alone should not determine land use and food security strategies (Börner, 2022; Ignatova, 2021; Ham, 2020; Stellmacher and Kelboro, 2019). To understand how technical and land use changes have developed and can improve livelihoods in the future, a structural and systemic analysis is necessary (Anderson et al., 2019), focusing on the relationships among the asset base of farmers, existing institutions and the prevailing policy environment of the spatial-temporal context (Hårsmar, 2013; Nyamwena-Mukonza, 2013). In the case of the study region, the studies of Azaare (2017), Kwoyiga and Stefan (2019) and Yomo (2020) can be a good entry point during the conception stages of any integrated landscape approach.

6 SUMMARY AND CONCLUSIONS

Fast and accelerating land use change in many regions of the world, such as West Africa, poses great challenges for the reproduction of ecosystem services and retention of the satisfaction of human needs. Given the ongoing change towards a techno-economic system in which biomass is increasingly replacing fossil materials, it is necessary to better anticipate the impact of land and biomass use in the satisfaction of ongoing human needs, particularly those populations where biomass is produced. This study contributes to the methodological development of regional planning tools aiming to enhance the value accrued by rural economies by estimating in a spatio-temporal explicit way the trends of nutrients, feed and fuel yields under alternative land use and technological change scenarios.

The web-based GISCAME platform was used due to the capacity of its cellular automata to simulate LULCC in the absence of a time-series of past LULC maps. Three LULCC scenarios were spatially- and temporally-explicit simulated: a scenario of uncontrolled cropland expansion (CEXP), a scenario preventing agricultural encroachment into dense savanna woodlands (AFPA) and a scenario of cropland expansion coupled with increasing tree cover within farmed lands (FLAF). The main features of the targeted LULC pattern were successfully simulated in the three scenarios (cropland expansion and landscape fragmentation in the CEXP and FLAF scenarios, combined with an increase in isolated woody vegetation cells in the latter; and the development of dense forest in marginal areas of the region coupled with tree clearance in farmlands in the AFPA scenario). However, the share of the region’s area occupied by each LULC class in each simulation was difficult to control. This is a shortcoming of the current approach, because one of the most valuable features of explorative LULCC scenario approaches in land use planning processes should be their ability to simulate the total area occupied by each LULC class, in order to better represent and quantify specific narratives and therefore be used as input of *ex ante* impact assessments.

Finding a good balance between the simulation of total LULC change and the locations where particular LULC transitions occur is one of the main struggles of LULCC science, and in the data-scarce context of the study region it has been particularly challenging. For example, the difference in total area occupied by croplands between the FLAF and the AFPA scenario was higher than the differences between the AFPA and the CEXP scenario. This means that the comparison between the LULC spatial patterns of the FLAF and the AFPA scenario cannot serve as a base to explore the impacts of different vegetation spatial patterns on regional-extent biomass provision. More and better data on proxies of LULCC drivers in the study region is necessary in order to define LULC transition rules and estimate their probability values. Economic land use change models are useful tools to explore alternative hypotheses. However, in the context of northern Ghana, the variability of the value of a piece of land is difficult to capture because typical economic LULCC models are based on land price data, whereas the marketization of land as a commodity is a relatively recent phenomenon. Moreover, the country does not have a land cadaster that could help to integrate farm- into landscape-scale models.

The spatially-explicit simulation of potential biomass provision was done through a land cover-based approach. This consisted of simulating the field-scale biomass production rates of a variety of LULC classes, and assigning the output value to their corresponding cells in the LULC maps. Therefore, scenario outputs (regional ecosystem services provision) are determined by one-dimensional field-scale data and the proportion of regional area covered by each LULC class. The quantification of the biomass provided by uncultivated savannas was subjected to numerous uncertainties and limited to woody biomass and grazed grasses because the few available input data on land management operations and their impact on biomass growth is limited to annual crop species. As a result, the uncontrolled cropland expansion scenario (CEXP) yielded the best and the parkland agroforestry scenario the worst (FLAF) outputs in all the assessed regional yield indicators.

The simulation of biomass supply dynamics at temporal scales relevant to development planning is dependent on the interaction between ecosystem functioning and land management. In this study, such interactions were simulated in cropland LULC classes with the one dimensional, process-based, APSIM crop modeling platform. The explicit description of management operations contributes to an increase in the transparency of scenario outcomes, as it provides a common understanding of the underlying land management assumptions. The management of four annual crop land use classes (groundnut-, millet-/sorghum-, maize-and rice-based cropping fields) was quantitatively defined in terms of sowing density, cultivar, rate of manure and mineral fertilizer application, and share of non-harvested biomass. Mineral fertilizer was assumed to be the most yield-determining factor and it was the only factor for which different levels were simulated and their outputs included in the study. Simulated agricultural yields showed good agreement with reported field-level observations across the Sudanian savanna belt and the official agricultural production statistics of the study districts. Additionally, the explicit description of management allows a comparison of the performance of different LULC classes at equal production costs. This is key for informing participatory landscape approaches because the chances of adoption of land use types that might be beneficial for long-term regional biomass provision potentials are very low if barriers for adoption are ignored. In any case, it is important to take in account that the estimated achievable yields should be understood as an indicator, but they may vary widely among years and specific locations due to landscape-scale processes and climate change. Appropriate management of each LULC class has been explicitly but loosely defined in this study. Therefore, it must not be taken as a prescription. One of the main hypotheses driving this research (i.e. the maintenance of the diversity of grain crop species enhances the sustainability of biomass consumption derived-benefits) could not properly be tested because the share of each crop species over total cropland area was not the same under each scenario. However, the results suggest that the hypothesis can be accepted because low grain-yielding crops provide higher yields of other biomass products essential for the rural economy, diminishing the need to source fuel and feed from uncultivated lands.

Available data and models to simulate the growth of woody vegetation are much scarcer. Therefore, the management of woody vegetation was described more roughly and only qualitatively. In the study region there is a lack of resource inventories and tree plantations are very scant. The simulation of woody vegetation growth was simplified by assuming that all woody cells were naturally re-growing vegetation assisted with human management by seed sowing and protection of growing stands from severe disturbances. One innovation introduced by this approach consists of the linkage of the temporally explicit simulation woody vegetation stand growth and land cover changes, and has been of higher relevance to regional policy-making than non-temporally dynamic scenarios. Woody biomass growth simulation was based on feeding an empirical logistic model with the few native species stand regrowth values reported in literature and observed in neighboring regions. The output growth curve must be understood as indicative of a medium level potential growth pace. Deviations from this curve can be expected due to particular stand level species composition, abiotic factors of the site, fire frequency and intensity, livestock, harvesting and other management factors. Finally, due to the lack of data and models, tree leaves and fruit production levels were not simulated.

Grassland productivity was assumed to be the same for all the grassland LULC cells of the region due to similar constraints compared to those that would have been faced to simulate perennial vegetation leaves and fruit production. The impacts of inter-annual weather variability, fire, livestock and management introduce the highest degrees of uncertainty on the spatial allocation of grassland biomass provision. As a result, the assessment of fuel, feed and food nutritional provision potential of the regional landscape has only been assessed through all the biomass components of annual crop LULC classes and the woody AGB biomass of perennial vegetation. The addition of models of grassland and perennial vegetation leaf production would increase the simulated regional feed provision levels, and the inclusion of fruit production models would increase the provision of nutritional yields, particularly a wide variety of micronutrient yields. The inclusion of these components of the landscape biomass production would better quantification of the trade-offs of cropland expansion. Additionally, because the production of grass, tree leaf and fruit biomass is more distributed throughout the year than that of rainfed cropland, it would be possible to better assess the differences between rainy and dry season regional biomass goods' availability levels, particularly if the simulation of irrigated agriculture production were also included. The simulation of this data would be of great value for the assessment of the impact of alternative LULC scenarios on food security, particularly in contexts such as the one of the study region, in which the biomass produced in the landscape at a certain point in time highly determines the biomass available to the population, due to the scarcity of storage and processing facilities, as well as its relative marginal location with respect to national and global markets.

Beyond the one-dimensional, pixel-based, biomass provision simulation, a spatially-explicit effect was introduced in the model to simulate the impact of woody vegetation pattern on field-scale herbaceous biomass production. Woody cells were assumed to also produce herbaceous vegetation in quantities equal to the average of the cells surrounding them and reduced proportionally to the amount of woody biomass contained in the cell (used as a proxy for the effect that shading has on limiting the photosynthetic activity under tree canopies). This feature of the model aims to better represent the distribution of biomass growth in savanna landscapes, where grasses and annual crops can grow vigorously next to and even under tree crowns due to the widely open canopy of the tree layer. The magnitude of this effect on total provision of regional biomass goods was considerably lower than the share of the total regions' area occupied by each LULC class and the field-scale management. However, it must be taken into account that this approach of including the impact of trees on herbaceous vegetation growth is very simplistic: its magnitude was roughly estimated based on median, field-scale, values found in literature rather than on the simulation of mechanistic processes and it did not differentiate among different species. Therefore, the model developed in this study might underestimate the effect of tree cover pattern on herbaceous vegetation biomass. Shortcomings in the spatio-temporal explicit simulation of ecosystem functions impeded to evaluate the impact of landscape patterns on biomass growth and its renewability rates. In conclusion, the other main hypothesis motivating this research (i.e. the maintenance of tree cover and its spatial pattern in parkland savanna landscapes enhances the sustainability of biomass consumption derived-benefits) could not be tested at all with the methodology explored in this study.

In summary, due to shortcomings related to the simulation of landscape-scale processes and their influence on the provision of different biomass goods, the outputs of this research should not be used to estimate renewability rates, but rather to estimate achievable yields under appropriate field-scale management. A more accurate description and simulation of specific LULC patterns is a requisite for exploration of the interactions between field-scale management and ecosystem functions operating on landscape or larger scales, such as the spatial-temporal patterns of water and nutrient flows that allow for the renewability of biomass supply rates. Water and nutrient cycles can be simulated at the field scale in the APSIM platform. However, simulating the impacts of landscape scale processes on field productivity in APSIM would require the coupling of APSIM to a dynamic spatially-explicit model, so that the outputs of the latter can be used to update the variable values of the APSIM soil water and nutrient modules. This would require an increase in the computational capacity to conduct the simulation that lies beyond the capacities of this research. An alternative can be to substitute the one-dimensional crop model by a landscape-scale production model. This would serve to better represent the impact LULC pattern on biomass production, but it would provide less accurate information on the levels of the different biomass compartments and potential derived benefits because, so far, landscape production models do not simulate different crop species as well as one-dimensional models do.

Baseline information on land management must also be increased. Hence, continuous monitoring through agricultural and forestry statistical services must be undertaken, and provide betters descriptions and mapping of observed land uses, including crop mixtures, rotations and tree plantations. The scientific community shall also address the development of production models of a wider range of annual (vegetables and tubers) and woody species able to simulate the growth conditions in West African savannas, so that a more comprehensive assessment, meaningful for regional (bio-)economic plans, can be conducted.

One of the main findings of this research is that the land of the study region has a very limited capacity to provide the amounts of agricultural crops necessary to fulfil the caloric needs of the population leaving within its boundaries. This is surprising because northern Ghana has historically been considered the “bread basket” of the country and nowadays it is widely acknowledged that micronutrient insufficiencies are the most widespread food security problem within the region. Current provision of calories might be, indeed, inferior to the aggregated requirements of the current population, and the gap may increase in the future without cropland expansion and steady yield increase. Furthermore, it must be considered that the simulated outputs did not even account for the reduced amounts of available food caused by pests and diseases that affect both farm yields and post-harvest losses.

The findings of this study are a clear example of how food security cannot be addressed through land production assessments alone. Yam and cassava products are one of the main sources of calories in the diets of peoples all across Ghana, including the study region, where they are imported from other parts of the country. The study region is specialized in the production of some high value products, such as tomato, onion, meat and shea butter whose revenues help to buy the cheap protein sources mentioned above. Additionally, although cereals have a more complete nutritional profile than yam and cassava tubers, the storage capacity of many farmers is low, and therefore they also sell their cereal production at low prices soon after harvest. This may have an effect on their diets, diminishing the share of cereals and increasing the share of low-nutritional quality tubers. Yam and cassava must be cultivated in rich soils of forested landscapes, ideally in fallow systems whose cycles are being shortened. Therefore, their increased production would be an important driver for the unprecedented tree cover loss experienced over recent decades at the national level, and as a result, be detrimental for the renewability rates of biomass production across the country.

Therefore, the debate on the sustainability of African agro-ecosystem must go beyond land-based solutions. A major part of the revenues on which African economies rely consists of the export of raw biomass products with low added value. Such exports consist of non-essential products such as cocoa and coffee and products used in the food or other industries outside Africa such as palm oil and cotton. Additionally, precious timbers have also been traditionally exported out of Africa, and during some periods of history, they have even been the main suppliers for some Western countries. Over recent decades, their importance in the exporting portfolio is not as prominent as it used to be, but mainly because the resource has become very scarce and exploitation unsustainable, and indeed illegal logging of precious timbers for export is still not uncommon. While large sections of the most economically valuable lands of Africa are used for the satisfaction of non-essential global demand, food imports rise because agricultural production is not enough to satisfy internal demand. Therefore, food and energy scarcity in African societies is not caused only by internal population growth, but by the global displacement of land use as well, enabled by the structure of global trade.

A radical transformation of African productive systems is a pre-requisite for optimizing their sustainability (including that of the land systems). The reliance of African revenues on the export of raw biomass-based products must diminish, which implies increasing the share of added value generated by industrial and tertiary sectors. Land use and technological development are intertwined. Therefore, the development of landscapes that sustainably optimize the satisfaction of internal demands can only be realized if they are accompanied by technologies and policies that increase the efficiency by which the produced biomass satisfies social demand.

7 REFERENCES

Abaidoo, R.C., Okogun, J.A., Kolawole, G.O., Diels, J., Randall, P., Sanginga, N., 2007. Evaluation of cowpea genotypes for variations in their contribution of N and P to subsequent maize crop in three agro-ecological zones of West Africa. In: Bationo, A., Waswa, B., Kihara, J., Kimetu, J. (Eds.), Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities. Springer Netherlands, Dordrecht, pp. 401–412.

Abane, J.A., 2015. The challenges of Millennium Development Goal 1 in Bongo District of the Upper East Region of Ghana. Glob Soc Welf 2 (3), 139–146.

Abass, A., 2014. Is Africa "ready" for an integrated bio-economy approach? Rural 21 - Bio-economy 48 (3), 32–33.

Abdi, A.M., Seaquist, J., Tenenbaum, D.E., Eklundh, L., Ardö, J., 2014. The supply and demand of net primary production in the Sahel. Environ. Res. Lett. 9 (9), 94003.

Abdoulaye, T., Bamire, A.S., Wiredu, A.N., Baco, M.N., Fofana, M., 2012. Characterization of maize-producing communities in Bénin, Ghana, Mali, and Nigeria. International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.

Abdul-Rahaman, I., Owusu-Sekyere, E., 2017. Climate variability and sustainable food production: Insights from north-eastern Ghana. Ghana Journal of Geography (9), 67–89.

Abdul-Razak, M., Kruse, S., 2017. The adaptive capacity of smallholder farmers to climate change in the Northern Region of Ghana. Climate Risk Management 17, 104–122.

Abelson, P.H., 1980. Energy from biomass (eng). Science 208 (4450), 1325.

Aboyeji, C., Dunsin, O., Adekiya, A.O., Chinedum, C., Suleiman, K.O., Okunlola, F.O., Aremu, C.O., Owolabi, I.O., Olofintoye, T.A.J., 2019. Zinc Sulphate and Boron-Based Foliar Fertilizer Effect on Growth, Yield, Minerals, and Heavy Metal Composition of Groundnut (Arachis hypogaea L) Grown on an Alfisol. International Journal of Agronomy 2019, 1–7.

Abugre, A.A., 2016. Resources and Masterplan for the Transformation of Agriculture in the SADA Zone: Volume V. Proposed value chains and technology portfolio. SADA, Tamale, Ghana.

Abungba, J.A., Khare, D., Pingale, S.M., Adjei, K.A., Gyamfi, C., Odai, S.N., 2020. Assessment of Hydro-climatic Trends and Variability over the Black Volta Basin in Ghana. Earth Syst Environ.

Adam, M., MacCarthy, D.S., Traoré, P.C.S., Nenkam, A., Freduah, B.S., Ly, M., Adiku, S.G.K., 2020. Which is more important to sorghum production systems in the Sudano-Sahelian zone of West Africa: Climate change or improved management practices? Agricultural Systems 185, 102920.

Adediran, J.A., 2014. Role of land clearing and tillage in improving soil fertility and yield of food crops. Proceedings of the International Soil Tillage Research Organisation (ISTRO) Nigerian Symposium, Akure 2014 November 3-6, Akure, Nigeria.

Adegbehin, J.O., Okojie, J.A., Nokoe, S., 1988. Growth of Eucalyptus tereticornis and Pinus caribaea at different sites in Northern Nigeria. Forest Ecology and Management 23 (4), 261–272.

Adeyemi, A.A., Ibrahim, T.M., 2020. Spatiotemporal analysis of land-use and land-cover changes in Kainji Lake National Park, Nigeria. Forestist 70 (2), 105–115.

Adole, T., Dash, J., Atkinson, P.M., 2018. Characterising the land surface phenology of Africa using 500 m MODIS EVI. Applied Geography 90, 187–199.

Adongo, T.A., Abagale, F.K., Kranjac-Berisavljevic, G., 2015. Performance of irrigation water delivery structures in six schemes of Northern Ghana. IJSTER 4 (9), 3170–3179.

Adu, S.V., 1972. Eroded savanna soils of the Navrongo-Bawku area, northern Ghana. Ghana Journal of Agricultural Sciences 5, 3–12.

Aduah, M.S., Toucher, M.L., Jewitt, G.P.W., 2019. Estimating potential future (2030 and 2040) land use in the Bonsa catchment, Ghana, West Africa. SA J of Geomatics 7 (3), 279.

Affoue, Y., 1995. La foret classe de Badenou.: Etat - accroisements de quelques espèces. Grandes décisions de l'aménagement. Association des paysans à sa gestión. In: Ouattara, N., Louppe, D. (Eds.), Cinquième reunion tripartite: Burkina Faso, Cote d'Ivoire, Mali. Republique de Cote d'Ivoire - Instute des Fôrets.

Agyei, K., Agyeman, V.K., Asare, R.A., Asante, W.A., Benefoh, D.T., Blaser, J.e.a., 2014. REDD+ in agricultural landscapes: evidence from Ghana's REDD+ process, Bern, Switzerland.

Ahmed, K.F., Wang, G., You, L., Yu, M., 2016. Potential impact of climate and socioeconomic changes on future agricultural land use in West Africa. Earth Syst. Dynam. 7 (1), 151–165.

AHMED, F.E., HALL, A.E., MADORE, M.A., 1993. Interactive effects of high temperature and elevated carbon dioxide concentration on cowpea [Vigna unguiculata (L.) Walp.]. Plant Cell Environ 16 (7), 835–842.

Akinseye, F.M., Adam, M., Agele, S.O., Hoffmann, M.P., Traore, P.C.S., Whitbread, A.M., 2017. Assessing crop model improvements through comparison of sorghum (sorghum bicolor L. moench) simulation models: A case study of West African varieties. Field Crops Research 201, 19–31.

Akinseye, F.M., Ajegbe, H.A., Kamara, A.Y., Adefisan, E.A., Whitbread, A.M., 2020. Understanding the response of sorghum cultivars to nitrogen applications in the semi-arid Nigeria using the agricultural production systems simulator. Journal of Plant Nutrition 43 (6), 834–850.

Akinyemi, F.O., Pontius, R.G., Braimoh, A.K., 2016. Land change dynamics: insights from Intensity Analysis applied to an African emerging city. Journal of Spatial Science 27 (9), 1–15.

Akolgo, I.A., 2018. Afro-euphoria: is Ghana's economy an exception to the growth paradox? Review of African Political Economy 45 (155), 146–157.

Akponikpé, P.B.I., 2008. Millet response to water and soil fertility management in the Sahelian Niger: experiments and modeling. Ph.D. Thesis, Louvain-la-Neuve, Belgium.

Akumaga, U., Tarhule, A., Piani, C., Traore, B., Yusuf, A., 2018. Utilizing Process-Based Modeling to Assess the Impact of Climate Change on Crop Yields and Adaptation Options in the Niger River Basin, West Africa. Agronomy 8 (2), 11.

Akumaga, U., Tarhule, A., Yusuf, A.A., 2017. Validation and testing of the FAO AquaCrop model under different levels of nitrogen fertilizer on rainfed maize in Nigeria, West Africa. Agricultural and Forest Meteorology 232, 225–234.

Alderman, H., Higgins, P., 1992. Food and nutritional adequacy in Ghana. Cornell Food and Nutrition Policy Program, Ithaca New York, vii, 61 ;

Aleman, J.C., Blarquez, O., Staver, C.A., 2016. Land-use change outweighs projected effects of changing rainfall on tree cover in sub-Saharan Africa (eng). Glob Change Biol 22 (9), 3013–3025.

Ali, E., 2018. Impact of climate variability on staple food crops production in Northern Togo. JAEID 112 (2), 321–341.

Alkhalil, A., Kadaoure, I., Kouadio, M., 2020. An Evaluation of 20-m ESA-CCI S2 Prototype LC Product. Front. Sustain. Food Syst. 4.

Amadou, M.L., Villamor, G.B., Kyei-Baffour, N., 2018. Simulating agricultural land-use adaptation decisions to climate change: An empirical agent-based modeling in northern Ghana. Agricultural Systems 166, 196–209.

Amapu, I.Y., Chude, V.O., Tarfa, B.D., 2018. Fertilizer Recommendation for Maize, Sorghum, Millet, Cowpea, Soybean and Cotton in Nigeria. In: Bationo, A., Ngaradoum, D., Youl, S., Lompo, F., Fening, J.O. (Eds.), Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems. Springer International Publishing, Cham, pp. 221–240.

Amoah, M., Cremer, T., 2017. Net calorific values and mineral concentration of thirteen tree and shrub species in Ghana. Journal of Sustainable Forestry 36 (7), 703–716.

Amole, T.A., Ayantunde, A.A., 2016a. Assessment of Existing and Potential Feed Resources for Improving Livestock Productivity in Niger. International J. of Agricultural Research 11 (2), 40–55.

Amole, T.A., Ayantunde, A.A., 2016b. Improving livestock productivity: Assessment of feed resources and livestock management practices in Sudan-Savanna zones of West Africa. Afr. J. Agric. Res. 11 (5), 422–440.

Amouzou, K.A., Lamers, J.P.A., Naab, J.B., Borgemeister, C., Vlek, P.L.G., Becker, M., 2019. Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa. Field Crops Research 235, 104–117.

Amouzou, K.A., Naab, J.B., Lamers, J.P.A., Borgemeister, C., Becker, M., Vlek, P.L.G., 2018. CROPGRO-Cotton model for determining climate change impacts on yield, water- and N-use efficiencies of cotton in the Dry Savanna of West Africa. Agricultural Systems 165, 85–96.

Ampim, P.A.Y., Ogbe, M., Obeng, E., Akley, E.K., MacCarthy, D.S., 2021. Land Cover Changes in Ghana over the Past 24 Years. Sustainability 13 (9), 4951.

Andam, K.S., Johnson, M.E., Ragasa, C., Kufoalor, D.S., Gupta, S.D., 2017. A chicken and maize situation. The poultry feed sector in Ghana. IFPRI Discussion Paper 01601. International Food Policy Research Institute.

Anderson, C.C., Denich, M., Neumann, K., Amankwah, K., Tortoe, C., 2019. Identifying Biomass-Based Value Webs for Food Security in Sub-Saharan Africa: A Systems Modeling Approach. Sustainability 11 (10), 2885.

Aniah, P., Kaunza-Nu-Dem, M.K., Ayembilla, J.A., 2019. Smallholder farmers' livelihood adaptation to climate variability and ecological changes in the savanna agro ecological zone of Ghana. Heliyon 5 (4), e01492.

Aniah, P., Wedam, E., Pukunyiem, M., Yinimi, G., 2013. Erosion and livelihood change in north east Ghana: A look into the bowl. IJSBAR 7 (1), 28–35.

Asante, M., Ahiabor, B.D.K., Atakora, W.K., 2020. Growth, Nodulation, and Yield Responses of Groundnut (Arachis hypogaea L.) as Influenced by Combined Application of Rhizobium Inoculant and Phosphorus in the Guinea Savanna Zone of Ghana. International Journal of Agronomy 2020, 1–7.

Asare, R., Akuffobea, M., Quaye, W., Atta-Antwi, K., 2015. Characteristics of micro, small and medium enterprises in Ghana: gender and implications for economic growth. African Journal of Science, Technology, Innovation and Development 7 (1), 26–35.

Asenso Barnieh, B., Jia, L., Menenti, M., Zhou, J., Zeng, Y., 2020. Mapping Land Use Land Cover Transitions at Different Spatiotemporal Scales in West Africa. Sustainability 12 (20), 8565.

Asibuo, J.Y., Akromah, R., Safo-Kantanka, O., Adu-Dapaah, H.K., Ohemeng-Dapaah, S., Agyeman, A., 2008. Chemical composition of groundnut Arachis hypogaea (L) landraces. African Journal of Biotechnology 7 (13), 2203–2208.

Assan, J.K., Caminade, C., Obeng, F., 2009. Environmental variability and vulnerable livelihoods: Minimising risks and optimising opportunities for poverty alleviation. J. Int. Dev. 21 (3), 403–418.

Assan, J.K., Kharisma, D.D., Adaboh, A.A., 2018. Demographic characteristics, migration and employment-seeking behaviour: a case study of Ghana. In: Binns, T., Lynch, K., Nel, E.L. (Eds.), The handbook of African development. Routledge, Taylor & Francis Group, London, pp. 71–91.

Assédé., E.S.P., Azihou, F.A., Adomou, A.C., Oumorou, M., Sinsin, B., 2015. Effet du relief sur la régéneration des espèces ligneuses en zone soudanienne du Bénin. Bois et Forêts des Tropiques 326 (4), 15–24.

Awedoba, A.K., 2010. An ethnographic study of Northern Ghanaian conflicts: Towards a sustainable peace. Sub-Saharan Publishers, Legon, Accra, Ghana.

Awo, M.A., 2012. Marketing and market queens: A study of tomato farmers in the Upper East region of Ghana. LIT, Zürich, Berlin, vii, 175 pages.

Ayamga, E.A., Kemausuor, F., Addo, A., 2015. Technical analysis of crop residue biomass energy in an agricultural region of Ghana. Resources, Conservation and Recycling 96, 51–60.

Ayantunde, A.A., Blummel, M., Grings, E., Duncan, A.J., 2014. Price and quality of livestock feeds in suburban markets of West Africa’s Sahel: Case study from Bamako, Mali. Revue d’élevage et de médecine vétérinaire des pays tropicaux 67 (1), 13–21.

Ayantunde, A.A., Fernández-Rivera, S., Hiernaux, P.H.Y., van Keulen, H., Udo, H.M.J., Chanono, M., 2001. Effect of timing and duration of grazing of growing cattle in the West African Sahel on diet selection, faecal output, eating time, forage intake and live-weight changes. Anim. Sci. 72 (1), 117–128.

Ayelazuno, J.A., 2019. Water and land investment in the “overseas” of Northern Ghana: The land question, agrarian change, and development implications. Land Use Policy 81, 915–928.

Ba, T., Yamoah, C.F., Diangar, S., 2000. An appraisal of irrigated temperate and tropical millet varieties in the semiarid region of Senegal. Afr. Crop Sci. J. 8 (3).

Bachmann, T., 2000. Restoration of soil fertility and improvement of cropping systems for sustainable development in the humid savannas of the Ivory Coast. In: FAO, IAEA (Eds.), Management and conservation of tropical acid soils for sustainable crop production.

Bacho, F.Z.L., 2005. An exploratory survey of small-scale off-farm economic activities and sustainable household livelihoods in the Bongo District of Ghana. Ghana J. Dev. Stud. 1 (2).

Badmos, O., Rienow, A., Callo-Concha, D., Greve, K., Jürgens, C., 2018. Urban Development in West Africa—Monitoring and Intensity Analysis of Slum Growth in Lagos: Linking Pattern and Process. Remote Sensing 10 (7), 1044.

Baker, T.R., Swaine, M.D., Burslem, D.F.R.P., 2003. Variation in tropical forest growth rates: combined effects of functional group composition and resource availability. Perspectives in Plant Ecology, Evolution and Systematics 6 (1-2), 21–36.

Bakhiet, A.G., 2008. Investigation of agricultural residues gasification for electricity production in Sudan as an example for biomass energy utilization under arid climate conditions in developing countries. Ph.D. Thesis, Germany.

Balima, L.H., Nacoulma, B.M.I., Bayen, P., Kouamé, F.N.'G., Thiombiano, A., 2020. Agricultural land use reduces plant biodiversity and carbon storage in tropical West African savanna ecosystems: Implications for sustainability. Global Ecology and Conservation 21, e00875.

Bamler, J.-N., 2015. Value for the vulnerable? Sustainable smallholder development in Northern Ghana and the value chains of tomato, chili and rice. Ph.D. Thesis, Cologne, Germany.

Barthès, B.G., Penche, A., Hien, E., Deleporte, P., Clermont-Dauphin, C., Cournac, L., Manlay, R.J., 2015. Effect of ramial wood amendment on sorghum production and topsoil quality in a Sudano-Sahelian ecosystem (central Burkina Faso). Agroforest Syst 89 (1), 81–93.

Bationo, A., Fening, J.O., Kwaw, A., 2018. Assessment of Soil Fertility Status and Integrated Soil Fertility Management in Ghana. In: Bationo, A., Ngaradoum, D., Youl, S., Lompo, F., Fening, J.O. (Eds.), Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems. Springer International Publishing, Cham, pp. 93–138.

Bayala, J., Balesdent, J., Marol, C., Zapata, F., Teklehaimanot, Z., Ouedraogo, S.J., 2007. Relative contribution of trees and crops to soil carbon content in a parkland system in Burkina Faso using variations in natural 13C abundance. Nutr Cycl Agroecosyst 76 (2-3), 193–201.

Bayala, J., Sanou, J., Teklehaimanot, Z., Ouedraogo, S.J., Kalinganire, A., Coe, R., Noordwijk, M.v., 2015. Advances in knowledge of processes in soil–tree–crop interactions in parkland systems in the West African Sahel: A review. Agriculture, Ecosystems & Environment 205, 25–35.

Bayala, J., Teklehaimanot, Z., Ouedraogo, S.J., 2002. Millet production under pruned tree crowns in a parkland system in Burkina Faso. Agroforest Syst 54 (3), 203–214.

Bazié, H.R., Bayala, J., Zombré, G., Sanou, J., Ilstedt, U., 2012. Separating competition-related factors limiting crop performance in an agroforestry parkland system in Burkina Faso. Agroforest Syst 84 (3), 377–388.

Beah, A., Kamara, A.Y., Jibrin, J.M., Akinseye, F.M., Tofa, A.I., Adam, A.M., 2021. Simulating the Response of Drought–Tolerant Maize Varieties to Nitrogen Application in Contrasting Environments in the Nigeria Savannas Using the APSIM Model. Agronomy 11 (1), 76.

Bellefontaine, R., 2000. Management of natural forests of dry tropical zones. FAO, Rome, X, 318 str.

Berg, A., Noblet-Ducoudré, N. de, Sultan, B., Lengaigne, M., Guimberteau, M., 2013. Projections of climate change impacts on potential C4 crop productivity over tropical regions. Agricultural and Forest Meteorology 170, 89–102.

Beuchelt, T.D., Nassl, M., 2019. Applying a Sustainable Development Lens to Global Biomass Potentials. Sustainability 11 (18), 5078.

Biyogue, D.N., Dioggban, J., 2015. Forest composition and productivity changes as affected by human activities in the natural forest- savanna zone in Northern Ghana. J. Ecol. Nat. Environ. 7 (4), 94–105.

Blench, R. (Ed.), 1999. Natural resource management in Ghana and its socio-economic context, London, 211 pp.

Bliefernicht, J., Berger, S., Salack, S., Guug, S., Hingerl, L., Heinzeller, D., Mauder, M., Steinbrecher, R., Steup, G., Bossa, A.Y., Waongo, M., Quansah, E., Balogun, A.A., Yira, Y., Arnault, J., Wagner, S., Klein, C., Gessner, U., Knauer, K., Straub, A., Schönrock, R., Kunkel, R., Okogbue, E.C., Rogmann, A., Neidl, F., Jahn, C., Diekkrüger, B., Aduna, A., Barry, B., Kunstmann, H., 2018. The WASCAL Hydrometeorological Observatory in the Sudan Savanna of Burkina Faso and Ghana. Vadose Zone Journal 17 (1), 180065.

Boateng, P., 2017. Land Access, Agricultural Land Use Changes and Narratives about Land Degradation in the Savannas of Northeast Ghana during the Pre-Colonial and Colonial Periods. Social Sciences 6 (1), 35.

Boateng, P., Appiah, D., Adjei, P., Mensah, H., 2016. Perceptions of Socio-Ecological Changes and Their Implications on Changes in Farming Practises and Agricultural Land Uses in the Savannas of Northeast Ghana. Environments 3 (4), 33.

Bodirsky, B.L., Rolinski, S., Biewald, A., Weindl, I., Popp, A., Lotze-Campen, H., 2015. Global Food Demand Scenarios for the 21st Century (eng). PLoS ONE 10 (11), e0139201.

Bond, W.J., Midgley, G.F., 2012. Carbon dioxide and the uneasy interactions of trees and savanna grasses (eng). Phil. Trans. R. Soc. B 367 (1588), 601–612.

Bonjour, S., Adair-Rohani, H., Wolf, J., Bruce, N.G., Mehta, S., Prüss-Ustün, A., Lahiff, M., Rehfuess, E.A., Mishra, V., Smith, K.R., 2013. Solid fuel use for household cooking: country and regional estimates for 1980-2010 (eng). Environmental health perspectives 121 (7), 784–790.

Bonkoungou, E.G., Framond, H. de, 1988. Dynamique du peuplement et évolution de la productivité d'une parcelle de formation naturelle en foret classée de Gonse, Burkina Faso. Bois et Forêts des Tropiques 218, 63–70.

Börner, J., 2022. "Global shifting agriculture" and bioeconomy: Challenges for the sustainable use of global land resources. In: Lanzerath, D., Schurr, U., Pinsdorf, C., Stake, M. (Eds.), Bioeconomy and Sustainability, 13-22. Springer.

Bouvet, A., Mermoz, S., Le Toan, T., Villard, L., Mathieu, R., Naidoo, L., Asner, G.P., 2018. An above-ground biomass map of African savannas and woodlands at 25 m resolution derived from ALOS PALSAR. Remote Sensing of Environment 206, 156–173.

Braimoh, A., 2004. Modeling of land use change in the Volta basin of Ghana. Ph.D. Thesis, Germany.

Brandt, M., Rasmussen, K., Hiernaux, P., Herrmann, S., Tucker, C.J., Tong, X., Tian, F., Mertz, O., Kergoat, L., Mbow, C., David, J.L., Melocik, K.A., Dendoncker, M., Vincke, C., Fensholt, R., 2018a. Reduction of tree cover in West African woodlands and promotion in semi-arid farmlands. Nature Geosci 11 (5), 328–333.

Brandt, M., Rasmussen, K., Peñuelas, J., Tian, F., Schurgers, G., Verger, A., Mertz, O., Palmer, J.R.B., Fensholt, R., 2017. Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa (eng). Nat Ecol Evol 1 (4), 81.

Brandt, M., Wigneron, J.-P., Chave, J., Tagesson, T., Penuelas, J., Ciais, P., Rasmussen, K., Tian, F., Mbow, C., Al-Yaari, A., Rodriguez-Fernandez, N., Schurgers, G., Zhang, W., Chang, J., Kerr, Y., Verger, A., Tucker, C., Mialon, A., Rasmussen, L.V., Fan, L., Fensholt, R., 2018b. Satellite passive microwaves reveal recent climate-induced carbon losses in African drylands. Nat Ecol Evol 2 (5), 827–835.

Breman, H., 2012. Woody plants in agro-ecosystems of semi-arid regions: With an emphasis on the sahelian. Springer, [Place of publication not identified], 1 online resource.

Brown, S., 1997. Estimating biomass and biomass change of tropical forests: A primer.

Brüll, A., 2015. Biomass - a renewable energy source?: Sustainable complementary biomass (re)production through Landscape Quality Management, Universität Lüneburg ed. Shaker Verlag GmbH, Aachen, Germany.

Buah, S.S.J., Abatania, L.N., Aflakpui, G.K.S., 2010. Quality Protein Maize Response to Nitrogen Rate and Plant Density in the Guinea Savanna Zone of Ghana. West African Journal of Applied Ecology 16 (1).

Bullock, J.M., Dhanjal-Adams, K.L., Milne, A., Oliver, T.H., Todman, L.C., Whitmore, A.P., Pywell, R.F., 2017. Resilience and food security: rethinking an ecological concept. J Ecol 105 (4), 880–884.

Buri, M.M., Ishida, F., Kubota, D., Masunaga, T., Wakatsuki, T., 1999. Soils of flood plains of west Africa: General fertility status. Soil Science and Plant Nutrition 45 (1), 37–50.

Burke, W.J., Frossard, E., Kabwe, S., Jayne, T.S., 2019. Understanding fertilizer adoption and effectiveness on maize in Zambia (eng). Food Policy 86, 101721.

Cabral, A.I.R., Costa, F.L., 2017. Land cover changes and landscape pattern dynamics in Senegal and Guinea Bissau borderland. Applied Geography 82, 115–128.

Caillault, S., Ballouche, A., Delahaye, D., 2012. Vers la disparition des brousses ? Analyse multi-scalaire de la dynamique des paysages à l’ouest du Burkina Faso depuis 1952. cybergeo.

Callo-Concha, D., Gaiser, T., Webber, H., Tischbein, B., Müller, M., Ewert, F., 2013. Farming in the West African Sudan Savanna: Insights in the context of climate change. Afr. J. Agric. Res. 8 (38), 4693–4705.

Camacho Olmedo, M.T., Pontius, R.G., Paegelow, M., Mas, J.-F., 2015. Comparison of simulation models in terms of quantity and allocation of land change. Environmental Modeling & Software 69, 214–221.

Carpenter, D.L., Bain, R.L., Davis, R.E., Dutta, A., Feik, C.J., Gaston, K.R., Jablonski, W., Phillips, S.D., Nimlos, M.R., 2010. Pilot-Scale Gasification of Corn Stover, Switchgrass, Wheat Straw, and Wood: 1. Parametric Study and Comparison with Literature. Ind. Eng. Chem. Res. 49 (4), 1859–1871.

Carsan, S., Orwa, C., Harwood, C., Kindt, R., Stroebel, A., Neufeldt, H., Jamnadass, R., 2014. Replication data for: African Wood Density Database. World Agroforestry Centre, Nairobi. https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/25337 (accessed 20 July 2020).

Ceperley, N.C., Mande, T., van de Giesen, N., Tyler, S., Yacouba, H., Parlange, M.B., 2017. Evaporation from cultivated and semi-wild Sudanian Savanna in west Africa. Hydrol. Earth Syst. Sci. 21 (8), 4149–4167.

Chabi, A., Lautenbach, S., Orekan, V.O.A., Kyei-Baffour, N., 2016. Allometric models and aboveground biomass stocks of a West African Sudan Savanna watershed in Benin. Carbon Balance Manage 11 (1).

Chagomoka, T., Drescher, A., Glaser, R., Marschner, B., Schlesinger, J., Nyandoro, G., 2015. Vegetable production, consumption and its contribution to diets along the urban-rural continuum in Northern Ghana. AFJAND 15 (4), 10352–10367.

Chen, C., Lawes, R., Fletcher, A., Oliver, Y., Robertson, M., Bell, M., Wang, E., 2016. How well can APSIM simulate nitrogen uptake and nitrogen fixation of legume crops? Field Crops Research 187, 35–48.

Chidumayo, E., 2015. Dry season watering alters the significance of climate factors influencing phenology and growth of saplings of savanna woody species in central Zambia, southern Africa. Austral Ecology 40 (7), 794–805.

Chidumayo, E.N., 1990. Above-ground woody biomass structure and productivity in a Zambezian woodland. Forest Ecology and Management 36 (1), 33–46.

Choudary, V., Christienson, G., Josserand, H., D'Alessandro, S., 2015. Ghana: Agricultural sector risk assessment: Risk prioritization. World Bank Group Report 94228-GH, Washington, USA.

CIRAD-FORET - FRA, 1993. Renforcement des activités de recherches menées dans les pays africains dans le domaine de la connaissance de la productivité et de la croissance des formations naturelles mixtes, forestières et graminéennes, dans le but de leur aménagement au Sénégal: Rapport final, Nogent-sur-Marne, France.

Cirera, X., Masset, E., 2010. Income distribution trends and future food demand (eng). Phil. Trans. R. Soc. B 365 (1554), 2821–2834.

Clément, J., 1982. Estimation des volumes et de la productivité des formations mixtes forestières et graminéennes tropicales. Bois et Forêts des Tropiques (198), 35–58.

Cline-Cole, R.A., Main, H.A.C., Nichol, J.E., 1990. On fuelwood consumption, population dynamics and deforestation in Africa. World Development 18 (4), 513–527.

Cobo, J.G., Dercon, G., Cadisch, G., 2010. Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. Agriculture, Ecosystems & Environment 136 (1-2), 1–15.

Codjoe, S.N.A., 2004. Population and land use/cover dynamics in the Volta River Basin of Ghana, 1960-2010. Ecology and Development 15. University of Bonn (ZEF), Gottingen, Germany.

Colgan, M.S., Asner, G.P., Levick, S.R., Martin, R.E., Chadwick, O.A., 2012. Topo-edaphic controls over woody plant biomass in South African savannas. Biogeosciences 9 (5), 1809–1821.

Cour, J.-M., Snrech, J.M., 1994. Pour préparer l'avenir de l'Afrique de l'Ouest. Une vision à l'horizon 2020: Étude des perspectives à long terme en Afrique de l'Ouest, Paris, France.

Cramer, M.D., an van Cauter, Bond, W.J., 2010. Growth of N2-fixing African savanna Acacia species is constrained by below-ground competition with grass. Journal of Ecology 98 (1), 156–167.

Cristofaro, D., 2020. The birth of a town. Indigenous planning and colonial intervention in Bolgatanga, Northern Territories of the Gold Coast. In: Nunes Silva, C. (Ed.), Routledge Handbook of Urban Planning in Africa. Routledge, pp. 15–29.

Cudjoe, G., Breisinger, C., Diao, X., 2010. Local impacts of a global crisis: Food price transmission, consumer welfare and poverty in Ghana. Food Policy 35 (4), 294–302.

Da Costa, P.Y.D., Nguetnkam, J.-P., Mvoubou, C.M., Togbé, K.A., Ettien, J.-B., Yao-Kouame, A., 2015. Old landscapes, pre-weathered materials, and pedogenesis in tropical Africa: How can the time factor of soil formation be assessed in these regions? Quaternary International 376, 47–74.

Danso, I., Gaiser, T., Webber, H., Naab, J., Ewert, F., 2018a. Response of Maize to Different Nitrogen Application Rates and Tillage Practices Under Two Slope Positions in the Face of Current Climate Variability in the Sudan Savanna of West Africa. In: Saito, O., Kranjac-Berisavljevic, G., Takeuchi, K., A. Gyasi, E. (Eds.), Strategies for building resilience against climate and ecosystem changes in Sub-Saharan Africa. Springer, Singapore, pp. 41–58.

Danso, I., Webber, H., Bourgault, M., Ewert, F., Naab, J.B., Gaiser, T., 2018b. Crop management adaptations to improve and stabilize crop yields under low-yielding conditions in the Sudan Savanna of West Africa. European Journal of Agronomy 101, 1–9.

Danso-Abbeam, G., Dagunga, G., Ehiakpor, D.S., 2019. Adoption of Zai technology for soil fertility management: evidence from Upper East region, Ghana. Economic Structures 8 (1).

Danuor, S.K., 2012. Vulnerability assessment maps for communities in Northern Ghana: Phase I - Final Reports. GreenWaterHut.

Danvi, A., Giertz, S., Zwart, S.J., Diekkrüger, B., 2017. Comparing water quantity and quality in three inland valley watersheds with different levels of agricultural development in central Benin. Agricultural Water Management 192, 257–270.

Dao, B.P., Abotsi, K.E., Kargbo, A., Kokou, K., Kone, D., 2021. Diversity of agroecosystems and ecosystem services gain for agrobiodiversity conservation in agricultural landscape in Northern Togo. Agronomie Africaine 33 (1), 21–32.

Darfour, B., Rosentrater, K.A., 2016. Agriculture and food security in Ghana. In: , Agricultural and Biosystems Engineering Conference Proceedings and Presentations, Paper No. 162460507. American Society of Agricultural and Biological Engineers, pp. 1–11.

Dayamba, S.D., Djoudi, H., Zida, M., Sawadogo, L., Verchot, L., 2016. Biodiversity and carbon stocks in different land use types in the Sudanian Zone of Burkina Faso, West Africa. Agriculture, Ecosystems & Environment 216, 61–72.

Deans, H., Ros-Tonen, M.A.F., Derkyi, M., 2018. Advanced value chain collaboration in Ghana's cocoa sector: an entry point for integrated landscape approaches? Environmental Management 62(1), 143-156.

DeFries, R., Mondal, P., Singh, D., Agrawal, I., Fanzo, J., Remans, R., Wood, S., 2016. Synergies and trade-offs for sustainable agriculture: Nutritional yields and climate-resilience for cereal crops in Central India. Global Food Security 11, 44–53.

Deklerck, V., Mil, T. de, Ilondea, B.A., Nsenga, L., Caluwé, C. de, van den Bulcke, J., van Acker, J., Beeckman, H., Hubau, W., 2019. Rate of forest recovery after fire exclusion on anthropogenic savannas in the Democratic Republic of Congo. Biological Conservation 233, 118–130.

Demeke, M., Di Marcantonio, F., Morales-Opazo, C., 2013. Understanding the performance of food production in sub-Saharan Africa and its implications for food security. J. Dev. Agric. Econ. 5 (11), 425–443.

Descheemaeker, K., Oosting, S.J., Homann-Kee Tui, S., Masikati, P., Falconnier, G.N., Giller, K.E., 2016. Climate change adaptation and mitigation in smallholder crop–livestock systems in sub-Saharan Africa: a call for integrated impact assessments. Reg Environ Change 16 (8), 2331–2343.

Dessalegn, T.Y., 2005. Modeling farm irrigation decisions under rainfall risk in the White-Volta basin of Ghana. Ph.D. Thesis, Bonn, Germany.

Devineau, J.-L., 1999. Seasonal rhythms and phenological plasticity of savanna woody species in a fallow farming system (south-west Burkina Faso). J. Trop. Ecol. 15 (4), 497–513.

Devineau, J.-L., Fournier, A., 1998. Écologie d'une savane africaine: Synthèse provisoire des résultats acquis (avril 1998). Rapport de recherche. http://www.documentation.ird.fr/hor/fdi:010049003 (accessed 15 July 2020).

Diallo, M.D., Wood, S.A., Diallo, A., Mahatma-Saleh, M., Ndiaye, O., Tine, A.K., Ngamb, T., Guisse, M., Seck, S., Diop, A., Guisse, A., 2016. Soil suitability for the production of rice, groundnut, and cassava in the peri-urban Niayes zone, Senegal. Soil and Tillage Research 155, 412–420.

Diangar, S., Fofana, A., Diagne, M., Yamoah, C.F., Dick, R.P., 2004. Pearl millet-based intercropping systems in the semiarid areas of Senegal. African Crop Science Journal 12 (2).

Diao, O., 1995. Comportement des systèmes racinaires des ligneux durant le cycle culture-jachère en Afrique soudanienne: Etude sur un terroir de la région de Kolda, Haute-Casamance, Sénégal. Master Thesis, Bambey, Senegal.

Diao, X., Hazell, P.B.R., Kolavalli, S., Resnick, D., 2019a. Ghana’s economic and agricultural transformation: Past performance and future prospects, Washington, DC.

Diao, X., Magalhaes, E., Silver, J., 2019b. Urbanization and its Impact on Ghana’s Rural Transformation. In: Diao, X., Hazell, P., Kolavalli, S., Resnick, D. (Eds.), Ghana's Economic and Agricultural Transformation. Oxford University Press, pp. 121–141.

Diarra, A., 1999. Étude d'un modèle d'aménagement des forêts naturelles en zone soudano-sahélienne au Burkina Faso. Master Thesis, Canada.

Dicko, M.K., Traoré, L., Kouyaté, Z., Koné, M., Sidibé, B., Kamissoko, N., Wortmann, S.C., Dioni, L., Diakité, C.H., 2018. Response of Rice, Maize and Millet to Fertilizers in Mali. In: Bationo, A., Ngaradoum, D., Youl, S., Lompo, F., Fening, J.O. (Eds.), Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems. Springer International Publishing, Cham, pp. 139–155.

Dietz, T., Millar, D., Dittoh, S., Obeng, F., Ofori-Sarpong, E., 2004. Climate and livelihood change in North East Ghana. In: Dietz, T., Ruben, R., Verhagen, A. (Eds.), The impact of climate change on drylands: With a focus on West Africa. Kluwer Academic, Dordrecht, London, pp. 149–172.

Dimobe, K., Goetze, D., Ouédraogo, A., Mensah, S., Akpagana, K., Porembski, S., Thiombiano, A., 2019a. Aboveground biomass allometric equations and carbon content of the shea butter tree (Vitellaria paradoxa C.F. Gaertn., Sapotaceae) components in Sudanian savannas (West Africa). Agroforest Syst 93 (3), 1119–1132.

Dimobe, K., Kouakou, J., Tondoh, J., Zoungrana, B., Forkuor, G., Ouédraogo, K., 2018a. Predicting the Potential Impact of Climate Change on Carbon Stock in Semi-Arid West African Savannas. Land 7 (4), 124.

Dimobe, K., Kuyah, S., Dabré, Z., Ouédraogo, A., Thiombiano, A., 2019b. Diversity-carbon stock relationship across vegetation types in W National park in Burkina Faso. Forest Ecology and Management 438, 243–254.

Dimobe, K., Mensah, S., Goetze, D., Ouédraogo, A., Kuyah, S., Porembski, S., Thiombiano, A., 2018b. Aboveground biomass partitioning and additive models for Combretum glutinosum and Terminalia laxiflora in West Africa. Biomass and Bioenergy 115, 151–159.

Dimobe, K., Tondoh, J.E., Weber, J.C., Bayala, J., Ouédraogo, K., Greenough, K., 2018c. Farmers’ preferred tree species and their potential carbon stocks in southern Burkina Faso: Implications for biocarbon initiatives. PLoS ONE 13 (12), e0199488.

Djagbletey, E.D., Logah, V., Ewusi-Mensah, N., Tuffour, H.O., 2018. Carbon stocks in the Guinea savanna of Ghana: estimates from three protected areas. Biotropica 50 (2), 225–233.

Donkoh, S.A., Ayambila, S., Abdulai, S., 2013. Technical efficiency of rice production at the Tono Irrigation Scheme in Northern Ghana. American Journal of Experimental Agriculture 3 (1), 25–42.

Donkoh, W.J., 2017. A comparative analysis of incidence of poverty in three urban centers in Ghana from 1945 to 1990. In: Falola, T., Odey, M.O. (Eds.), Poverty reduction strategies in Africa, 1st ed. Routledge, London, pp. 215–242.

D'Onofrio, D., Sweeney, L., Hardenberg, J. von, Baudena, M., 2019. Grass and tree cover responses to intra-seasonal rainfall variability vary along a rainfall gradient in African tropical grassy biomes (eng). Sci Rep 9 (1), 2334.

Dooley, K., Kartha, S., 2018. Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. Int Environ Agreements 18 (1), 79–98.

Douxchamps, S., Ayantunde, A., Barron, J., 2012. Evolution of agricultural water management in rainfed crop-livestock systems of the Volta Basin. CPWF R4D Working Paper 04. CGIAR, Colombo, Srik Lanka, 74 pp.

Doyi, I., Oppon, O.C., Glover, E.T., Gbeddy, G., Kokroko, W., 2013. Assessment of occupational radiation exposure in underground artisanal gold mines in Tongo, Upper East Region of Ghana (eng). Journal of environmental radioactivity 126, 77–82.

DPCU Bongo, 2010. Strategic Environmental Assessment of Bongo District: Medium Term Development Plan from 2010-2013. District Planning and Coordination Unit of Bongo, Bongo, Ghana.

Duadze, S.E.K., 2004. Land use and land cover study on the savanna ecosystem in the Upper West Region (Ghana) using remote sensing. Ph.D. Thesis, Bonn, Germany.

Duah-Gyamfi, A., Swaine, E.K., Adam, K.A., Pinard, M.A., Swaine, M.D., 2014. Can harvesting for timber in tropical forest enhance timber tree regeneration? Forest Ecology and Management 314, 26–37.

Duku, C., Zwart, S.J., van Bussel, L.G.J., Hein, L., 2018. Quantifying trade-offs between future yield levels, food availability and forest and woodland conservation in Benin (eng). The Science of the total environment 610-611, 1581–1589.

Duku, M.H., Gu, S., Hagan, E.B., 2011. A comprehensive review of biomass resources and biofuels potential in Ghana. Renewable and Sustainable Energy Reviews 15 (1), 404–415.

Dumenu, W.K., Obeng, E.A., 2016. Climate change and rural communities in Ghana: Social vulnerability, impacts, adaptations and policy implications. Environmental Science & Policy 55, 208–217.

Ekpe, E.K., Hinkle, C.R., Quigley, M.F., Owusu, E.H., 2014. Natural resource and biodiversity conservation in Ghana: the use of livelihoods support activities to achieve conservation objectives. International Journal of Biodiversity Science, Ecosystem Services & Management 10 (4), 253–261.

Elbehri, A. (Ed.), 2013. Rebuilding West Africa's food potential: Policies and market incentives for smallholder-inclusive food value chains (eng). The Food and Agriculture Organization of the United Nations, Rome, 535 pp.

Elias, M., Arora-Jonsson, S., 2017. Negotiating across difference: Gendered exclusions and cooperation in the shea value chain. Environ Plan D 35 (1), 107–125.

Emmanuel, A.B., Dibi, N.d.H., Victor, R.B., Stefan, P., Michael, T., Francois, N.K., Daouda, K., 2015. Threat of agricultural production on woody plant diversity in Tankwidi riparian buffer in the Sudanian Savanna of Ghana. Int. J. Biodivers. Conserv. 7 (7), 354–363.

Energy Commission, 2006. Strategic National Energy Plan—2006-2020 (SNEP). Energy Commision of Ghana, Accra, Ghana (accessed http://energycom.gov.gh/files/snep/MAIN%20REPORT%20final%20PD.pdf).

Energy Commission, 2015. National Energy Statistics 2005-2014. Energy Commision of Ghana, Accra, Ghana.

Erakhrumen, A.A., 2009. Energy value as a factor of agroforestry wood species selectivity in Akinyele and Ido local government areas of Oyo State, Nigeria. Biomass and Bioenergy 33 (10), 1428–1434.

Erb, K.-H., Krausmann, F., Lucht, W., Haberl, H., 2009. Embodied HANPP: Mapping the spatial disconnect between global biomass production and consumption. Ecological Economics 69 (2), 328–334.

Eriksson, D., Akoroda, M., Azmach, G., Labuschagne, M., Mahungu, N., Ortiz, R., 2018. Measuring the impact of plant breeding on sub-Saharan African staple crops. Outlook Agric 47 (3), 163–180.

Esteban, L.S., Ciria, P., Carrasco, J.E., 2008. An assessment of relevant methodological elements and criteria for surveying sustainable agricultural and forestry biomass by products for energy purposes. BioResources 3 (3), 910–928.

Fagerholm, N., Käyhkö, N., Ndumbaro, F., Khamis, M., 2012. Community stakeholders' knowledge in landscape assessments – Mapping indicators for landscape services. Ecological Indicators 18, 421–433.

Falconnier, G.N., Corbeels, M., Boote, K.J., Affholder, F., Adam, M., MacCarthy, D.S., Ruane, A.C., Nendel, C., Whitbread, A.M., Justes, É., Ahuja, L.R., Akinseye, F.M., Alou, I.N., Amouzou, K.A., Anapalli, S.S., Baron, C., Basso, B., Baudron, F., Bertuzzi, P., Challinor, A.J., Chen, Y., Deryng, D., Elsayed, M.L., Faye, B., Gaiser, T., Galdos, M., Gayler, S., Gerardeaux, E., Giner, M., Grant, B., Hoogenboom, G., Ibrahim, E.S., Kamali, B., Kersebaum, K.C., Kim, S.-H., van der Laan, M., Leroux, L., Lizaso, J.I., Maestrini, B., Meier, E.A., Mequanint, F., Ndoli, A., Porter, C.H., Priesack, E., Ripoche, D., Sida, T.S., Singh, U., Smith, W.N., Srivastava, A., Sinha, S., Tao, F., Thorburn, P.J., Timlin, D., Traore, B., Twine, T., Webber, H., 2020. Modeling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa (eng). Glob Change Biol.

Falconnier, G.N., Descheemaeker, K., Mourik, T.A.V., Giller, K.E., 2016. Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali. Field Crops Research 187, 113–126.

FAO, 2009. The state of food insecurity in the world: Economic crises - impacts and lessons learned. Food and Agriculture Organization of the United Nations, Rome, Italy.

Faye, B., Webber, H., Diop, M., Mbaye, M.L., Owusu-Sekyere, J.D., Naab, J.B., Gaiser, T., 2018a. Potential impact of climate change on peanut yield in Senegal, West Africa. Field Crops Research 219, 148–159.

Faye, B., Webber, H., Naab, J.B., MacCarthy, D.S., Adam, M., Ewert, F., Lamers, J.P.A., Schleussner, C.-F., Ruane, A., Gessner, U., Hoogenboom, G., Boote, K., Shelia, V., Saeed, F., Wisser, D., Hadir, S., Laux, P., Gaiser, T., 2018b. Impacts of 1.5 versus 2.0 °C on cereal yields in the West African Sudan Savanna. Environ. Res. Lett. 13 (3), 34014.

February, E.C., Higgins, S.I., Bond, W.J., Swemmer, L., 2013. Influence of competition and rainfall manipulation on the growth responses of savanna trees and grasses. Ecology 94 (5), 1155–1164.

Fekedulegn, D., Mac Siurtain, M., Colbert, J., 1999. Parameter estimation of nonlinear growth models in forestry. Silva Fenn. 33 (4).

Ferner, J., Schmidtlein, S., Guuroh, R.T., Lopatin, J., Linstädter, A., 2018. Disentangling effects of climate and land-use change on West African drylands' forage supply. Global Environmental Change 53, 24–38.

Ferrio, J.P., Dubbert, M., Máguas, C., 2020. Editorial: The Green Side of the Water Cycle: New Advances in the Study of Plant Water Dynamics (eng). Frontiers in plant science 11, 582846.

Fetzel, T., Niedertscheider, M., Erb, K.-H., Gaube, V., Gingrich, S., Haberl, H., Krausmann, F.e.a., 2012. Human appropriation of net primary production in Africa: Patterns, trajectories, processes and policy implications. Social Ecology Working Paper 137. Alpen-Adria Universität, Vienna, Austria. https://boku.ac.at/fileadmin/data/H03000/H73000/H73700/Publikationen/Working_Papers/working-paper-137-web.pdf (accessed 6 July 2020).

Field, J.L., Tanger, P., Shackley, S.J., Haefele, S.M., 2016. Agricultural residue gasification for low-cost, low-carbon decentralized power: An empirical case study in Cambodia. Applied Energy 177, 612–624.

Findlay, J.B.R., 2001. Maize no-tillage systems for reduced labour requirements, improved soil conditions and productivity. In: Miko, S., Valencia, J.A., Falaki, A.M. (Eds.), Maize for better nutrition.

Fischer, C., Kleinn, C., Fehrmann, L., Fuchs, H., Panferov, O., 2011. A national level forest resource assessment for Burkina Faso – A field based forest inventory in a semiarid environment combining small sample size with large observation plots. Forest Ecology and Management 262 (8), 1532–1540.

Foli, S., Ros-Tonen, M.A.F., Reed, J., Sunderland, T., 2018. Natural resource management schemes as entry points for integrated landscape approaches: evidence from Ghana and Burkina Faso. Environmental Management 62, 82-97.

Forestry Commission, 2016. Ghana REDD+ Strategy 2016-2035, 102 pp.

Forkuor, G., 2014. Agricultural land use mapping in West Africa using multi-sensor satellite imagery. Ph.D. Thesis, Germany.

Forkuor, G., Conrad, C., Thiel, M., Landmann, T., Barry, B., 2015. Evaluating the sequential masking classification approach for improving crop discrimination in the Sudanian Savanna of West Africa. Computers and Electronics in Agriculture 118, 380–389.

Fournier, A., 1991. Phénologie, croissance et production végétales dans quelques savanes d'Afrique de l'Ouest, variations selon un gradient de sécheresse. Thèse d'Etat, Paris, France.

Frank, S., Fürst, C., Pietzsch, F., 2015. Cross-Sectoral Resource Management: How Forest Management Alternatives Affect the Provision of Biomass and Other Ecosystem Services. Forests 6 (12), 533–560.

Freeman, O.E., Duguma, L.A., Minang, P.A., 2015. Operationalizing the integrated landscape approach in practice. Ecology and Society 20(1), 24.

Frey, G., West, T., Hickler, T., Rausch, L., Gibbs, H., Börner, J., 2018. Simulated Impacts of Soy and Infrastructure Expansion in the Brazilian Amazon: A Maximum Entropy Approach. Forests 9 (10), 600.

Fritsche, U.R., Berndes, G., Cowie, A.L., Dale, V.H., Kline, K.L., Johnson, F.e.a., 2017. Energy and land use. Global Land Outlook Working Paper 2.

Frost, P., Campbell, B., Medina, G., Usongo, L., 2006. Landscape-scale approaches for integrated natural resource management in tropical forest landscapes. Ecology and Society 11(2), 30.

Fugger, W.-D., 1999. Evaluation of potential indicators for soil quality in savanna soils in Northern Ghana (West Africa). University of Göttingen, Germany, 185 pp.

Fujisaki, K., Chevallier, T., Chapuis-Lardy, L., Albrecht, A., Razafimbelo, T., Masse, D., Ndour, Y.B., Chotte, J.-L., 2018. Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: A synthesis. Agriculture, Ecosystems & Environment 259, 147–158.

Fürst, C., Frank, S., Jiménez, M., Rozas Vásquez, D.A., Pietzsch, K., Pietzsch, F., 2016. Impacts of agricultural and forest management on biodiversity and ecosystem services. In: Geneletti, D. (Ed.), Handbook on Biodiversity and Ecosystem Services in Impact Assessment. Edward Elgar Publishing, pp. 195–221.

Fürst, C., Frank, S., Pietzsch, K., Pietzsch, F., 2015. GISCAME: Handbook V2.4. PiSolution GmbH. https://www.biomassnet.org/downloads/giscame-2-0-manual-v2-4/ (accessed 10 June 2020).

Fuwape, J.A., 2011. Secondary forests and fuel wood utilization in Africa. In: Günter, S., Weber, M., Stimm, B., Mosandl, R. (Eds.), Silviculture in the Tropics. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 369–376.

Gaikpa, D.S., Akromah, R., Asibuo, J.Y., Nyadanu, D., 2017. Molecular and phenotypic resistance of groundnut varieties to leaf spots disease in Ghana. JMBFS 6(4), 1043-1048.

Ganeshamurthy, A.N., Ravindra, V., Venugopalan, R., Mathiazhagan, M., Bhat, R.M., 2016. Biomass Distribution and Development of Allometric Equations for Non-Destructive Estimation of Carbon Sequestration in Grafted Mango Trees. JAS 8 (8), 201.

Gautier, D., Bazile, D., Picard, N., 2006. Interactions between sudano-sahelian savannas and parklands in space and time: the effect on biomass and biodiverty with regards to stakeholder strategies. In: Mistry, J., Berardi, A. (Eds.), Savannas and dry forests: Linking people with nature, 1st ed. Ashgate, Aldershot, Hants, England, pp. 227–240.

Gaydon, D.S., Balwinder-Singh, Wang, E., Poulton, P.L., Ahmad, B., Ahmed, F., Akhter, S., Ali, I., Amarasingha, R., Chaki, A.K., Chen, C., Choudhury, B.U., Darai, R., Das, A., Hochman, Z., Horan, H., Hosang, E.Y., Kumar, P.V., Khan, A.S.M.M.R., Laing, A.M., Liu, L., Malaviachichi, M.A.P.W.K., Mohapatra, K.P., Muttaleb, M.A., Power, B., Radanielson, A.M., Rai, G.S., Rashid, M.H., Rathanayake, W.M.U.K., Sarker, M.M.R., Sena, D.R., Shamim, M., Subash, N., Suriadi, A., Suriyagoda, L.D.B., Wang, G., Wang, J., Yadav, R.K., Roth, C.H., 2017. Evaluation of the APSIM model in cropping systems of Asia. Field Crops Research 204, 52–75.

Gebremariam, G., 2018. Sustainable Agricultural Practices (SAPs) in northern Ghana: Impacts on welfare, environmental reliance and agricultural land expansion. Ph.D. Thesis, Germany.

Gessner, U., Machwitz, M., Esch, T., Tillack, A., Naeimi, V., Kuenzer, C., Dech, S., 2015. Multi-sensor mapping of West African land cover using MODIS, ASAR and TanDEM-X/TerraSAR-X data. Remote Sensing of Environment 164, 282–297.

Gignoux, J., Barot, S., Menaut, J.-C., Vuattoux, R., 2006. Structure, long-term dynamics, and demography of the tree community. In: Abbadie, L., Gignoux, J., Roux, X., Lepage, M. (Eds.), Lamto: Structure, functioning, and dynamics of a savanna ecosystem. Springer Science, New York, pp. 335–364.

Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., Ridder, N. de, Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C., Vanlauwe, B., 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agricultural Systems 104 (2), 191–203.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people (eng). Science 327 (5967), 812–818.

Gould, P.R., 1960. The development of the transportation pattern in Ghana. Northwestern University, Department of Geography, Evanston, IL, USA.

Gounaridis, D., Chorianopoulos, I., Koukoulas, S., 2018. Exploring prospective urban growth trends under different economic outlooks and land-use planning scenarios: The case of Athens. Applied Geography 90, 134–144.

Gounaridis, D., Chorianopoulos, I., Symeonakis, E., Koukoulas, S., 2019. A Random Forest-Cellular Automata modeling approach to explore future land use/cover change in Attica (Greece), under different socio-economic realities and scales (eng). The Science of the total environment 646, 320–335.

Gourlet-Fleury, S., Mortier, F., Fayolle, A., Baya, F., Ouédraogo, D., Bénédet, F., Picard, N., 2013. Tropical forest recovery from logging: a 24 year silvicultural experiment from Central Africa. Phil. Trans. R. Soc. B 368 (1625), 20120302.

Government of Ghana, 2015. National Spatial Development Framework (2015-2035): Volume II: Overall Spatial Development Strategy, Accra, Ghana.

Grainger, A., Iverson, L.R., Marland, G.H., Prasad, A., 2019. Comment on "The global tree restoration potential" (eng). Science 366 (6463).

Groenendijk, P., van der Sleen, P., Vlam, M., Bunyavejchewin, S., Bongers, F., Zuidema, P.A., 2015. No evidence for consistent long-term growth stimulation of 13 tropical tree species: results from tree-ring analysis (eng). Glob Change Biol 21 (10), 3762–3776.

GSS, 2013. Population & Housing Census 2010: Regional analytical report. Upper East Region. Ghana Statistical Service, Accra, Ghana.

GSS, 2014a. Population & Housing Census 2010: District analytical report. Bongo. Ghana Statistical Service, Accra, Ghana. https://www2.statsghana.gov.gh/docfiles/2010_District_Report/Upper%20East/Bongo.pdf (accessed 6 August 2021).

GSS, 2014b. Population & Housing Census 2010: District analytical report. Bolgatanga Municipality. Ghana Statistical Service, Accra, Ghana. https://www2.statsghana.gov.gh/docfiles/2010_District_Report/Upper%20East/Bolga.pdf (accessed 6 August 2021).

GSS, 2021. Population of regions and districts. Ghana 2021 Population & Housing Census. General Report Volume 3A. Ghana Statistical Service, Accra, Ghana.

Guan, K., Sultan, B., Biasutti, M., Baron, C., Lobell, D.B., 2015. What aspects of future rainfall changes matter for crop yields in West Africa? Geophys. Res. Lett. 42 (19), 8001–8010.

Guan, K., Sultan, B., Biasutti, M., Baron, C., Lobell, D.B., 2017. Assessing climate adaptation options and uncertainties for cereal systems in West Africa. Agricultural and Forest Meteorology 232, 291–305.

Guilpart, N., Grassini, P., van Wart, J., Yang, H., van Ittersum, M.K., van Bussel, L.G.J., Wolf, J., Claessens, L., Leenaars, J.G.B., Cassman, K.G., 2017. Rooting for food security in Sub-Saharan Africa. Environ. Res. Lett. 12 (11), 114036.

Guuroh, R.T., Ruppert, J.C., Ferner, J., Čanak, K., Schmidtlein, S., Linstädter, A., 2018. Drivers of forage provision and erosion control in West African savannas—A macroecological perspective. Agriculture, Ecosystems & Environment 251, 257–267.

Guzha, A.C., Rufino, M.C., Okoth, S., Jacobs, S., Nóbrega, R.L.B., 2018. Impacts of land use and land cover change on surface runoff, discharge and low flows: Evidence from East Africa. Journal of Hydrology: Regional Studies 15, 49–67.

Hackman, K.O., Gong, P., Wang, J., 2017. New land-cover maps of Ghana for 2015 using Landsat 8 and three popular classifiers for biodiversity assessment. International Journal of Remote Sensing 38 (14), 4008–4021.

Ham, J.R., 2020. “Every day it’s tuo zaafi”: considering food preference in a food insecure region of Ghana. Agric Hum Values 37 (3), 907–917.

Harou, I.L., 2015. Agroforestry parklands of the sudan savanna in the context of climate change: Firewood energy in North-western Benin, West Africa. Master Research Degree Thesis, Togo.

Harris, J., 1991. Energy statistics: A manual for developing countries. United Nations, New York, x, 141.

Hårsmar, M., 2013. Relations Key to Innovations – Peasants, Institutions and Technical Change on the Mossi Plateau in Burkina Faso. African Journal of Science, Technology, Innovation and Development 5 (1), 5–18.

Hasegawa, S., Kasubuchi, T., Miyazaki, T., 2006. Water regimes in fields with vegetation. In: Miyazaki, T. (Ed.), Water flow in soils, 2nd ed. ed. Taylor & Francis, Boca Raton, pp. 301–350.

Hauck, J., Görg, C., Varjopuro, R., Ratamäki, O., Maes, J., Wittmer, H., Jax, K., 2013. "Maps have an air of authority": Potential benefits and challenges of ecosystem service maps at different levels of decision making. Ecosystem Services 4, 25-32.

Henry, M., Picard, N., Trotta, C., Manlay, R., Valentini, R., Bernoux, M., Saint-André, L., 2011. Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. Silva Fenn. 45 (3B).

Herrmann, S.M., Brandt, M., Rasmussen, K., Fensholt, R., 2020. Accelerating land cover change in West Africa over four decades as population pressure increased. Commun Earth Environ 1 (1).

Heubes, J., Kühn, I., König, K., Wittig, R., Zizka, G., Hahn, K., 2011. Modeling biome shifts and tree cover change for 2050 in West Africa. Journal of Biogeography 38 (12), 2248–2258.

Hickel, J., Dorninger, C., Wieland, H., Suwandi, I., 2022a. Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990-2015. Global Environmental Change 73, 102467.

Hickel, J., O'Neill, D.W., Fanning, A.L., Zoomkawala, H.B.S., 2022b. National responsibility for ecological breakdown: a fair-shares assessment of resource use, 1970-2017. The Lancet: Planetary Health 6(4), E342-E349.

Hiernaux, P., Ayantunde, A., Kalilou, A., Mougin, E., Gérard, B., Baup, F., Grippa, M., Djaby, B., 2009a. Trends in productivity of crops, fallow and rangelands in Southwest Niger: Impact of land use, management and variable rainfall. Journal of Hydrology 375 (1-2), 65–77.

Hiernaux, P., Diarra, L., Trichon, V., Mougin, E., Soumaguel, N., Baup, F., 2009b. Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali). Journal of Hydrology 375 (1-2), 103–113.

Hjelm, L., Dasori, W., 2012. Ghana comprehensive food security and vulnerability analysis, 2012: Focus on Northern Ghana, Rome, Italy.

Holdo, R.M., Mack, M.C., Arnold, S.G., 2012. Tree canopies explain fire effects on soil nitrogen, phosphorus and carbon in a savanna ecosystem. J Veg Sci 23 (2), 352–360.

Ickowitz, A., Powell, B., Rowland, D., Jones, A., Sunderland, T., 2019. Agricultural intensification, dietary diversity, and markets in the global food security narrative. Global Food Security 20, 9–16.

Idriss, S., Mohamed, D., Korodjouma, O., Baba, S., Charles, W., 2018. Rainfed rice response to fertilizer in the Sudan Savanna of West Africa. Afr. J. Agric. Res. 13 (20), 1033–1041.

Ignatova, J.A., 2021. Contesting Africa's New Green Revolution. Biotechnology and philanthropistcapitalist development in Ghana. Zed Books, 216 pp.

Igué, M.A., Oga, A.C., Saïdou, A., Balogoun, I., Anago, F., Ezui, G., Youl, S., Kpagbin, G., Mando, A., Sogbedji, J., 2015. Updating fertilizer formulation for maize cultivation (Zea mays L.) on Ferric Luvisols and Gleysols in the municipality of Tanguiéta, North-West Benin. Glob Adv Res J Agric Sci 4 (12), 858–863.

Iledun, O.C., Harira, S., Tanko, M.U., 2016. Sustainable crop production: growth and yield response of three varieties of groundnut (Arachis hypogaea L.) sown to three weeding regimes and two planting spacing in Anyigba, Kogi State, Nigeria. Agriculture & Food 4, 373–385.

Ilstedt, U., Bargués Tobella, A., Bazié, H.R., Bayala, J., Verbeeten, E., Nyberg, G., Sanou, J., Benegas, L., Murdiyarso, D., Laudon, H., Sheil, D., Malmer, A., 2016. Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. Sci Rep 6 (1).

Inkoom, J.N., Frank, S., Greve, K., Fürst, C., 2018a. A framework to assess landscape structural capacity to provide regulating ecosystem services in West Africa (eng). Journal of Environmental Management 209, 393–408.

Inkoom, J.N., Frank, S., Greve, K., Walz, U., Fürst, C., 2018b. Suitability of different landscape metrics for the assessments of patchy landscapes in West Africa. Ecological Indicators 85, 117–127.

Inusah, B.I.Y., Dogbe, W., Abdulai, A.L., Yirzagla, J., Mawunya, M., Issahak, A.S., 2014. Yield Gap Survey in Sudanno-Guinea Savanna Agro-Ecological Zones of Ghana. SAR 4 (1), 127.

Jazaïry, I., Alamgir, M., Panuccio, T., 1992. The state of world rural poverty: An inquiry into its causes and consequences. New York University Press, New York, USA.

Jiménez Martínez, M., Fürst, C., 2021. Simulating the capacity of rainfed food crop species to meet social demands in Sudanian savanna agro-ecologies. Land 10(8), 827.

Johnson, B., Villumsen, G., 2018. Environmental aspects of natural resource intensive development: the case of agriculture. Innovation and Development 8 (1), 167–188.

Jonathan, A., Owolabi, M.T., Olatunji, I.B., Duntoye, B.T., Henshaw, E.E., 2020. Economic analysis of the effect of flood disaster on food security of arable farming households in Southern Guinea Savanna Zone, Nigeria. Journal of Agriculture and Food Sciences 18 (1), 59–69.

Joy, E.J.M., Ander, E.L., Young, S.D., Black, C.R., Watts, M.J., Chilimba, A.D.C., Chilima, B., Siyame, E.W.P., Kalimbira, A.A., Hurst, R., Fairweather-Tait, S.J., Stein, A.J., Gibson, R.S., White, P.J., Broadley, M.R., 2014. Dietary mineral supplies in Africa. Physiol Plantarum 151 (3), 208–229.

Kachamba, D.J., Eid, T., 2016. Total tree, merchantable stem and branch volume models for miombo woodlands of Malawi. Southern Forests: a Journal of Forest Science 78 (1), 41–51.

Kadyampakeni, D.M., Mul, M.L., Obuobie, E., Appoh, R., Owusu, A., Ghansah, B., Boakye-Acheampong, E., Barron, J., 2017. Agro-climatic and hydrological characterization of selected watersheds in northern Ghana. International Water Management Institute (IWMI).

Kahiluoto, H., Kaseva, J., Hakala, K., Himanen, S.J., Jauhiainen, L., Rötter, R.P., Salo, T., Trnka, M., 2014. Cultivating resilience by empirically revealing response diversity. Global Environmental Change 25, 186–193.

Kairé, M., 1999. La production ligneuse des jachères et son utilization par l'homme au Sénégal, Aix-Marseille, France.

Kambatuku, J.R., Cramer, M.D., Ward, D., 2013. Overlap in soil water sources of savanna woody seedlings and grasses. Ecohydrol. 6 (3), 464–473.

Kaminski, J., Elbehri, A., Zoma, J.-P., 2013. An analysis of maize value chain and competitiveness in Burkina Faso: Implications for smallholder-inclusive policies and initiatives. In: Elbehri, A. (Ed.), Rebuilding West Africa's food potential: Policies and market incentives for smallholder-inclusive food value chains. The Food and Agriculture Organization of the United Nations and the International Fund for Agriculture Development, Rome, pp. 451–478.

Kamusoko, C., Gamba, J., 2015. Simulating Urban Growth Using a Random Forest-Cellular Automata (RF-CA) Model. IJGI 4 (2), 447–470.

Kanton, R.A.L., Frimpong, O., Terbobri, P., Sadik, A.S., 2000. Influence of tillage systems and seedbed types on sorghum yields and economics in northern Ghana. Soil and Tillage Research 55 (1-2), 79–85.

Karbo, N., Agyare, W.A., 2002. Crop-livestock systems in northern Ghana. In: Tarawali, G., Hiernaux, P. (Ed.), Improving crop-livestock systems in the dry savannas of West and Central Africa. International Institute of Tropical Agriculture, pp. 112–126.

Karlson, M., Ostwald, M., Reese, H., Sanou, J., Tankoano, B., Mattsson, E., 2015. Mapping Tree Canopy Cover and Aboveground Biomass in Sudano-Sahelian Woodlands Using Landsat 8 and Random Forest. Remote Sensing 7 (8), 10017–10041.

Kasei, R., Diekkrüger, B., Leemhuis, C., 2010. Drought frequency in the Volta Basin of West Africa. Sustain Sci 5 (1), 89–97.

Kastner, T., Erb, K.-H., Haberl, H., 2015. Global Human Appropriation of Net Primary Production for Biomass Consumption in the European Union, 1986-2007. Journal of Industrial Ecology 19 (5), 825–836.

Kayo, C., Tojo, S., Iwaoka, M., Matsumoto, T., 2014. Evaluation of biomass production and utilization systems. In: Tojo, S., Hirasawa, T. (eds.). Research approaches to sustainable biomass systems. Academic Press, Elsevier, London (UK) and Waltham (USA).

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy 18 (3-4), 267–288.

Keche, A.J., Gaddale, A.P.R., Tated, R.G., 2015. Simulation of biomass gasification in downdraft gasifier for different biomass fuels using ASPEN PLUS. Clean Techn Environ Policy 17 (2), 465–473.

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., Huising, J., 2016. Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa (eng). Agriculture, Ecosystems & Environment 229, 1–12.

Kircher, M., Breves, R., Taden, A., Herzberg, D., 2018. How to capture the bioeconomy's industrial and regional potential through professional cluster management. New Biotechnology 40, 119-128.

Kleemann, J., Baysal, G., Bulley, H.N.N., Fürst, C., 2017a. Assessing driving forces of land use and land cover change by a mixed-method approach in north-eastern Ghana, West Africa. Journal of Environmental Management 196, 411–442.

Kleemann, J., Celio, E., Nyarko, B.K., Jimenez-Martinez, M., Fürst, C., 2017b. Assessing the risk of seasonal food insecurity with an expert-based Bayesian Belief Network approach in northern Ghana, West Africa. Ecological Complexity 32, 53–73.

Knauer, K., Gessner, U., Fensholt, R., Forkuor, G., Kuenzer, C., 2017. Monitoring Agricultural Expansion in Burkina Faso over 14 Years with 30 m Resolution Time Series: The Role of Population Growth and Implications for the Environment. Remote Sensing 9 (2), 132.

Kolavalli, S., Robinson, E., Diao, X., Alpuerto, V., Folledo, R., Slavova, M.e.a., 2012. Economic transformation in Ghana – Where will the path lead? IFPRI Discussion Paper 01161. International Food Policy Research Institute.

Kombiok, J.M., Buah, S.S.J., Dzomeku, I.K., Abdulai, H., 2012. Sources of pod yield losses in groundnut in the Northern Savanna Zone of Ghana. West African Journal of Applied Ecology 20 (2), 53–63.

Kombiok, J.M., Safo, E.Y., Quansah, C., 2005. Yield and Nitrogen fixation of cowpea as affected by tillage and cropping systems in the Northern Savanna zone of Ghana. West African Journal of Applied Ecology 7 (1), 95–108.

Kone, B., Sylvester, O., Diatta, S., Somado, E., Valere, K., Sahrawat, K.L., 2011. Response of interspecific and sativa upland rices to Mali phosphate rock and soluble phosphate fertilizer. Archives of Agronomy and Soil Science 57 (4), 421–434.

Koné, M., Konaré, H., Dicko, M., Sissoko, F., 2018. Taking Stock of Fertilization in the Cultivation of Maize, Millet/Sorghum, Cowpea, Rice and Cotton in Mali. In: Bationo, A., Ngaradoum, D., Youl, S., Lompo, F., Fening, J.O. (Eds.), Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems. Springer International Publishing, Cham, pp. 209–220.

Konlan, S., Sarkodie-Addo, J., Asare, E., Kombiok, M.J., 2013. Groundnut (Arachis hypogaea L.) varietal response to spacing in the Guinea savanna agro-ecological zone of Ghana: Growth and yield. African Journal of Agricultural Research 8 (22), 2769–2777.

Konlan, S.P., Ayantunde, A.A., Addah, W., Dei, H.K., Karbo, N., 2018. Emerging feed markets for ruminant production in urban and peri-urban areas of Northern Ghana (eng). Tropical animal health and production 50 (1), 169–176.

Koo, H., Kleemann, J., Fürst, C., 2018. Land Use Scenario Modeling Based on Local Knowledge for the Provision of Ecosystem Services in Northern Ghana. Land 7 (2), 59.

Koulibaly, A., Goetze, D., Porembski, S., Traoré, D., Aké-Assi, L., 2010. Vegetation characteristics and changes under cash crop cultivation in forest-savanna mosaics in Côte d'Ivoire. In: van der Burgt, X.M., van der Maesen, L.J.G., Onana, J.-M. (Eds.), Systematics and conservation of African plants: Proceedings of the 18th AETFAT Congress. Kew Pub, Richmond, pp. 805–814.

Kpongor, D., 2007. Spatially explicit modeling of sorghum (Sorghum bicolor (L) Moench) production in a complex terrain in a semi-arid region of Ghana. Ph.D. Thesis, Germany.

Kranjac-Berisavljevic, G., Bayorbor, T.B., Abdulai, A.S., Obeng, F., Blench, R.M., Turton, C.N., Boyd, C., Drake, E., 1999. Rethinking natural resource degradation in semi arid Sub-Saharan Africa: the case of semi arid Ghana.

Krausmann, F., Schaffartzik, A., Mayer, A., Eisenmenger, N., Gingrich, S., Haberl, H., Fischer-Kowalski, M., 2016. Long-Term Trends in Global Material and Energy Use. In: Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V. (Eds.), Social Ecology. Springer International Publishing, pp. 199–216.

Kugbe, J.X., Kombat, R., Atakora, W., 2019. Secondary and micronutrient inclusion in fertilizer formulation impact on maize growth and yield across northern Ghana. Cogent Food & Agriculture 5 (1).

Kugbe, X.J., Issahaku, Z., 2015. Effects of soil conservation technologies in improving soil productivity in northern Ghana. J Soil Sci Env Manag 6 (6), 158–167.

Kuyah, S., Mbow, C., Sileshi, G.W., van Noordwijk, M., Tully, K.L., Rosenstock, T.S., 2016. Quantifying Tree Biomass Carbon Stocks and Fluxes in Agricultural Landscapes. In: Rosenstock, T.S., Rufino, M.C., Butterbach-Bahl, K., Wollenberg, L., Richards, M. (Eds.), Methods for Measuring Greenhouse Gas Balances and Evaluating Mitigation Options in Smallholder Agriculture. Springer International Publishing, Cham, pp. 119–134.

Kwofie, E.M., Ngadi, M., 2016. Sustainable energy supply for local rice parboiling in West Africa: The potential of rice husk. Renewable and Sustainable Energy Reviews 56, 1409–1418.

Kwoyiga, L., Stefan, C., 2019. Institutional Feasibility of Managed Aquifer Recharge in Northeast Ghana. Sustainability 11 (2), 379.

Kyereh, D., Darko, B.O., Agbenyega, O., Opuni-Frimpong, E., 2015. Analysis of smallholder forests for poverty alleviation and climate change mitigation in the Nkoranza South District of the Brong-Ahafo Region of Ghana. JOGEE 38 (1), 68–73.

La Notte, A., D'Amato, D., Mäkinen, H., Paracchini, M.L., Liquete, C., Egoh, B., Geneletti, D., Crossman, N.D., 2017. Ecosystem services classification: A systems ecology perspective of the cascade framework. Ecological Indicators 74, 392–402.

Lale, N.E.S., Yusuf, B.A., 2000. Insect pests infesting stored pearl millet Pennisetum glaucum (L.) R. Br. in northeastern Nigeria and their damage potential. CEREAL RESEARCH COMMUNICATIONS 28 (1-2), 181–186.

Lambin, E.F., D'haen, S.A.L., Mertz, O., Nielsen, J.Ø., Rasmussen, K., 2014a. Scenarios on future land changes in the West African Sahel. Geografisk Tidsskrift-Danish Journal of Geography 114 (1), 76–83.

Lambin, E.F., Meyfroidt, P., Rueda, X., Blackman, A., Börner, J., Cerutti, P.O., Dietsch, T., Jungmann, L., Lamarque, P., Lister, J., Walker, N.F., Wunder, S., 2014b. Effectiveness and synergies of policy instruments for land use governance in tropical regions. Global Environmental Change 28, 129–140.

Lamers, J.P.A., Michels, K., Vandenbeldt, R.J., 1994. Trees and windbreaks in the Sahel: establishment, growth, nutritive, and calorific values. Agroforest Syst 26 (3), 171–184.

Langewiesche, K., 2004. Les limites du reboisement au Burkina Faso et au Bénin. Politique africaine 96 (4), 196.

Larbi, I., Forkuor, G., Hountondji, F.C.C., Agyare, W.A., Mama, D., 2019. Predictive Land Use Change under Business-As-Usual and Afforestation Scenarios in the Vea Catchment, West Africa. IJARSG 8 (1), 3011–3029.

Laube, W., 2007. Actors, structures and institutional change: external interventions and the (de-)institutionalization of local natural resource regimes in Northern Ghana. Ph.D. Thesis, Cologne, Germany.

Laube, W., Schraven, B., Awo, M., 2012. Smallholder adaptation to climate change: dynamics and limits in Northern Ghana. Climatic Change 111 (3-4), 753–774.

Laux, P., Kunstmann, H., Bárdossy, A., 2008. Predicting the regional onset of the rainy season in West Africa. Int. J. Climatol. 28 (3), 329–342.

Leeuw, P.N. de, Reid, R.S., 1995. Impact of human activities and livestock on the African environment: An attempt to partition the pressure. In: Wilson, R.T., Ehui, S., Mack, S. (Eds.), Livestock development strategies for low income countries: Proceedings of the Joint FAO/ILRI Roundtable on Livestock Development Strategies for Low Income Countries, International Livestock Research Institute, Addis Ababa, Ethiopia 27 February _ 02 March 1995. ILRI, Nairobi.

Leh, M.D.K., Matlock, M.D., Cummings, E.C., Nalley, L.L., 2013. Quantifying and mapping multiple ecosystem services change in West Africa. Agriculture, Ecosystems & Environment 165, 6–18.

Lentz, C., 2006. Ethnicity and the making of history in northern Ghana. Edinburgh University Press for the International African Institute, Edinburgh.

Leroux, L., Bégué, A., Lo Seen, D., Jolivot, A., Kayitakire, F., 2017. Driving forces of recent vegetation changes in the Sahel: Lessons learned from regional and local level analyses. Remote Sensing of Environment 191, 38–54.

Limantol, A.M., Keith, B.E., Azabre, B.A., Lennartz, B., 2016. Farmers' perception and adaptation practice to climate variability and change: a case study of the Vea catchment in Ghana (eng). SpringerPlus 5 (1), 830.

Liu, Z., Wimberly, M., Dwomoh, F., 2017. Vegetation Dynamics in the Upper Guinean Forest Region of West Africa from 2001 to 2015. Remote Sensing 9 (1), 5.

Liverpool-Tasie. L.S.O., Omonona, B.T., Sanou, A., Ogunleye, W.O., 2017. Is increasing inorganic fertilizer use for maize production in SSA a profitable proposition? Evidence from Nigeria. Food Policy 67, 41-51.

Lombin, G., Singh, L., Yayock, J.Y., 1985. A decade of fertilizer research on groundnuts (Arachis hypogaea L) in the savanna zone of Nigeria. Nutr Cycl Agroecosyst 6 (2), 157–170.

López, R., 1997. Environmental externalities in traditional agriculture and the impact of trade liberalization: the case of Ghana. Journal of Development Economics 53 (1), 17–39.

Luedeling, E., Börner, J., Amelung, W., Schiffers, K., Shepherd, K., Rosenstock, T., 2019. Forest restoration: Overlooked constraints (eng). Science 366 (6463), 315.

Luedeling, E., Neufeldt, H., 2012. Carbon sequestration potential of parkland agroforestry in the Sahel. Climatic Change 115 (3-4), 443–461.

Luedeling, E., Smethurst, P.J., Baudron, F., Bayala, J., Huth, N.I., van Noordwijk, M., Ong, C.K., Mulia, R., Lusiana, B., Muthuri, C., Sinclair, F.L., 2016. Field-scale modeling of tree–crop interactions: Challenges and development needs. Agricultural Systems 142, 51–69.

Lund, C., 2001. Local Politics and the Dynamics of Property in Africa. Cambridge University Press, Cambridge.

Ly, J., Grageola, F., Batista, R., Lemus, C., Macías, M., Delgado, E., Santana, I., Díaz, C., 2011. Effect of genotype and diet on rectal digestibility of nutrients and faecal output in Cuban creole pigs. Tropical and Subtropical Agroecosystems 14 (2), 661–666.

MacCarthy, D.S., Adam, M., Freduah, B.S., Fosu-Mensah, B.Y., Ampim, P.A.Y., Ly, M., Traore, P.S., Adiku, S.G.K., 2021. Climate Change Impact and Variability on Cereal Productivity among Smallholder Farmers under Future Production Systems in West Africa. Sustainability 13 (9), 5191.

MacCarthy, D.S., Sommer, R., Vlek, P.L.G., 2009. Modeling the impacts of contrasting nutrient and residue management practices on grain yield of sorghum (Sorghum bicolor (L.)

Moench) in a semi-arid region of Ghana using APSIM. Field Crops Research 113 (2), 105–115.

MacCarthy, D.S., Vlek, P.L.G., Bationo, A., Tabo, R., Fosu, M., 2010. Modeling nutrient and water productivity of sorghum in smallholder farming systems in a semi-arid region of Ghana. Field Crops Research 118 (3), 251–258.

Machwitz, M., Gessner, U., Conrad, C., Falk, U., Richters, J., Dech, S., 2015. Modeling the Gross Primary Productivity of West Africa with the Regional Biomass Model RBM+, using optimized 250m MODIS FPAR and fractional vegetation cover information. International Journal of Applied Earth Observation and Geoinformation 43, 177–194.

Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., Rapidel, B., Tourdonnet, S., Valantin-Morison, M., 2009. Mixing plant species in cropping systems: concepts, tools and models. A review. Agron. Sustain. Dev. 29 (1), 43–62.

Mande, T., Ceperley, N.C., Katul, G.G., Tyler, S.W., Yacouba, H., Parlange, M.B., 2015. Suppressed convective rainfall by agricultural expansion in southeastern B urkina F aso. Water Resour. Res. 51 (7), 5521–5530.

Manlay, R.J., Kairé, M., Masse, D., Chotte, J.-L., Ciornei, G., Floret, C., 2002. Carbon, nitrogen and phosphorus allocation in agro-ecosystems of a West African savanna. Agriculture, Ecosystems & Environment 88 (3), 215–232.

Manouchehrinejad, M., Mani, S., 2019. Process simulation of an integrated biomass torrefaction and pelletization (iBTP) plant to produce solid biofuels. Energy Conversion and Management: X 1, 100008.

Maranan, M., Fink, A.H., Knippertz, P., 2018. Rainfall types over southern West Africa: Objective identification, climatology and synoptic environment. Q.J.R. Meteorol. Soc. 144 (714), 1628–1648.

Mbow, C., Chhin, S., Sambou, B., Skole, D., 2013. Potential of dendrochronology to assess annual rates of biomass productivity in savanna trees of West Africa. Dendrochronologia 31 (1), 41–51.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D., Huth, N.I., 1995. APSIM: an agricultural production system simulation model for operational research. Mathematics and Computers in Simulation 39 (3-4), 225–231.

Melin, M., Heiskanen, J., Packalen, P., Valbuena, R., 2016. Inventory of biomass and forest resources. In: Mononen, K., Pitkänen, S. (Eds.), Sustainable fuelwood management in West Africa. University of Eastern Finland, Jyväskylä, Finland, pp. 27–63.

Menaut, J.C., Cesar, J., 1979. Structure and Primary Productivty of Lamto Savannas, Ivory Coast. Ecology 60 (6), 1197.

Miao, Z., Grift, T.E., Hansen, A.C., Ting, K.C., 2013. Energy requirement for lignocellulosic feedstock densifications in relation to particle physical properties, preheating, and binding agents. Energy Fuels 27(1), 588-595.

Millar, D., Yeboah, R.W.N., 2006. Enhancing rural economies: women in groundnut marketing in the Bolgatanga area. Ghana J. Dev. Stud. 3 (1).

Millington, A.C., Critchley, R.W., Douglas, T.D., Ryan, P., 1994. Estimating woody biomass in Sub-Saharan Africa. http://documents.worldbank.org/curated/en/678641468003294109/Estimating-woody-biomass-in-Sub-Saharan-Africa (accessed 15 July 2020).

Miranda, J., Börner, J., Kalkuhl, M., Soares-Filho, B., 2019. Land speculation and conservation policy leakage in Brazil. Environ. Res. Lett. 14 (4), 45006.

MoFA, 2008. Agriculture sustainable land management: Strategy and action plan (2009- 2015), Accra, Ghana.

MoFA, 2011. Agriculture in Ghana: Facts and figures (2010), Accra, Ghana.

MoFA, 2014. Ghana Agricultural Production Survey (Minor Season) 2013: Second Round, Accra, Ghana. http://www2.statsghana.gov.gh/nada/index.php/catalog/87 (accessed 25 June 2020).

Mohammed, Y.S., Mokhtar, A.S., Bashir, N., Saidur, R., 2013. An overview of agricultural biomass for decentralized rural energy in Ghana. Renewable and Sustainable Energy Reviews 20, 15–25.

Mola-Yudego, B., Díaz-Yañez, O., Haapala, 2016. Wood energy on a global scale. In: Mononen, K., Pitkänen, S. (Eds.), Sustainable fuelwood management in West Africa. University of Eastern Finland, Jyväskylä, Finland, pp. 1–26.

Montgomery, R.F., 1988. Some Characteristics of Moist Savanna Soils and Constraints on Development with Particular Reference to Brazil and Nigeria. Journal of Biogeography 15 (1), 11.

Moore, S., Adu-Bredu, S., Duah-Gyamfi, A., Addo-Danso, S.D., Ibrahim, F., Mbou, A.T., Grandcourt, A. de, Valentini, R., Nicolini, G., Djagbletey, G., Owusu-Afriyie, K., Gvozdevaite, A., Oliveras, I., Ruiz-Jaen, M.C., Malhi, Y., 2018. Forest biomass, productivity and carbon cycling along a rainfall gradient in West Africa (eng). Glob Change Biol 24 (2), e496-e510.

Moriarty, P., Honnery, D., 2016. Review: Assessing the climate mitigation potential of biomass. AIMS Energy 5 (1), 20–38.

Moser-Nørgaard, P.M., Denich, M., 2011. Influence of livestock on the regeneration of fodder trees along ephemeral rivers of Namibia. Journal of Arid Environments 75 (4), 371–376.

Moulds, S., Buytaert, W., Mijic, A., 2015. An open and extensible framework for spatially explicit land use change modeling: the lulcc R package. Geosci. Model Dev. 8 (10), 3215–3229.

Muiambo, A.M., 2016. Growth and productivity of some selected indigenous tree species in monoculture plots in Morogoro - Tanzania. M.Sc. Thesis, Morogoro, Tanzania.

Mukunda, H.S., Dasappa, S., Paul, P.J., Rajan, N.K.S., Mahesh Yagnaraman, Ravi Kumar, D., Mukund Deogaonkar, 2010. Gasifier stoves – science, technology and field outreach. Current Science 98 (5), 627–638.

Mul, M., Obuobie, E., Appoh, R., Kankam-Yeboah, K., Bekoe-Obeng, E., Amisigo, B., Logah, F.Y., Ghansah, B., McCartney, M., 2015. Water resources assessment of the Volta River Basin.

Müller, M., Dembélé, S., Zougmoré, R., Gaiser, T., Partey, S., 2020. Performance of Three Sorghum Cultivars under Excessive Rainfall and Waterlogged Conditions in the Sudano-Sahelian Zone of West Africa: A Case Study at the Climate-Smart Village of Cinzana in Mali. Water 12 (10), 2655.

N’Dri, A.B., Gignoux, J., Barot, S., Konaté, S., Dembélé, A., Werner, P.A., 2014. The dynamics of hollowing in annually burnt savanna trees and its effect on adult tree mortality. Plant Ecol 215 (1), 27–37.

NAAB, J.B., BOOTE, K.J., PRASAD, P.V.V., SEINI, S.S., JONES, J.W., 2009a. Influence of fungicide and sowing density on the growth and yield of two groundnut cultivars. J. Agric. Sci. 147 (2), 179–191.

NAAB, J.B., Koo, J., Traore, P.C.S., Adiku, S.G.K., JONES, J.W., BOOTE, K.J., 2008. Carbon enhancing systems (CEMS). Estimation of soil carbon sequestration potential in smallholder farming systems in Northern Ghana. SM CRSP Bulletin, USA. https://vtechworks.lib.vt.edu/handle/10919/69022 (accessed 29 June 2020).

NAAB, J.B., SEINI, S.S., Gyasi, K.O., MAHAMA, G.Y., Prasad, P.V.V., BOOTE, K.J., JONES, J.W., 2009b. Groundnut yield response and economic benefits of fungicide and phosphorus application in farmer-managed trials in Northern Ghana. Ex. Agric. 45 (4), 385–399.

NAAB, J.B., Singh, P., BOOTE, K.J., JONES, J.W., Marfo, K.O., 2004. Using the CROPGRO-Peanut Model to Quantify Yield Gaps of Peanut in the Guinean Savanna Zone of Ghana. Agron. J. 96 (5), 1231–1242.

Najafi, E., Devineni, N., Khanbilvardi, R.M., Kogan, F., 2018. Understanding the Changes in Global Crop Yields Through Changes in Climate and Technology. Earth's Future 6 (3), 410–427.

Namara, R.E., Horowitz, L., Kolavalli, S., Kranjac-Berisavljevic, G., Dawuni, B.N., Barry, B., 2010. Typology of irrigation systems in Ghana. IWMI Working Paper 42. International Water Management Institute (IWMI), Colombo, Sri Lanka, 135 pp.

Nanang, D.M., 1996. The silviculture, growth and yield of neem (Azadirachta indica A. Juss.) plantations in Northern Ghana. M.Sc. Thesis, Orillia, Canada.

Narh, S., Boote, K.J., Naab, J.B., JONES, J.W., Tillman, B.L., Abudulai, M., Sankara, P., M'Bi Bertin, Z., Burow, M.D., Brandenburg, R.L., Jordan, D.L., 2015. Genetic Improvement of Peanut Cultivars for West Africa Evaluated with the CSM-CROPGRO-Peanut Model. Agronomy Journal 107 (6), 2213–2229.

Nartey, E., Dowuona, G.N., Ahenkorah, Y., Mermut, A.R., Tiessen, H., 1997. Variability in the properties of soils on two toposequences in northern Ghana. Ghana Journal of Agricultural Science 30 (2).

Narvaez-Vallejo, A., 2016. Land Use / Land Cover Classification Districts Bolgatanga and Bongo, Ghana, 2013. WASCAL.

Naylor, R., 2011. Expanding the boundaries of agricultural development. Food Sec. 3 (2), 233–251.

Ndamani, F., Watanabe, T., 2015. Farmers’ Perceptions about Adaptation Practices to Climate Change and Barriers to Adaptation: A Micro-Level Study in Ghana. Water 7 (12), 4593–4604.

Niang, A., Becker, M., Ewert, F., Dieng, I., Gaiser, T., Tanaka, A., Senthilkumar, K., Rodenburg, J., Johnson, J.-M., Akakpo, C., Segda, Z., Gbakatchetche, H., Jaiteh, F., Bam, R.K., Dogbe, W., Keita, S., Kamissoko, N., Mossi, I.M., Bakare, O.S., Cissé, M., Baggie, I., Ablede, K.A., Saito, K., 2017. Variability and determinants of yields in rice production systems of West Africa. Field Crops Research 207, 1–12.

Nichol, J.E., 1989. Ecology of fuelwood production in Kano Region, Northern Nigeria. Journal of Arid Environments 16 (3), 347–360.

Niedertscheider, M., Fetzel, T., Haberl, H., Krausmann, F., Gaube, V., Gingrich, S.e.a., 2016. Africa’s Land System Trajectories 1980–2005. In: Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V. (Eds.), Social Ecology. Springer International Publishing, pp. 361–373.

Nimoh, F., 2012. Seasonal food shortages and coping strategies adopted by rural households in Northern Ghana. J. Dev. Agric. Econ. 4 (3).

Nindel, S., 2017. Forest fire dynamics and carbon stocks in different ecological zones of Ghana. Ph.D. Thesis, Chemnitz, Germany.

Nin-Pratt, A., McBride, L., 2014. Agricultural intensification in Ghana: Evaluating the optimist's case for a Green Revolution. Food Policy 48, 153–167.

Nketiah, K.S., Asante, J., 2018. Estimating national charcoal production in Ghana. Tropenbos Ghana. https://ifro.ku.dk/english/research/projects/ax/publications/Estimating-national-charcoal-production-in-Ghana_report-2018.pdf (accessed 6 July 2020).

Nkonya, E., Karsenty, A., Msangi, S., Souza, C., Shah, M., Braun, J., Galford, G., Park, S., 2012. Sustainable land use for the 21st century: Sustainable Development in the 21st Century (SD21). United Nations, Department of Economic and Social Affairs, Division for Sustainable Development, 82 pp.

Noma, I., 2012. Rapid market assessment in Tamale, Bolgatanga, and Wa. World Food Programme, Regional Bureau for West Africa, Dakar, Senegal.

Noma, I., 2020. Rapid market assessment in Tamale, Bolgatanga, and Wa. World Food Programme, Regional Bureau for West Africa, Dakar, Senegal. https://documents.wfp.org/stellent/groups/public/documents/ena/wfp253277.pdf (accessed 6 July 2020).

Noulèkoun, F., Lamers, J.P.A., Naab, J., Khamzina, A., 2017. Shoot and root responses of woody species to silvicultural management for afforestation of degraded croplands in the Sudano-Sahelian zone of Benin. Forest Ecology and Management 385, 254–263.

Nouvellet, Y., 1993. Évolution d'un taillis de formation naturelle soudano-sahélienne au Burkina Faso. Bois et Fôrets des Tropiques 237, 45–59.

Nunifu, T.K., Murchison, H.G., 1999. Provisional yield models of Teak (Tectona grandis Linn F.) plantations in northern Ghana. Forest Ecology and Management 120 (1-3), 171–178.

Nwuneli, N., Diaw, A., Kwadzokpo, F., Elbehri, A., 2013. The role of the private sector and the engagement of smallholder farmers in food value chains: initiatives and successful cases from Nigeria, Senegal, and Ghana. In: Elbehri, A. (Ed.), Rebuilding West Africa's food potential: Policies and market incentives for smallholder-inclusive food value chains. The Food and Agriculture Organization of the United Nations, Rome, pp. 187–210.

Nyamwena-Mukonza, C., 2013. A Conceptual Framework for Implementing Sustainable Livelihoods and Innovation in Biofuel Production among Smallholder Farmers. African Journal of Science, Technology, Innovation and Development 5 (3), 180–188.

Nyantakyi-Frimpong, H., Bezner Kerr, R., 2015. A political ecology of high-input agriculture in northern Ghana. African Geographical Review 34 (1), 13–35.

Nyantakyi-Frimpong, H., Colecraft, E.K., Awuah, R.B., Adjorlolo, L.K., Wilson, M.L., Jones, A.D., 2018. Leveraging smallholder livestock production to reduce anemia: A qualitative study of three agroecological zones in Ghana (eng). Social science & medicine (1982) 212, 191–202.

Nygård, R., Sawadogo, L., Elfving, B., 2004. Wood-fuel yields in short-rotation coppice growth in the north Sudan savanna in Burkina Faso. Forest Ecology and Management 189 (1-3), 77–85.

Nykänen, E.-P.A., Dunning, H.E., Aryeetey, R.N.O., Robertson, A., Parlesak, A., 2018. Nutritionally Optimized, Culturally Acceptable, Cost-Minimized Diets for Low Income Ghanaian Families Using Linear Programming (eng). Nutrients 10 (4).

Obi, O.F., Ezema, J.C., Okonkwo, W.I., 2020. Energy performance of biomass cookstoves using fuel briquettes. Biofuels 11 (4), 467–478.

Obi, O.F., Ezeoha, S.L., Okorie, I.C., 2016. Energetic performance of a top-lit updraft (TLUD) cookstove. Renewable Energy 99, 730–737.

ODI, CEPA, 2005. Economic growth in Northern Ghana. Overseas Development Institute (ODI); Centre for Policy Analysis (CEPA), London & Accra.

OECD, 2013. Settlement, market and food security. OECD Publishing.

Ofosu, E.A., van der Zaag, P., van de Giesen, N.C., Odai, S.N., 2010. Productivity of irrigation technologies in the White Volta basin. Physics and Chemistry of the Earth, Parts A/B/C 35 (13-14), 706–716.

Oguntunde, P.G., Fasinmirin, J.T., van de Giesen, N., 2011. Influence of Tree Age and Variety on Allometric Characteristics and Water Use of Mangifera indica L. Growing in Plantation. Journal of Botany 2011, 1–8.

Ogutu, S.O., Gödecke, T., Qaim, M., 2020. Agricultural Commercialisation and Nutrition in Smallholder Farm Households. J Agric Econ 71 (2), 534–555.

Okafor, G.C., Annor, T., Odai, S.N., Larbi, I., 2020. Land Use Landcover Change Monitoring and Projection in the Dano Catchment, Southwest Burkina Faso. IJARSG 9 (1), 3185–3204.

Okorio, J., Maghembe, J.A., 1994. The growth and yield of Acacia albida intercropped with maize (Zea mays) and beans (Phaseolus vulgaris) at Morogoro, Tanzania. Forest Ecology and Management 64 (2-3), 183–190.

Olander, L.P., Johnston, R.J., Tallis, H., Kagan, J., Maguire, L.A., Polasky, S., Urban, D., Boyd, J., Wainger, L., Palmer, M., 2018. Benefit relevant indicators: Ecosystem services measures that link ecological and social outcomes. Ecological Indicators 85, 1262–1272.

Oliver, C.D., Nassar, N.T., Lippke, B.R., McCarter, J.B., 2014. Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests. Journal of Sustainable Forestry 33 (3), 248–275.

Oluwasemire, K.O., Stigter, C.J., Owonubi, J.J., Jagtap, S.S., 2002. Seasonal water use and water productivity of millet-based cropping systems in the Nigerian Sudan savanna near Kano. Agricultural Water Management 56 (3), 207–227.

O'Mara, F.P., 2012. The role of grasslands in food security and climate change. Annals of Botany 110 (6), 1263–1270.

Onuk, E.G., Alimba, J.O., Kasali, R., 2015. A comparative study of production efficiencies under cowpea-maize and groundnut-millet intercropping systems in the North Central Zone, Nigeria. PAT 11 (2), 108–121.

Orthmann, B., 2005. Vegetation ecology of a woodland-savanna mosaic in central Benin (West Africa): Ecosystem analysis with a focus on the impact of selective logging, 1 CD-ROM ;

Ostberg, S., Schewe, J., Childers, K., Frieler, K., 2018. Changes in crop yields and their variability at different levels of global warming. Earth Syst. Dynam. 9 (2), 479–496.

O'Sullivan, K., Barnes, D.F., 2007. Energy policies and multitopic household surveys: Guidelines for questionnaire design in living standards measurement studies / Kyran O'Sullivan and Douglas F. Barnes. World Bank, Washington, D.C.

Oteng-Darko, P., Kyei-Baffour, N., Ofori, E., 2012. Simulating rice yields under climate change scenarios using the CERES-Rice model (English). Afr Crop Sci J 20 (s2), 401–408.

Ouattara, D., 2015. Sorghum grain yield and nutrient dynamics under varying rates of fertilizer application in the sub-Sudanian zone of Burkina Faso. M.Sc. Thesis, Kumasi, Ghana.

Ouedraogo, I., Savadogo, P., Tigabu, M., Dayamba, S.D., Odén, P.C., 2011. Systematic and random transitions of land-cover types in Burkina Faso, West Africa. International Journal of Remote Sensing 32 (18), 5229–5245.

Ouedraogo, S., Sanou, L., Savadogo, P., Zoungrana/Kabore, C.Y., 2019. Structural characterization and pod yields of populations of the fodder legumes trees Piliostigma thonningii and Prosopis africana along the toposequence in western Burkina Faso. Int. J. Bio. Chem. Sci 13 (6), 2433–2448.

Ouédraogo, M.C.M., 2006. Contribution a l'amenagement et a la gestion des forets villageoises dans la province du Bazega: Cas de la forêt de Kongtenga dans le Departement de Sapone. Diplome d'Inspecteur des Eaux et Forêts, Bobo-Dioulasso, Burkina Faso.

Ouma, S., Boeckler, M., Lindner, P., 2013. Extending the margins of marketization: Frontier regions and the making of agro-export markets in northern Ghana. Geoforum 48, 225–235.

Overmars, K.P., Groot, W.T. de, Huigen, M.G.A., 2007. Comparing Inductive and Deductive Modeling of Land Use Decisions: Principles, a Model and an Illustration from the Philippines. Hum Ecol 35 (4), 439–452.

Owusu, A.B., 2009. Detecting and quantifying the extent of desertification and its impact in the semi-arid Sub-Saharan Africa – A case study of the Upper East Region, Ghana. Ph.D. Thesis, Fairfax, Virginia, USA.

Owusu, G., Oteng-Ababio, M., 2015. Moving Unruly Contemporary Urbanism Toward Sustainable Urban Development in Ghana by 2030. American Behavioral Scientist 59 (3), 311–327.

Owusu, S., Yigini, Y., Olmedo, G.F., Omuto, C.T., 2020. Spatial prediction of soil organic carbon stocks in Ghana using legacy data. Geoderma 360, 114008.

Pabi, O., 2007. Understanding land-use/cover change process for land and environmental resources use management policy in Ghana. GeoJournal 68 (4), 369–383.

Padonou, E.A., Assogbadjo, A.E., Bachmann, Y., Sinsin, B., 2013. How far bowalization affects phytodiversity, life forms and plant morphology in Sub-humid tropic in West Africa. Afr. J. Ecol. 51 (2), 255–262.

Padonou, E.A., Lykke, A.M., Bachmann, Y., Idohou, R., Sinsin, B., 2017. Mapping changes in land use/land cover and prediction of future extension of bowé in Benin, West Africa. Land Use Policy 69, 85–92.

Padonou, E.A., Teka, O., Bachmann, Y., Schmidt, M., Lykke, A.M., Sinsin, B., 2015. Using species distribution models to select species resistant to climate change for ecological restoration of bowé in West Africa. Afr. J. Ecol. 53 (1), 83–92.

Paine, C.E.T., Marthews, T.R., Vogt, D.R., Purves, D., Rees, M., Hector, A., Turnbull, L.A., 2012. How to fit nonlinear plant growth models and calculate growth rates: an update for ecologists. Methods in Ecology and Evolution 3 (2), 245–256.

Palm, C.A., Smukler, S.M., Sullivan, C.C., Mutuo, P.K., Nyadzi, G.I., Walsh, M.G., 2010. Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa (eng). Proc Natl Acad Sci USA 107 (46), 19661–19666.

Palmer, P.I., Feng, L., Baker, D., Chevallier, F., Bösch, H., Somkuti, P., 2019. Net carbon emissions from African biosphere dominate pan-tropical atmospheric CO2 signal (eng). Nat Commun 10 (1), 3344.

Pandeya, B., Buytaert, W., Zulkafli, Z., Karpouzoglou, T., Mao, F., Hannah, D.M., 2016. A comparative analysis of ecosystem services valuation approaches for application at the local scale and in data scarce regions. Ecosystem Services 22, 250–259.

Paré, S., 2008. Land use dynamics, tree diversity and local perception of dry forest decline in Southerrrn Burkina Faso, West Africa. Ph.D. Thesis, Sweden.

Parish, A., Gelli, A., 2015. Trade-offs in costs, diet quality and regional diversity: an analysis of the nutritional value of school meals in Ghana. AFJAND 15 (4), 10217–10240.

Pellegrini, A.F.A., Pringle, R.M., Govender, N., Hedin, L.O., 2017. Woody plant biomass and carbon exchange depend on elephant-fire interactions across a productivity gradient in African savanna. J Ecol 105 (1), 111–121.

Peprah, K., Amoah, S.T., Achana, G.T.W., 2015. The reticulation irrigation scheme at Sankana, Upper West Region, Ghana: Current usage, productivity and incomes. Ghana Journal of Geography 7 (1), 25–46.

Picard, N., Ballo, M., Dembelé, F., Gautier, D., Kaïré, M., Karmbé, M., 2006. Évaluation de la productivité et de la biomasse des savanes sèches africaines: l'apport du collectif Savafor. Bois et Forêts des Tropiques 288 (2), 75–80.

Pieri, C., 1989. Fertilité des terres de savanes: Bilan de trente ans de recherche et de développement agricoles au sud du Sahara. Ministère de la Coopération et du Développement, Paris, France.

Plange, N.-K., 1979. 'Opportunity Cost' and Labour Migration: a Misinterpretation of Proletarianisation in Northern Ghana. J. Mod. Afr. Stud. 17 (4), 655–676.

Plange, N.-K., 1984. The Colonial state in Northern Ghana: the political economy of pacification. Review of African Political Economy 11 (31), 29–43.

Pontius, R.G., Millones, M., 2011. Death to Kappa: birth of quantity disagreement and allocation disagreement for accuracy assessment. International Journal of Remote Sensing 32 (15), 4407–4429.

Porsö, C., Hammar, T., Nilsson, D., Hansson, P.A., 2018. Time-dependent climate impact and energy efficiency of internationally traded non-torrefied and torrefied wood pellets from logging residues. BioEnergy Research 11, 139-151.

Pouliot, M., Treue, T., Obiri, B.D., Ouedraogo, B., 2012. Deforestation and the Limited Contribution of Forests to Rural Livelihoods in West Africa: Evidence from Burkina Faso and Ghana. AMBIO 41 (7), 738–750.

Powar, R., Bandgar, P.S., Kadu, P., 2014. Clean energy from cotton stalk exercise of cook stove. International Journal of Emerging Technology and Advanced Engineering 4 (7).

Pretzsch, H., 2009. Forest dynamics, growth, and yield. Springer, Berlin, xix, 664.

Pringle, R.M., Doak, D.F., Brody, A.K., Jocqué, R., Palmer, T.M., 2010. Spatial pattern enhances ecosystem functioning in an African savanna. PLoS Biol 8(5), e1000377.

PROFOR. Using forests to enhance resilience to climate change: The case of the wood-energy sector in Burkina Faso. https://www.profor.info/sites/profor.info/files/Country%20case%20study%20-%20Burkina%20Faso_0.pdf (accessed 9 July 2020).

PROFOR, 2011. Assessment of forest landscape restoration opportunities in Ghana: Final Report. https://www.profor.info/sites/profor.info/files/Ghana%20FLR%20PROFOR%20final%20report%2029%20September_0.pdf (accessed 24 June 2020).

Puig-Arnavat, M., Shang, L., Sárossy, Z., Ahrenfeldt, J., Henriksen, U.B., 2016. From a single pellet press to a bench scale pellet mill - Pelletizing six different biomass feedstocks. Fuel Processing Technology 142, 27-33.

Qasim, M., Porembski, S., Sattler, D., Stein, K., Thiombiano, A., Lindner, A., 2016. Vegetation Structure and Carbon Stocks of Two Protected Areas within the South-Sudanian Savannas of Burkina Faso. Environments 3 (4), 25.

Quiñones, E.J., Muñoz, J., Ngeleza, G.A., 2011. A strategy for agricultural statistics in Ghana. GSSP Working Paper 25. International Food Policy Research Institute (IFPRI), Accra, Ghana.

Raes, D., Waongo, M., Vanuytrecht, E., Mejias Moreno, P., 2021. Improved management may alleviate some but not all of the adverse effects of climate change on crop yields in smallholder farms in West Africa. Agricultural and Forest Meteorology 308-309, 108563.

Ramírez-Cuesta, J.M., Allen, R.G., Zarco-Tejada, P.J., Kilic, A., Santos, C., Lorite, I.J., 2019. Impact of the spatial resolution on the energy balance components on an open-canopy olive orchard. International Journal of Applied Earth Observation and Geoinformation 74, 88–102.

Rasoulkhani, M., Ebrahimi-Nik, M., Abbaspour-Fard, M.H., Rohani, A., 2018. Comparative evaluation of the performance of an improved biomass cook stove and the traditional stoves of Iran. Sustainable Environment Research 28 (6), 438–443.

Rattalino Edreira, J.I., Cassman, K.G., Hochman, Z., van Ittersum, M.K., van Bussel, L., Claessens, L., Grassini, P., 2018. Beyond the plot: technology extrapolation domains for scaling out agronomic science. Environ. Res. Lett. 13 (5), 54027.

Reed, J., van Vianen, J., Deakin, E.L., Barlow, J., Sunderland, T., 2016. Integrated landscape approaches to managing social and environmental issues in the tropics: learning from the past to guide the future. 22, 2540-2554.

Reenberg, A., Moussa, I.B., Some, B., D'haen, S., 2014. Encapsulating knowledge from local documents: Time lines of social and environmental drivers of land system changes and their impact in Burkina Faso and Niger since 1960. LaSyRe Working Paper 11. Dep. of Geoscience and Natural Resource Management, Copenhagen. https://ign.ku.dk/ansatte/geografi/?pure=da%2Fpublications%2Fencapsulating-knowledge-from-local-documents(17c2522c-ff35-48f4-9a91-942b65c2c42a).html (accessed 6 July 2020).

Remans, R., Flynn, D.F.B., DeClerck, F., Diru, W., Fanzo, J., Gaynor, K., Lambrecht, I., Mudiope, J., Mutuo, P.K., Nkhoma, P., Siriri, D., Sullivan, C., Palm, C.A., 2011. Assessing Nutritional Diversity of Cropping Systems in African Villages. PLoS ONE 6 (6), e21235.

Renes, G.J.B., 1991. Regeneration capacity and productivity of natural forest in Burkina Faso. Forest Ecology and Management 41 (3-4), 291–308.

Reynolds, T.W., Anderson, C.L., Slakie, E., Gugerty, M.K., 2015. How Common Crop Yield Measures Misrepresent Productivity among Smallholder Farmers. 29th International Conference of Agricultural Economists August 9-14, 2015, Milan, Italy.

Riginos, C., 2009. Grass competition suppresses savanna tree growth across multiple demographic stages. Ecology 90 (2), 335–340.

Ritchie, J.T., 1985. A user-oriented model of the soil water balance in wheat. In: Day, W., Atkin, R.K. (Eds.), Wheat Growth and Modeling. Springer US; Imprint; Springer, Boston, MA, pp. 293–305.

Rosa, I.M.D., Purves, D., Carreiras, J.M.B., Ewers, R.M., 2015. Modeling land cover change in the Brazilian Amazon: temporal changes in drivers and calibration issues (eng). Reg Environ Change 15 (1), 123–137.

Rosa, I.M.D., Purves, D., Souza, C., Ewers, R.M., 2013. Predictive modeling of contagious deforestation in the Brazilian Amazon (eng). PLoS ONE 8 (10), e77231.

Roth, C., 2014. Micro-gasification: cooking with gas from dry biomass: Second Revised Edition. GIZ, Eschborn, Germany.

Rouch, J., 1990. Les cavaliers aux vautours. Les conquêtes zerma dans le Gurunsi (1856-1900). Journal des Africanistes 60 (2), 5–36.

Roudier, P., Sultan, B., Quirion, P., Berg, A., 2011. The impact of future climate change on West African crop yields: What does the recent literature say? Global Environmental Change 21 (3), 1073–1083.

Rudel, T.K., Meyfroidt, P., 2014. Organizing anarchy: The food security–biodiversity–climate crisis and the genesis of rural land use planning in the developing world. Land Use Policy 36, 239–247.

S.E.R.F, 2004. Projet de Plan d'Amenagement de la Forêt Classée de Kari: Periode 2005-2019. Version amendée, Ouagadougou, Burkina Faso. http://www.reseau-cicle.org/wp-content/uploads/riaed/pdf/PAF_Kari.pdf (accessed 5 July 2020).

Saïdou, A., Balogoun, I., Ahoton, E.L., Igué, A.M., Youl, S., Ezui, G., Mando, A., 2018. Fertilizer recommendations for maize production in the South Sudan and Sudano-Guinean zones of Benin. Nutr Cycl Agroecosyst 110 (3), 361–373.

Saito, M., Luyssaert, S., Poulter, B., Williams, M., Ciais, P., Bellassen, V., Ryan, C.M., Yue, C., Cadule, P., Peylin, P., 2014. Fire regimes and variability in aboveground woody biomass in miombo woodland. J. Geophys. Res. Biogeosci. 119 (5), 1014–1029.

Sakthivadivel, D., Iniyan, S., 2018. Experimental design and 4E (energy, exergy, emission, and economical) analysis of a fixed bed advanced microgasifier stove. Environ. Prog. Sustainable Energy 37 (6), 2139–2147.

Sallah, P.Y., Twumasi-Afriyie, S., Ahenkora, K., Asiedu, E.A., Obenh-Antwi, E., Osei-Yeboah, S., Frimpong-Mango, P.P., Ankomah, A., Dzah, B.D., 2007. Agronomic potentials of quality protein maize hybrids developed in Ghana. Ghana Journal of Agriculture 40 (1), 81–89.

Samson, R., Mani, S., Boddey, R., Sokhansanj, S., Quesada, D., Urquiaga, S., Reis, V., Ho Lem, C., 2005. The Potential of C 4 Perennial Grasses for Developing a Global BIOHEAT Industry. Critical Reviews in Plant Sciences 24 (5-6), 461–495.

Sankaran, M., Hanan, N.P., Scholes, R.J., Ratnam, J., Augustine, D.J., Cade, B.S., Gignoux, J., Higgins, S.I., Le Roux, X., Ludwig, F., Ardo, J., Banyikwa, F., Bronn, A., Bucini, G., Caylor, K.K., Coughenour, M.B., Diouf, A., Ekaya, W., Feral, C.J., February, E.C., Frost, P.G.H., Hiernaux, P., Hrabar, H., Metzger, K.L., Prins, H.H.T., Ringrose, S., Sea, W., Tews, J., Worden, J., Zambatis, N., 2005. Determinants of woody cover in African savannas. Nature 438 (7069), 846–849.

Sanou, B., 2014. Potentiel des ligneux fourragers du terroir de Sokouraba. Master Thesis, Burkina Faso.

Sanou, J., Bayala, J., Teklehaimanot, Z., Bazié, P., 2012. Effect of shading by baobab (Adansonia digitata) and néré (Parkia biglobosa) on yields of millet (Pennisetum glaucum) and taro (Colocasia esculenta) in parkland systems in Burkina Faso, West Africa. Agroforest Syst 85 (3), 431–441.

Sarker, T.R., Nanda, S., Dalai, A.K., Meda, V., 2021. A review of torrefaction technology for upgrading lignocellulosic biomass to solid biofuels. BioEnergy Research 14, 645-669.

Savadogo, P., Tiveau, D., Sawadogo, L., Tigabu, M., 2008. Herbaceous species responses to long-term effects of prescribed fire, grazing and selective tree cutting in the savanna-woodlands of West Africa. Perspectives in Plant Ecology, Evolution and Systematics 10 (3), 179–195.

Sawadogo, L., 2007. Etat de la biodiversité et la de production des ligneux du Chantier d’Aménagement Forestier du Nazinon après une vingtaine d’années de pratiques d’aménagement, Bogor, Indonesia.

SCHEITER, S., Higgins, S.I., 2009. Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modeling approach. Glob Change Biol 15 (9), 2224–2246.

Scheiterle, L., Birner, R., 2018. Assessment of Ghana's Comparative Advantage in Maize Production and the Role of Fertilizers. Sustainability 10 (11), 4181.

Schraven, B., Rademacher-Schulz, C., 2015. Shifting rainfalls, shifting livelihoods: Seasonal migration, food security and social inequality in Northern Ghana. In: McLeman, R.A., Schade, J., Faist, T. (Eds.), Environmental migration and social inequality. Springer, Cham, 43–56.

Searchinger, T.D., Estes, L., Thornton, P.K., Beringer, T., an Notenbaert, Rubenstein, D., Heimlich, R., Licker, R., Herrero, M., 2015. High carbon and biodiversity costs from converting Africa's wet savannas to cropland. Nature Clim Change 5 (5), 481–486.

Sedem Ehiakpor, D., Apumbora, J., Danso-Abbeam, G., Adzawla, W., 2017. Households' Preference for Local Rice in the Upper East Region, Ghana. Advances in Agriculture 2017, 1–9.

Sekyi-Annan, E., 2019. Performance evaluation of reservoir-based irrigation schemes in the Upper East region of Ghana. Ph.D. Thesis. University of Bonn, Germany.

Sekyi-Annan, E., Tischbein, B., Diekkrüger, B., Khamzina, A., 2018a. Performance evaluation of reservoir-based irrigation schemes in the Upper East region of Ghana. Agricultural Water Management 202, 134–145.

Sekyi-Annan, E., Tischbein, B., Diekkrüger, B., Khamzina, A., 2018b. Year-Round Irrigation Schedule for a Tomato–Maize Rotation System in Reservoir-Based Irrigation Schemes in Ghana. Water 10 (5), 624.

SHACKLETON, C.M., Clarke, J.M., 2007. Research and management of miombo woodlands for products in support of local livelihoods: Paper I. Genesis Analytics, Johannesburg, South Africa. https://www2.cifor.org/miombo/docs/SilviculturalOptions_December2007-Genesis.pdf (accessed 20 September 2020).

Shanahan, H., Carlsson-Kanyama, A., Offei-Ansah, C., Ekstrom, M.P., Potapova, M., 2003. Family meals and disparities in global ecosystem dependency. Three examples: Ghana, Russia and Sweden. Int J Cons Stud 27 (4), 283–293.

Shiyam, J.O., 2010. Growth and yield response of groundnut (Arachis hypogaea L.) to plant densities and phosphorus on an ultisol in Southeastern Nigeria. Libyan Agriculture Research Center Journal International 1 (4), 211–214.

Shoyama, K., Braimoh, A.K., Avtar, R., Saito, O., 2018. Land Transition and Intensity Analysis of Cropland Expansion in Northern Ghana. Environmental Management 62 (5), 892–905.

Shrestha, R.B., Alenyorege, B., 2008. Physical feasibility of domestic biogas in the Upper East Region of Ghana: A report prepared for SNV Ghana, Northern Portofolio. http://www.bibalex.org/Search4Dev/files/338820/172302.pdf (accessed 6 February 2021).

Shrestha, S., Becker, M., Lamers, J.P.A., Wimmer, M.A., 2020. Diagnosis of zinc and boron availability in emerging vegetable-based crop rotations in Nepal. J. Plant Nutr. Soil Sci. 183 (4), 429–438.

Shuaibu, Y.M., Garba, A.A., Voncir, N., 2015. Influence of legume residue and nitrogen fertilizer on the growth and yield of sorghum (Sorghum bicolor (L.) Moench) in Bauchi State, Nigeria. AFJAND 15 (3), 10060–10075.

Sikarwar, V.S., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M.Z., Shah, N., Anthony, E.J., Fennell, P.S., 2016. An overview of advances in biomass gasification. Energy Environ. Sci. 9 (10), 2939–2977.

Sileshi, G., Akinnifesi, F.K., Debusho, L.K., Beedy, T., Ajayi, O.C., Mong'omba, S., 2010. Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa. Field Crops Research 116 (1-2), 1–13.

Sillanpää, M., Ncibi, C., 2017. Sustainable bioeconomy. The Green Industrial Revolution. Springer, 343 pp.

Singh, J., Levick, S.R., Guderle, M., Schmullius, C., Trumbore, S.E., 2018. Variability in fire-induced change to vegetation physiognomy and biomass in semi-arid savanna. Ecosphere 9 (12), e02514.

Singh, P., BOOTE, K.J., Kadiyala, M.D.M., Nedumaran, S., Gupta, S.K., Srinivas, K., Bantilan, M.C.S., 2017. An assessment of yield gains under climate change due to genetic modification of pearl millet (eng). The Science of the total environment 601-602, 1226–1237.

Sissoko, P., Lebailly, P., 2016. Comparative analysis of agricultural production systems performances: case of millet and sorghum in Mali. In: Kovacevic, D. (Ed.), Book of Proceedings, 10.7251/AGRENG1607409. CIP - Каталогизација у публикацији, Banja Luka, Republika Srpska, pp. 2722–2728.

Sivakumar, M.V.K., Hatfield, J.L., 1990. Spatial variability of rainfall at an experimental station in Niger, West Africa. Theor Appl Climatol 42 (1), 33–39.

Smith, J., Sones, K., Grace, D., MacMillan, S., Tarawali, S., Herrero, M., 2013. Beyond milk, meat, and eggs: Role of livestock in food and nutrition security. Animal Frontiers 3 (1), 6–13.

Soltani, A., Alimagham, S.M., Nehbandani, A., Torabi, B., Zeinali, E., Dadrasi, A., Zand, E., Ghassemi, S., Pourshirazi, S., Alasti, O., Hosseini, R.S., Zahed, M., Arabameri, R., Mohammadzadeh, Z., Rahban, S., Kamari, H., Fayazi, H., Mohammadi, S., Keramat, S., Vadez, V., van Ittersum, M.K., Sinclair, T.R., 2020. SSM-iCrop2: A simple model for diverse crop species over large areas. Agricultural Systems 182, 102855.

Some, N.A., Traoré, K., Traoré, O., Tassembedo, M., 2007. Potentiel des jachères artificielles à Andropogon spp. dans l'amélioration des propriétés chimiques et biologiques des sols en zone soudanienne (Burkina Faso). Biotechnol. Agron. Soc. Environ. 11 (3), 245–252.

Sonaiya, E.B., Swan, S.E.J., 2004. Small-scale poultry production: Technical Guide, Rome, Italy.

Sotelo Montes, C., Weber, J.C., Silva, D.A., Andrade, C., Muñiz, G.I.B., Garcia, R.A., Kalinganire, A., 2012. Effects of region, soil, land use, and terrain type on fuelwood properties of five tree/shrub species in the Sahelian and Sudanian ecozones of Mali. Annals of Forest Science 69 (6), 747–756.

Soto Flandez, M., 1995. Dry forest silviculture in the Sudano-Sahelian region: Burkina Faso's experience. In: Ball, J., Linares Bensimon, C., Kuusela, K., Hagner, S., Johnson, P., Löche-Wilkie, M., Agrawal, A. (Eds.), Silviculture. FAO, Rome, Italy.

Souverijns, N., Buchhorn, M., Horion, S., Fensholt, R., Verbeeck, H., Verbesselt, J., Herold, M., Tsendbazar, N.-E., Bernardino, P.N., Somers, B., van de Kerchove, R., 2020. Thirty Years of Land Cover and Fraction Cover Changes over the Sudano-Sahel Using Landsat Time Series. Remote Sensing 12 (22), 3817.

Souza, G.M., Ballester, M.V.R., Brito Cruz, C.H. de, Chum, H., Dale, B., Dale, V.H., Fernandes, E.C.M., Foust, T., Karp, A., Lynd, L., Maciel Filho, R., Milanez, A., Nigro, F., Osseweijer, P., Verdade, L.M., Victoria, R.L., van der Wielen, L., 2017. The role of bioenergy in a climate-changing world. Environmental Development 23, 57–64.

Sow, O., 2012. Caractéristiques de la végétation ligneuse et impact des traitements sylvicoles dans la dynamique évolutive des forêts naturelles: cas de la forêt classée du Nazinon dans le Centre-Ouest du Burkina Faso. Diplome d'Ingenieur du Developpement Rural, Burkina Faso.

Srivastava, A.K., Mboh, C.M., Gaiser, T., Ewert, F., 2017. Impact of climatic variables on the spatial and temporal variability of crop yield and biomass gap in Sub-Saharan Africa- a case study in Central Ghana. Field Crops Research 203, 33–46.

Srivastava, A.K., Mboh, C.M., Zhao, G., Gaiser, T., Ewert, F., 2018. Climate change impact under alternate realizations of climate scenarios on maize yield and biomass in Ghana. Agricultural Systems 159, 157–174.

Stadlmayr, B., 2010. Composition of selected foods from West Africa. Food and Agriculture Organization of the United Nations, Rome, 43 pp.

Staniland, M., 1975. The Lions of Dagbon - Political change in Northern Ghana. Cambridge University Press.

Staver, A.C., Asner, G.P., Rodriguez-Iturbe, I., Levin, S.A., Smit, I.P.J., 2019. Spatial patterning among savanna trees in high-resolution, spatially extensive data. Proc Natl Acad Sci USA 116 (22), 10681–10685.

Stein, A., Brouwer, J., Bouma, J., 1997. Methods for Comparing Spatial Variability Patterns of Millet Yield and Soil Data. Soil Science Society of America Journal 61 (3), 861–870.

Stellmacher, T., Kelboro, G., 2019. Family Farms, Agricultural Productivity, and the Terrain of Food (In)security in Ethiopia. Sustainability 11 (18), 4981.

Stuch, B., Alcamo, J., Schaldach, R., 2021. Projected climate change impacts on mean and year-to-year variability of yield of key smallholder crops in Sub-Saharan Africa. Climate and Development 13 (3), 268–282.

Sugri, I., Kusi, F., Kanton, R.A.L., Nutsugah, S.K., Zakaria, M., 2013. Sustaining frafra potato (Solenostemon rotundifolius Poir.) in the food chain; current opportunities in Ghana. Journal of Plant Sciences 1 (4), 68–75.

Sugri, I., Maalekuu, B.K., Gaveh, E., Kusi, F., 2017. Sweet Potato Value Chain Analysis Reveals Opportunities for Increased Income and Food Security in Northern Ghana. Advances in Agriculture 2017, 1–14.

Sultan, B., Defrance, D., Iizumi, T., 2019. Evidence of crop production losses in West Africa due to historical global warming in two crop models (eng). Sci Rep 9 (1), 12834.

Sultan, B., Gaetani, M., 2016. Agriculture in West Africa in the Twenty-First Century: Climate Change and Impacts Scenarios, and Potential for Adaptation (eng). Frontiers in plant science 7, 1262.

Sultan, B., Guan, K., Kouressy, M., Biasutti, M., Piani, C., Hammer, G.L., McLean, G., Lobell, D.B., 2014. Robust features of future climate change impacts on sorghum yields in West Africa. Environ. Res. Lett. 9 (10), 104006.

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciais, P., Guimberteau, M., Traore, S., Baron, C., 2013. Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. Environ. Res. Lett. 8 (1), 14040.

Swaine, M.D., 1992. Characteristics of dry forest in West Africa and the influence of fire. Journal of Vegetation Science 3 (3), 365–374.

Tachie-Obeng, E., Akponikpè, P.B.I., Adiku, S., 2013. Considering effective adaptation options to impacts of climate change for maize production in Ghana. Environmental Development 5, 131–145.

Takimoto, A., 2007. Carbon sequestration potential of agroforestry systems in the West African Sahel: an assessment of biological and socioeconomic feasibility. Ph.D. Thesis, Gainesville, 184 pp.

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman, M., Hallin, S., 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield. Science Advances 6(45), DOI: 10.1126/sciadv.aba1715.

Tanaka, A., Johnson, J.-M., Senthilkumar, K., Akakpo, C., Segda, Z., Yameogo, L.P., Bassoro, I., Lamare, D.M., Allarangaye, M.D., Gbakatchetche, H., Bayuh, B.A., Jaiteh, F., Bam, R.K., Dogbe, W., Sékou, K., Rabeson, R., Rakotoarisoa, N.M., Kamissoko, N., Mossi, I.M., Bakare, O.S., Mabone, F.L., Gasore, E.R., Baggie, I., Kajiru, G.J., Mghase, J., Ablede, K.A., Nanfumba, D., Saito, K., 2017. On-farm rice yield and its association with biophysical factors in sub-Saharan Africa. European Journal of Agronomy 85, 1–11.

Tao, F., Palosuo, T., Rötter, R.P., Díaz-Ambrona, C.G.H., Inés Mínguez, M., Semenov, M.A., Kersebaum, K.C., Cammarano, D., Specka, X., Nendel, C., Srivastava, A.K., Ewert, F., Padovan, G., Ferrise, R., Martre, P., Rodríguez, L., Ruiz-Ramos, M., Gaiser, T., Höhn, J.G., Salo, T., Dibari, C., Schulman, A.H., 2020. Why do crop models diverge substantially in climate impact projections? A comprehensive analysis based on eight barley crop models. Agricultural and Forest Meteorology 281, 107851.

Tappan, G. G., Cushing, W.M., Cotillon, S.E., Mathis, M.L., Hutchinson, J.A., Herrmann, S.M., Dalsted, K.J., 2016. West Africa Land Use Land Cover Time Series: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F73N21JF. Last time accessed: 16.12.2021.

Taylor, I., 2016. Dependency redux: why Africa is not rising. Review of African Political Economy 43 (147), 8–25.

Tian, G., Kang, B.T., Kolawole, G.O., Idinoba, P., Salako, F.K., 2005. Long-term effects of fallow systems and lengths on crop production and soil fertility maintenance in West Africa. Nutr Cycl Agroecosyst 71 (2), 139–150.

Timberlake, J., Chidumayo, E., Sawadogo, L., 2010. Distribution and characteristics of African dry forests and woodlands. In: Chidumayo, E.N., Gumbo, D.J. (Eds.), The dry forests and woodlands of Africa: Managing for products and services, First edition ed. Routledge; Taylor & Francis, Boca Raton, FL, pp. 11–41.

Tittonell, P., Muriuki, A., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., Valauwe, B., 2010. The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa: A typology of smallholder farms. Agricultural Systems 103, 83–97.

Tohinlo, Y., Lebailly, P., Floquet, A., 2016. Une soudure alimentaire persistance après deux décennies d’intervention pour la sécurité alimentaire dans l’Atacora (Nord-Ouest du Bénin), 10–11.

Tomlinson, H., Traore, A., Teklehaimanot, Z., 1998. An investigation of the root distribution of Parkia biglobosa in Burkina Faso, West Africa, using a logarithmic spiral trench. Forest Ecology and Management 107 (1-3), 173–182.

Tomlinson, K.W., Sterck, F.J., Barbosa, E.R.M., Bie, S. de, Prins, H.H.T., van Langevelde, F., 2019. Seedling growth of savanna tree species from three continents under grass competition and nutrient limitation in a greenhouse experiment. J Ecol 107 (3), 1051–1066.

Traore, B., Descheemaeker, K., van Wijk, M.T., Corbeels, M., Supit, I., Giller, K.E., 2017. Modeling cereal crops to assess future climate risk for family food self-sufficiency in southern Mali. Field Crops Research 201, 133–145.

Traoré, K., Sidibe, D.K., Coulibaly, H., Bayala, J., 2017. Optimizing yield of improved varieties of millet and sorghum under highly variable rainfall conditions using contour ridges in Cinzana, Mali. Agric & Food Secur 6 (1).

Traoré, S.M.A., Oumarou, D.H., Issoufou, B., Balla, A., 2020. Offre et demande en cereales au Sahel et in Afrique de l'Ouest. Agronomie Africaine 32 (3), 251–264.

Tredennick, A.T., Hanan, N.P., 2015. Effects of Tree Harvest on the Stable-State Dynamics of Savanna and Forest. The American Naturalist 185 (5), E153-E165.

Tryner, J., Willson, B.D., Marchese, A.J., 2014. The effects of fuel type and stove design on emissions and efficiency of natural-draft semi-gasifier biomass cookstoves. Energy for Sustainable Development 23, 99–109.

Tsujimoto, Y., Rakotoson, T., Tanaka, A., Saito, K., 2019. Challenges and opportunities for improving N use efficiency for rice production in sub-Saharan Africa. Plant Production Science 22 (4), 413–427.

Turner, M., 1995. The sustainability of rangeland to cropland nutrient transfer in semi-arid West Africa: Ecological and social dimensions neglected in the debate. In: Powell, J.M. (Ed.), Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa: Proceedings of an international conference, International Livestock Centre for Africa (ILCA) Addis Ababa, Ethiopia, 22-26 November 1993. International Livestock Centre for Africa, Addis Ababa Ethiopia, pp. 149–170.

Turner, M.D., Hiernaux, P., 2015. The effects of management history and landscape position on inter-field variation in soil fertility and millet yields in southwestern Niger. Agriculture, Ecosystems & Environment 211, 73–83.

United Nations University, World Health Organization, Food and Agriculture Organization of the United Nations, 2004. Human energy requirements: Report of a joint FAO/WHO/UNU expert consultation : Rome, 17-24 October 2001. United Nations University, Rome.

Valbuena, R., Heiskanen, J., Aynekulu, E., Pitkänen, S., Packalen, P., 2016. Sensitivity of Above-Ground Biomass Estimates to Height-Diameter Modeling in Mixed-Species West African Woodlands (eng). PLoS ONE 11 (7), e0158198.

Vallet, A., Locatelli, B., Levrel, H., Brenes Pérez, C., Imbach, P., Estrada Carmona, N., Manlay, R., Oszwald, J., 2016. Dynamics of Ecosystem Services during Forest Transitions in Reventazón, Costa Rica (eng). PLoS ONE 11 (7), e0158615.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—A review. Field Crops Research 143, 4–17.

van Ittersum, M.K., van Bussel, L.G.J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., Groot, H. de, Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P.A.J., van Loon, M.P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016. Can sub-Saharan Africa feed itself? (eng). Proc Natl Acad Sci USA 113 (52), 14964–14969.

van Melle, C., Buschmann, S., 2013. Comparative analysis of mango value chain models in Benin, Burkina Faso and Ghana. In: Elbehri, A. (Ed.), Rebuilding West Africa's food potential: Policies and market incentives for smallholder-inclusive food value chains. The Food and Agriculture Organization of the United Nations, Rome.

van Noordwijk, M., Duguma, L.A., Dewi, S., Leimona, B., Catacutan, D.C., Lusiana, B., Öborn, I., Hairiah, K., Minang, P.A., 2018. SDG synergy between agriculture and forestry in the food, energy, water and income nexus: reinventing agroforestry? Current Opinion in Environmental Sustainability 34, 33–42.

Minang, P.A., van Noordwijk, M., Freeman, O.E., Mbow, C., Leeuw, J. de, Catacutan, D. (Eds.), 2015. Climate-smart landscapes: Multifunctionality in practice. World Agroforestry Centre (ICRAF), Nairobi, Kenya, 405 pp.

van Oort, P.A.J., Zwart, S.J., 2018. Impacts of climate change on rice production in Africa and causes of simulated yield changes (eng). Glob Change Biol 24 (3), 1029–1045.

van Wart, J., Grassini, P., Cassman, K.G., 2013. Impact of derived global weather data on simulated crop yields (eng). Glob Change Biol 19 (12), 3822–3834.

Vanclay, J.K., 2001. Modeling forest growth and yield: Applications to mixed tropical forests. CAB International, Wallingford, 312 pp.

Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., Nziguheba, G., Schut, M., van Asten, P., 2014. Sustainable intensification and the African smallholder farmer. Current Opinion in Environmental Sustainability 8, 15–22.

Veldhuis, M.P., Hulshof, A., Fokkema, W., Berg, M.P., Olff, H., 2016. Understanding nutrient dynamics in an African savanna: local biotic interactions outweigh a major regional rainfall gradient. J Ecol 104 (4), 913–923.

Veldhuis, M.P., Rozen-Rechels, D., Le Roux, E., Cromsigt, J.P.G.M., Berg, M.P., Olff, H., 2017. Determinants of patchiness of woody vegetation in an African savanna. J Veg Sci 28 (1), 93–104.

Venot, J.P., Andreini, M., Pinkstaff, C.B., 2011. Planning and corrupting water resources development: The case of small reservoirs in Ghana. Water Alternatives 4 (3).

Verburg, P.H., SOEPBOER, W., VELDKAMP, A., LIMPIADA, R., ESPALDON, V., MASTURA, S.S.A., 2002. Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. Environmental Management 30 (3), 391–405.

Verstegen, J.A., Karssenberg, D., van der Hilst, F., Faaij, A., 2012. Spatio-temporal uncertainty in Spatial Decision Support Systems: A case study of changing land availability for bioenergy crops in Mozambique. Computers, Environment and Urban Systems 36 (1), 30–42.

Verstegen, J.A., Karssenberg, D., van der Hilst, F., Faaij, A.P.C., 2014. Identifying a land use change cellular automaton by Bayesian data assimilation. Environmental Modeling & Software 53, 121–136.

Virchow, D., Beuchelt, T.D., Kuhn, A., Denich, M., 2016. Biomass-Based Value Webs: A Novel Perspective for Emerging Bioeconomies in Sub-Saharan Africa. In: Gatzweiler, F.W., Braun, J. von (Eds.), Technological and Institutional Innovations for Marginalized Smallholders in Agricultural Development. Springer International Publishing, Cham, pp. 225–238.

Vlek, P., Khamzina, A., Azadi, H., Bhaduri, A., Bharati, L., Braimoh, A., Martius, C., Sunderland, T., Taheri, F., 2017. Trade-Offs in Multi-Purpose Land Use under Land Degradation. Sustainability 9 (12), 2196.

Vodouhe, G.F., O. Dossou-Yovo, H., Chadaré, F.J., Gélinas, N., E. Assogbadjo, A., Coulibaly, O., 2016. Valuing the Potential of Non-timber Forest Products in Financial Valuation of Savanna Formation in Sudanian Region. ujar 4 (5), 183–197.

Volta River Authority, 2014. Pwalugu multipurpose dam environmental and social impact assessment: Final Scoping Report, June 2014, Accra, Ghana.

Vose, J.M., Sun, G., Ford, C.R., Bredemeier, M., Otsuki, K., Wei, X., Zhang, Z., Zhang, L., 2011. Forest ecohydrological research in the 21st century: what are the critical needs? Ecohydrol. 4 (2), 146–158.

Vrebos, D., Staes, J., Vandenbroucke, T., D'Haeyer, T., Johnston, R., Muhumuza, M., Kasabeke, C., Meire, P., 2015. Mapping ecosystem service flows with land cover scoring maps for data-scarce regions. Ecosystem Services 13, 28–40.

Wang, E., Martre, P., Zhao, Z., Ewert, F., Maiorano, A., Rötter, R.P., Kimball, B.A., Ottman, M.J., Wall, G.W., White, J.W., Reynolds, M.P., Alderman, P.D., Aggarwal, P.K., Anothai, J., Basso, B., Biernath, C., Cammarano, D., Challinor, A.J., Sanctis, G. de, Doltra, J., Dumont, B., Fereres, E., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L.A., Izaurralde, R.C., Jabloun, M., Jones, C.D., Kersebaum, K.C., Koehler, A.-K., Liu, L., Müller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J.E., Palosuo, T., Priesack, E., Eyshi Rezaei, E., Ripoche, D., Ruane, A.C., Semenov, M.A., Shcherbak, I., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, P., Waha, K., Wallach, D., Wang, Z., Wolf, J., Zhu, Y., Asseng, S., 2017. The uncertainty of crop yield projections is reduced by improved temperature response functions (eng). Nature plants 3, 17102.

Wardell, A., Fold, N., 2013. Globalisations in a nutshell: Historical perspectives on the changing governance of the shea commodity chain in northern Ghana. Int J Commons 7 (2), 367-405.

Wardell, D.A., 2005. Moving the boundaries of forest and land use history: The case of Upper East Region in northern Ghana. In: Gausset, Q., Whyte, M.A., Birch-Thomsen, T. (Eds.), Beyond territory and scarcity: Exploring conflicts over natural resource management. Nordic Africa Institute; London: Global [distributor], Uppsala, Sweden, pp. 168–194.

Wardell, D.A., Lund, C., 2006. Governing Access to Forests in Northern Ghana: Micro-Politics and the Rents of Non-Enforcement. World Development 34 (11), 1887–1906.

Wardell, D.A., Reenberg, A., Tøttrup, C., 2003. Historical footprints in contemporary land use systems: forest cover changes in savanna woodlands in the Sudano-Sahelian zone. Global Environmental Change 13 (4), 235–254.

Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence drives the global displacement of land use. Global Environmental Change 23 (2), 433–438.

Wood, S.A., 2018. Nutritional functional trait diversity of crops in south-eastern Senegal. J Appl Ecol 55 (1), 81–91.

Workie, T.G., Debella, H.J., 2018. Climate change and its effects on vegetation phenology across ecoregions of Ethiopia. Global Ecology and Conservation 13, e00366.

World Health Organization, Food and Agriculture Organization of the United Nations, 2004. Vitamin and mineral requirements in human nutrition: [report of a joint FAO/WHO expert consultation, Bangkok, Thailand, 21-30 September 1998 / World Health Organization and Food and Agriculture Organization of the United Nations.], 2nd ed. ed. World Health Organization, Geneva.

Wu, X.D., Guo, J.L., Han, M.Y., Chen, G.Q., 2018. An overview of arable land use for the world economy: From source to sink via the global supply chain. Land Use Policy 76, 201–214.

Xu, X., Medvigy, D., Trugman, A.T., Guan, K., Good, S.P., Rodriguez-Iturbe, I., 2018. Tree cover shows strong sensitivity to precipitation variability across the global tropics. Global Ecol Biogeogr 27 (4), 450–460.

Yameogo, J.T., Hien, M., am Lykke, an Some, Thiombiano, A., 2011. Effet des techniques de conservation des eaux et des sols, zaï forestier et cordons pierreux, sur la réhabilitation de la végétation herbacée à l'Ouest du Burkina Faso. Int. J. Bio. Chem. Sci 5 (1).

Yegbemey, R.N., Kabir, H., Awoye, O.H.R., Yabi, J.A., Paraïso, A.A., 2014. Managing the agricultural calendar as coping mechanism to climate variability: A case study of maize farming in northern Benin, West Africa. Climate Risk Management 3, 13–23.

Yomo, M., Villamor, G.B., Aziadekey, M., Olorunfemi, F., Mourad, K.A., 2020. Climate change adaptation in semi-arid ecosystems: A case study from Ghana. Climate Risk Management 27, 100206.

8 APPENDICES

Appendix 1: Baseline share of each LULC total area covering each soil type class

	Cereals	Legumes	Maize	Rice	Grass	Perennial
Hydromorphic	0.057	0.062	0.067	0.117	0.074	0.081
Medium fertility	0.338	0.249	0.345	0.302	0.275	0.376
Low fertility	0.605	0.688	0.589	0.581	0.651	0.542
Total	1	1	1	1	1	1

Appendix 2: Table: Baseline share of each soil type class covered by each LULC class

	Cereals	Legumes	Maize	Rice	Grassland	Perennial	Total
Hydromorphic	0.108	0.091	0.039	0.239	0.178	0.263	1
Medium fertility	0.164	0.094	0.052	0.160	0.171	0.314	1
Low fertility	0.153	0.136	0.046	0.160	0.211	0.236	1

Appendix 3: FLAF scenario LULC transition probability values introduced in GISCAME to simulate LULCC on a five-year time step basis.

LULC class		**SCENARIO** *Transition probability value (%)*			**Soil rank restriction**	**Neighborhood rule**
Origin	**Target**	**CEXP**	**AFPA**	**FLAF**		
Grassland	Cereals			*6.00*	< 3	-
	Groundnut			*6.00*	< 3	-
	Maize			*8.00*	> 1	-
	Rice			*27.00*	= 3	-
	Perennial			*12.00*	-	Perennial < 4
Cereals	Grassland			*2.00*	-	-
	Perennial			*8.00*	-	-

Maize	Grassland			*2.00*	-	-
	Perennial			*8.00*	-	-
Groundnut	Grassland			*2.00*	-	-
	Perennial			*9.00*	-	-
Rice	Grassland			*2.00*	-	-
	Perennial			*10.00*	-	-
Perennial	Cereals			*4.50*	< 3	-
	Groundnut			*4.00*	< 3	-
	Maize			*7.00*	> 1	-
	Rice			*17.00*	= 3	-
	Grassland			*17.00*		

Appendix 4: AFPA scenario LULC transition probability values for all iterations between the first and sixth introduced in GISCAME to simulate LULCC on a five-year time step basis.

LULC class		**SCENARIO**			**Soil rank restriction**	**Neighborhood rule**
		Transition probability value				
Origin	**Target**	**CEXP**	**AFPA**	**FLAF**		
Grassland	Cereals		*6.50*		< 3	-
	Groundnut		*6.50*		< 3	-
	Maize		*6.50*		> 1	-
	Rice		*27.00*		= 3	-
Perennial	Cereals		*1.00*		< 3	-
	Groundnut		*1.00*		< 3	-
	Maize		*2.00*		> 1	-

	Rice		*7.50*		= 3	-

Appendix 5: AFPA scenario LULC transition probability values introduced for the seventh and eighth iteration in GISCAME to simulate LULCC on a five-year time step basis.

LULC class		**SCENARIO**			**Soil rank restriction**	**Neighborhood rule**
		Transition probability value				
Origin	**Target**	**CEXP**	**AFPA**	**FLAF**		
Grassland	Cereals		*33.00*		< 3	-
	Groundnut		*33.00*		< 3	-
	Maize		*3.00*		> 1	-
	Rice		*7.00*		= 3	-
	Perennial		*3.00*			
Cereals	Grassland		*30.00*		> 1	-
	Perennial		*15.00*		> 1	-
Maize	Grassland		*2.00*		< 3	-
	Perennial		*20.00*		< 3	-
Groundnut	Grassland		*40.00*		> 1	-
	Perennial		*20.00*		> 1	-
Rice	Grassland		*2.00*		< 3	-
	Perennial		*10.00*		< 3	-
Perennial	Cereals		*20.00*		< 3	-
	Groundnut		*20.00*		< 3	-
	Maize		*25.00*		> 1	-
	Rice		*12.50*		= 3	-

Appendix 6: CEXP scenario LULC transition probability values introduced in GISCAME to simulate LULCC on a five-year time step basis.

LULC class		**SCENARIO** *Transition probability value*			**Soil rank restriction**	**Neighborhood rule**
Origin	**Target**	**CEXP**	**AFPA**	**FLAF**		
Grassland	Cereals	*15.00*			< 3	
	Groundnut	*15.00*			< 3	
	Maize	*15.00*			> 1	
	Rice	*22.00*			= 3	
Cereals	Grassland	*4.00*			-	-
	Perennial	*5.00*			-	-
Maize	Grassland	*4.00*			-	-
	Perennial	*3.50*			-	-
Groundnut	Grassland	*5.00*			-	-
	Perennial	*5.50*			-	-
Rice	Grassland	*0.50*			-	-
	Perennial	*1.00*			-	-
Perennial	Cereals	*9.00*			< 3	
	Groundnut	*9.00*			< 3	
	Maize	*5.00*			> 1	
	Rice	*22.00*			= 3	

Appendix 7: Input values used for APSIM simulations: soil properties

		Soil type of source data		
Soil property	**Acronym in APSIM (soil layer depth)**	**Bush farm Regosol**	**Compound Regosol**	**Fluvisol**
		Fertility rank		
		1	**2**	**3**
Bulk Density	BD (0-15 cm)	1.56	1.54	1.65
	BD (15-30 cm)	1.58	1.53	1.69
Evaporation-dried soil water content	AirDry (0-15)	0.023	0.027	0.025
	AirDry (15-30)	0.077	0.075	0.079
15 bar lower limit of soil water content	LL15 (0-15)	0.046	0.054	0.049
	LL15 (15-30)	0.096	0.094	0.099
Drained upper limit of soil water content (field capacity)	DUL (0-15)	0.203	0.231	0.201
	DUL (15-30)	0.209	0.219	0.203
Saturated water content	SAT (0-15)	0.352	0.353	0.353
	SAT (15-30)	0.321	0.357	0.357
	KL (0-30)	0.07		
	XF (0-30)	1		
Soil Organic Carbon	OC % (0-15)	0.39	0.58	1.40
	OC % (15-30)	0.36	0.56	0.95
Fraction of biomass carbon	FBiom (0-15)	0.015	0.020	0.020
	FBiom (15-30)	0.001	0.020	0.020
Fraction of inert carbon	FInert (0-15)	0.350	0.350	0.350
	FInert (15-30)	0.350	0.400	0.400
C:N ratio	C:N	12	12	10.7
pH	pH 1:5 H_2O (0-15)	6.39	6.39	5.5
	pH 1:5 H_2O (15-30)	6.39	6.39	5.7
Labile Phosphorus	LabileP mg kg^{-1} (0-15)	15.0	21.0	7.6
	LabileP mg kg^{-1} (15-30)	5.2	6.2	7.6
Phosphorus Sorption Capacity	Sorption (0-15)	50	79	79
	Sorption (15-30)	75	150	150

Appendix 8: Sowing values of the APSIM simulations

Land use class: cereals

Cropping system	Crop	Cultivar	Sowing window	Sowing density	Row spacing
			date	*plants m-2*	*mm*
Monocrop	Millet	CIVT[1] ZATIB*	20th May – 19th June	2.75	1200
				5.5	900
				11	450
	Sorghum	Fadda[2] Medium*	1st June – 1th July	2.75	1200
				5.5	900
				11	450
Relay	Millet	Same as the monocrop		2.75 – 5.5	1200 600
	Sorghum	Same as the monocrop	5th June – 9th July	2.75 – 5.5	1200 600
Intercropping	Millet	Same as the monocrop	5th June – 9th July	2.75 – 5.5	1200 600
	Groundnut	Virginia bunch*		4 8	1000 700
Intercropping	Sorghum	Same as the monocrop	10th June – 10th July	2.75 – 5.5	1200 600
	Groundnut	Virginia bunch*		4 8	1000 700
Relay intercropping	Millet	Same as the monocrop	20th May – 19th June	2.75 – 5.5	1200 600
	Sorghum	Same as the monocrop	14th June – 13th July	2.75 – 5.5	1200 600
	Groundnut	Virginia bunch*	14th June – 13th July	4	1000

*Cultivar available in the APSIM default module; [1]Akponikpé, 2008; [2]Akinseye et al., 2017.

Appendix 8: cont.

Land use class: maize

Cropping system	Crop	Cultivar	Sowing window	Sowing density	Row spacing
			date	*plants m-2*	*mm*
Monocrop	Maize	Landrace[+]	10th June – 10th July	3.3	1200
		Improved landrace[+]		6.6	600
Intercropping	Maize	Same as the monocrop	14th June – 13th July	3.3	1200
				6.6	600
	Groundnut	Virginia bunch[*]		4	1000
				8	700

*Cultivar available in the APSIM default module; [+]Tachie-Obeng et al., 2013.

Land use class: groundnut

Cropping system	Crop	Cultivar	Sowing window	Sowing density	Row spacing
			date	*plants m-2*	*mm*
Monocrop	Groundnut	Virginia bunch	14th June – 13th July	4	1000
				8	700
				12	400
Intercropping	Millet Groundnut	Same as the millet/groundnut intercrop			
	Sorghum Groundnut	Same as the sorghum/groundnut intercrop			
	Maize Groundnut	Same as the maize/groundnut intercrop			

*Cultivar available in the APSIM default module.

Land use class: rice

Cropping system	Crop	Cultivar	Sowing window	Sowing density	Row spacing
			date	*plants m-2*	*mm*
Monocrop	Rice	Local* *(Oryza sativa)*	7th July	25	Undefined (direct seeding)
				75	
				100	
Intercropping	Rice	Same as the monocrop			
	Millet	Same as the monocrop	7th July	25	120
				75	40

*Cultivar available in the APSIM default module

Appendix 9: Energy (kcal) average Daily Recommended Intake per age and sex cohort, assuming medium activity levels diets of the population of Bolgatanga Municipal and Bongo districts (Jiménez Martínez and Fürst, 2021).

Population group	**Assumed body weight**	**Population**	**Percentage over total population**	**DRI person^{-1}**
< 1 year males	6	2960.4	1%	639
< 1 year females	9	2760	1%	599
1 – 4 males	12	11841.6	5%	1110
1 – 4 females	17	11040	5%	1023
5 – 9 males	21	14367	7%	1641
5 – 9 females	21	14066	6%	1503
10 – 14 males	25	13917	6%	2456
10 – 14 females	47	13760	6%	2200
15 – 18 males	49	12256	6%	3225
15 – 18 females	55	12461	6%	2488
18 – 30 males	70	16093	7%	3050
18 – 30 females	60	19047	9%	2400
30 – 60 males	70	23814	11%	2950
30 – 60 females	60	29899	14%	2350
>60 males	70	7618	4%	2450
>60 females	60	11185	5%	1950
Total population		217,254	**Average kcal DRI**	**2,227**

Appendix 10: Iron (Fe) Daily Recommended Intake per age and sex cohort, assuming 10% bioavailability diets of the population of Bolgatanga Municipal and Bongo districts (Jiménez Martínez and Fürst, 2021).

Population group	**Assumed body weight**	**Population**	**Percentage over total population**	**DRI person^{-1}**
0-6 months		2,945	1%	-
7-12 months	9	2,945	1%	9.3
1-3 years	13	17,161	8%	5.8
4-6 years	19	17,094	8%	6.3
7-10 years	28	22,595	10%	8.9
11-14 males	45	11,134	5%	14.6
11-14 females	46	11,008	5%	23.4
15-17 males	64	7,354	3%	18.8
15-17 females	56	7,477	3%	31.0
18+ males	75	52,427	24%	13.7
18-50 females	62	47,115	22%	29.4
50+ females	62	18,000	8%	11
Total population		217,254	**Average Fe DRI**	**16.26**

Appendix 11: Zinc (Zn) Daily Recommended Intake per age and sex cohort, assuming moderate zinc bioavailability diets of the population of Bolgatanga Municipal and Bongo districts (Jiménez Martínez and Fürst, 2021).

Population group	Assumed body weight	Population	Percentage over total population	DRI person^{-1}
0-6 months	6	2,945	6%	2.8
7-12 months	9	2,945	9%	4.1
1-3 years	12	17,161	12%	4.1
4-6 years	17	17,094	17%	4.8
7-9 years	25	17,060	25%	5.6
10-19 females	47	26,221	47%	7.2
10-19 males	49	26,173	49%	8.6
20-65 females	55	51,811	55%	4.9
20-65 males	65	41,941	65%	7.0
65+ females	55	8,320	55%	4.9
65+ males	65	5,584	65%	7.0
Total population		217,254	**Average Zn DRI**	**6.02**

Appendix 12: Population, nutritional (calories, iron and zinc) and fuel demand (useful biomass-based fuel energy demand) at each time step of the simulation, under slow and fast population growth scenarios.

	T0	T1	T2	T3	T4	T5	T6	T7	T8
Population (*1,000 inhabitants)									
Slow	237	250	260	267	273	279	285	290	295
Fast	240	267	295	326	359	394	432	472	515
Calories demand (*thousand million kilocalories)									
Slow	193	203	211	217	222	227	231	236	240
Fast	195	216	237	260	283	307	331	356	380
Iron demand (*million micrograms)									
Slow	1,406	1,481	1,541	1,586	1,621	1,655	1,689	1,721	1,753
Fast	1,425	1,576	1,734	1,898	2,068	2,242	2,419	2,597	2,775

Zinc demand (*million micrograms)									
Slow	520	548	570	587	600	613	625	637	649
Fast	528	583	642	703	766	830	896	962	1,027
Useful biomass-based fuel energy demand (*1,000 megajoules)									
Slow	236	248	258	266	272	278	283	289	294
Fast	239	265	294	324	357	392	430	470	513

Appendix 13: LULC-change matrices of the CEXP scenario (each iteration simulates a 5-year time span)

CEXP T0-T1	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.912	0.000	0.000	0.000	0.040	0.048
Legumes	0.000	0.896	0.000	0.000	0.050	0.054
Maize	0.000	0.000	0.928	0.000	0.037	0.035
Rice	0.000	0.000	0.000	0.983	0.007	0.010
Grassland	0.126	0.139	0.056	0.019	0.659	0.000
Perennial	0.076	0.080	0.020	0.017	0.000	0.806

CEXP T1-T2	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.897	0.010	0.005	0.002	0.040	0.047
Legumes	0.012	0.877	0.008	0.002	0.049	0.052
Maize	0.014	0.017	0.872	0.027	0.038	0.032
Rice	0.001	0.002	0.010	0.972	0.006	0.009
Grassland	0.128	0.141	0.053	0.017	0.660	0.000
Perennial	0.076	0.080	0.019	0.016	0.000	0.809

CEXP T2-T3	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.881	0.024	0.009	0.003	0.039	0.044
Legumes	0.028	0.854	0.014	0.004	0.049	0.050
Maize	0.024	0.031	0.831	0.050	0.036	0.029
Rice	0.003	0.004	0.020	0.959	0.005	0.009
Grassland	0.129	0.142	0.050	0.016	0.662	0.000
Perennial	0.076	0.080	0.018	0.016	0.000	0.810

CEXP T3-T4	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.865	0.038	0.013	0.004	0.039	0.041
Legumes	0.045	0.831	0.019	0.006	0.049	0.049
Maize	0.033	0.041	0.797	0.067	0.035	0.027
Rice	0.005	0.005	0.029	0.947	0.005	0.009
Grassland	0.130	0.143	0.048	0.015	0.663	0.000
Perennial	0.076	0.080	0.018	0.015	0.000	0.811

CEXP T4-T5	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.851	0.053	0.016	0.005	0.037	0.038
Legumes	0.062	0.812	0.023	0.007	0.048	0.048
Maize	0.038	0.049	0.775	0.079	0.034	0.025
Rice	0.006	0.007	0.036	0.937	0.005	0.009
Grassland	0.131	0.144	0.046	0.014	0.664	0.000
Perennial	0.076	0.080	0.018	0.015	0.000	0.811

CEXP T5-T6	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.928	0.000	0.000	0.000	0.036	0.036
Legumes	0.000	0.905	0.000	0.000	0.047	0.048
Maize	0.000	0.000	0.942	0.000	0.034	0.024
Rice	0.000	0.000	0.000	0.987	0.004	0.009
Grassland	0.131	0.145	0.047	0.012	0.664	0.000
Perennial	0.076	0.080	0.017	0.015	0.000	0.812

CEXP T6-T7	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.929	0.000	0.000	0.000	0.036	0.035
Legumes	0.000	0.906	0.000	0.000	0.047	0.047
Maize	0.000	0.000	0.943	0.000	0.034	0.023
Rice	0.000	0.000	0.000	0.989	0.003	0.008
Grassland	0.128	0.140	0.048	0.011	0.672	0.000
Perennial	0.076	0.080	0.018	0.016	0.000	0.810

CEXP T7-T8	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.813	0.095	0.019	0.006	0.035	0.032
Legumes	0.102	0.770	0.027	0.009	0.046	0.046
Maize	0.047	0.061	0.734	0.102	0.033	0.023
Rice	0.008	0.009	0.049	0.925	0.002	0.008
Grassland	0.129	0.142	0.048	0.011	0.669	0.000
Perennial	0.076	0.080	0.017	0.015	0.000	0.812

Appendix 13: LULC-change matrices of the CEXP scenario (each iteration simulates a 5-year timespan)

Appendix 14: LULC-change matrices of the FLAF scenario (each iteration simulates a 5-year time span)

FLAF T0-T1	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.901	0.000	0.000	0.000	0.019	0.079
Legumes	0.000	0.901	0.000	0.000	0.014	0.085
Maize	0.000	0.000	0.892	0.000	0.021	0.087
Rice	0.000	0.000	0.000	0.882	0.023	0.095
Grassland	0.046	0.049	0.022	0.020	0.766	0.078
Perennial	0.037	0.038	0.026	0.013	0.017	0.868

FLAF T4-T5	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.914	0.000	0.000	0.000	0.017	0.069
Legumes	0.000	0.914	0.000	0.000	0.012	0.075
Maize	0.000	0.000	0.903	0.000	0.019	0.078
Rice	0.000	0.000	0.000	0.901	0.020	0.079
Grassland	0.051	0.054	0.013	0.012	0.820	0.032
Perennial	0.040	0.039	0.032	0.009	0.014	0.866

FLAF T1-T2	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.904	0.000	0.000	0.000	0.019	0.078
Legumes	0.000	0.904	0.000	0.000	0.013	0.082
Maize	0.000	0.000	0.899	0.000	0.019	0.081
Rice	0.000	0.000	0.000	0.887	0.022	0.091
Grassland	0.048	0.051	0.018	0.017	0.800	0.047
Perennial	0.038	0.038	0.028	0.011	0.016	0.869

FLAF T5-T6	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.917	0.000	0.000	0.000	0.016	0.067
Legumes	0.000	0.916	0.000	0.000	0.012	0.072
Maize	0.000	0.000	0.903	0.000	0.019	0.077
Rice	0.000	0.000	0.000	0.905	0.019	0.076
Grassland	0.051	0.055	0.011	0.011	0.820	0.033
Perennial	0.040	0.039	0.032	0.009	0.013	0.867

FLAF T2-T3	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.907	0.000	0.000	0.000	0.018	0.075
Legumes	0.000	0.908	0.000	0.000	0.013	0.079
Maize	0.000	0.000	0.900	0.000	0.019	0.080
Rice	0.000	0.000	0.000	0.892	0.021	0.087
Grassland	0.049	0.053	0.015	0.014	0.811	0.038
Perennial	0.039	0.039	0.030	0.010	0.015	0.867

FLAF T6-T7	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.918	0.000	0.000	0.000	0.016	0.066
Legumes	0.000	0.919	0.000	0.000	0.012	0.070
Maize	0.000	0.000	0.905	0.000	0.019	0.077
Rice	0.000	0.000	0.000	0.910	0.018	0.072
Grassland	0.049	0.053	0.012	0.011	0.824	0.032
Perennial	0.040	0.039	0.033	0.009	0.013	0.866

FLAF T3-T4	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.911	0.000	0.000	0.000	0.018	0.072
Legumes	0.000	0.910	0.000	0.000	0.013	0.077
Maize	0.000	0.000	0.902	0.000	0.020	0.078
Rice	0.000	0.000	0.000	0.897	0.020	0.082
Grassland	0.050	0.054	0.013	0.012	0.817	0.034
Perennial	0.039	0.039	0.031	0.010	0.014	0.867

FLAF T7-T8	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.922	0.000	0.000	0.000	0.015	0.063
Legumes	0.000	0.921	0.000	0.000	0.011	0.068
Maize	0.000	0.000	0.905	0.000	0.018	0.076
Rice	0.000	0.000	0.000	0.913	0.017	0.069
Grassland	0.050	0.054	0.012	0.011	0.821	0.032
Perennial	0.040	0.040	0.033	0.009	0.013	0.865

Appendix 15: LULC-change matrices of the AFPA scenario (each iteration simulates a 5-year time span)

AFPA T0-T1	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	1.000	0.000	0.000	0.000	0.000	0.000
Legumes	0.000	1.000	0.000	0.000	0.000	0.000
Maize	0.000	0.000	1.000	0.000	0.000	0.000
Rice	0.000	0.000	0.000	1.000	0.000	0.000
Grassland	0.052	0.055	0.023	0.020	0.850	0.000
Perennial	0.008	0.008	0.008	0.005	0.000	0.971

AFPA T1-T2	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	1.000	0.000	0.000	0.000	0.000	0.000
Legumes	0.000	1.000	0.000	0.000	0.000	0.000
Maize	0.000	0.000	1.000	0.000	0.000	0.000
Rice	0.000	0.000	0.000	1.000	0.000	0.000
Grassland	0.053	0.056	0.018	0.015	0.857	0.000
Perennial	0.008	0.008	0.008	0.004	0.000	0.971

AFPA T2-T3	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	1.000	0.000	0.000	0.000	0.000	0.000
Legumes	0.000	1.000	0.000	0.000	0.000	0.000
Maize	0.000	0.000	1.000	0.000	0.000	0.000
Rice	0.000	0.000	0.000	1.000	0.000	0.000
Grassland	0.054	0.057	0.014	0.011	0.864	0.000
Perennial	0.008	0.009	0.008	0.003	0.000	0.972

AFPA T3-T4	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	1.000	0.000	0.000	0.000	0.000	0.000
Legumes	0.000	1.000	0.000	0.000	0.000	0.000
Maize	0.000	0.000	1.000	0.000	0.000	0.000
Rice	0.000	0.000	0.000	1.000	0.000	0.000
Grassland	0.054	0.056	0.010	0.009	0.871	0.000
Perennial	0.008	0.009	0.008	0.003	0.000	0.973

AFPA T4-T5	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	1.000	0.000	0.000	0.000	0.000	0.000
Legumes	0.000	1.000	0.000	0.000	0.000	0.000
Maize	0.000	0.000	1.000	0.000	0.000	0.000
Rice	0.000	0.000	0.000	1.000	0.000	0.000
Grassland	0.055	0.058	0.008	0.006	0.873	0.000
Perennial	0.009	0.009	0.008	0.002	0.000	0.972

AFPA T5-T6	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	1.000	0.000	0.000	0.000	0.000	0.000
Legumes	0.000	1.000	0.000	0.000	0.000	0.000
Maize	0.000	0.000	1.000	0.000	0.000	0.000
Rice	0.000	0.000	0.000	1.000	0.000	0.000
Grassland	0.055	0.059	0.006	0.005	0.876	0.000
Perennial	0.009	0.009	0.008	0.002	0.000	0.973

AFPA T6-T7	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.792	0.059	0.005	0.003	0.092	0.049
Legumes	0.076	0.740	0.007	0.005	0.112	0.060
Maize	0.014	0.016	0.758	0.075	0.010	0.127
Rice	0.003	0.004	0.030	0.942	0.003	0.018
Grassland	0.277	0.264	0.012	0.010	0.435	0.002
Perennial	0.055	0.045	0.046	0.016	0.001	0.837

AFPA T7-T8	Cereals	Legumes	Maize	Rice	Grassland	Perennial
Cereals	0.780	0.076	0.006	0.003	0.082	0.054
Legumes	0.083	0.757	0.007	0.005	0.094	0.054
Maize	0.017	0.020	0.746	0.080	0.006	0.131
Rice	0.004	0.005	0.031	0.940	0.002	0.018
Grassland	0.302	0.316	0.009	0.008	0.363	0.002
Perennial	0.062	0.063	0.054	0.017	0.000	0.804

Appendix 16: Biomass yields simulated with APSIM of the LULCs under their corresponding management (as described in section 3.3.3 and table 3.6) and associated yield benefits used in the regional extent assessments.

Soil: 1 = Low soil fertility, 2 = Medium soil fertility, 3 = Hydromorphic; ReturnSoil = biomass returned to the soil at the beginning of each cropping season.

LULC	Soil	N *kg ha^{-1}*	Total biomass *kg ha^{-1}*	Grain yield *kg ha^{-1}*	Stem harvest *kg ha^{-1}*	Leaves harvest *kg ha^{-1}*	ReturnSoil *kg ha^{-1}*	Caloric yield *persons ha^{-1}*	Zinc yield *persons ha^{-1}*	Iron yield *persons ha^{-1}*	Fuel yield *MJ ha^{-1}*	Feed yield *MEruminants ha^{-1}*
Cereals	1	0	3,109	920	1,306	630	0	1.79	3.19	2.10	20,787	5,857
Cereals	2	0	3,933	1,142	1,677	812	0	2.22	3.99	2.63	26,605	7,553
Cereals	3	0	3,674	1,111	1,599	731	0	2.19	3.53	2.29	25,753	6,797
Legumes	1	0	2,032	769	556	453	0	2.24	6.65	5.57	0	7,325
Legumes	2	0	3,804	1,442	1,057	847	0	4.20	12.46	10.44	0	13,823
Legumes	3	0	1,722	654	464	374	0	1.91	5.65	4.74	0	6,090
Cereals	1	5	5,770	1,411	665	294	0	3.25	5.80	5.28	9,071	3,613
Cereals	2	5	6,488	1,507	775	330	0	3.38	6.10	5.33	10,890	3,850
Cereals	3	5	9,218	2,001	1,146	470	0	4.35	7.70	6.36	16,732	5,129
Maize	1	5	2,517	1,067	1,030	420	0	1.77	2.67	2.52	15,965	3,306
Maize	2	5	3,833	1,686	1,529	619	0	2.80	4.22	3.98	23,693	4,875
Maize	3	5	4,822	2,550	1,622	650	0	4.24	6.38	6.02	25,134	5,122
Legumes	1	15	6,393	2,401	464	371	749	7.00	20.76	17.40	0	6,060
Legumes	2	15	7,611	2,868	551	437	889	8.36	24.80	20.78	0	7,179
Legumes	3	15	5,510	2,083	391	312	643	6.07	18.01	15.09	0	5,106
Legumes	1	20	7,527	3,733	226	250	711	8.13	7.78	10.43	779	4,435
Legumes	2	20	7,830	3,946	231	254	728	8.55	8.05	10.81	783	4,518
Legumes	3	20	7,949	4,012	234	258	738	8.70	8.22	11.03	786	4,581
Maize	1	20	7,527	3,733	226	250	711	8.13	7.78	10.43	779	4,435
Maize	2	20	7,830	3,946	231	254	728	8.55	8.05	10.81	783	4,518
Maize	3	20	7,949	4,012	234	258	738	8.70	8.22	11.03	786	4,581
Rice	1	20	5,765	1,672	590	305	2,686	2.76	4.18	2.39	9,203	1,893
Rice	2	20	6,848	2,098	680	368	3,145	3.46	5.25	3.00	10,608	2,283
Rice	3	20	8,488	2,854	802	451	3,757	4.71	7.14	4.09	12,505	2,796
Cereals	1	50	7,232	1,630	882	364	1,050	3.54	6.38	5.28	12,796	4,016
Cereals	2	50	8,146	1,718	1,025	414	1,205	3.66	6.65	5.34	15,105	4,407
Cereals	3	50	10,935	2,397	1,377	561	1,601	5.22	8.94	7.37	20,174	6,102
Rice	1	50	6,136	2,171	2,498	1,293	2,844	3.89	1.18	2.73	38,873	2,038
Rice	2	50	9,548	3,370	4,000	1,990	4,493	6.18	5.29	5.58	61,982	3,739
Maize	1	100	7,863	3,975	228	253	729	8.58	8.04	10.79	788	4,482
Maize	2	100	7,937	4,006	233	256	737	8.66	8.14	10.92	790	4,556
Maize	3	100	7,963	4,022	233	257	739	8.71	8.20	11.01	791	4,569
Rice	1	150	11,693	4,780	1,092	573	5,184	8.56	2.59	6.00	61,111	3,609
Rice	2	150	12,033	5,169	1,086	564	5,148	9.26	2.80	6.49	61,015	3,551
Rice	3	150	12,805	5,526	1,144	612	5,459	9.90	2.99	6.94	55,776	3,857

Appendix 17: Simulated aboveground biomass (AGB) growth of (semi-)natural woody vegetation stands in South Sudanian savanna zone of West Africa

Regeneration age	**Wood AGB**	**MAI**	**CAI**
years	*t ha^{-1}*	*t ha^{-1} year^{-1}*	*t ha^{-1}*
5	8.59	1.72	1.70
10	16.49	1.65	1.50
15	23.46	1.56	1.32
20	29.60	1.48	1.17
25	35.01	1.40	1.03
30	39.77	1.33	0.90
35	43.97	1.26	0.80
40	47.65	1.19	0.70
45	50.89	1.13	0.62
50	53.74	1.07	0.54
55	56.25	1.02	0.48
60	58.45	0.97	0.42
65	60.38	0.93	0.37
70	62.08	0.89	0.32
75	63.57	0.85	0.28
80	64.88	0.81	0.25
85	66.03	0.78	0.22
90	67.03	0.74	0.19
95	67.92	0.71	0.17
100	68.70	0.69	0.15
105	69.38	0.66	0.13
110	69.98	0.64	0.11
115	70.50	0.61	0.10

Appendix 18: Potential useful energy supply (in GJ) of the region's harvested wood in cooking devices with different biomass-to-useful heat conversion efficiencies

Raw wood biomass (Traditional cook stoves)

	T1	T2	T3	T4	T5	T6	T7	T8
CEXP	31,425	62,456	69,478	73,495	73,097	21,733	35,421	114,423
FLAF	45,351	57,503	67,631	74,648	81,145	151,880	88,722	91,421
AFPA	9,701	12,081	13,596	14,771	24,789	16,935	104,153	61,151

Raw wood biomass (Efficient cook stoves)

	T1	T2	T3	T4	T5	T6	T7	T8
CEXP	52,375	104,094	115,797	122,491	121,829	36,221	59,034	190,705
FLAF	75,585	95,839	112,719	124,413	135,242	253,133	147,870	152,368
AFPA	16,169	20,134	22,659	24,618	41,315	28,225	173,588	101,919

Wood pellets (Micro-gasifier) *

	T1	T2	T3	T4	T5	T6	T7	T8
CEXP	79,610	158,222	176,012	186,187	185,180	55,057	89,732	289,871
FLAF	114,889	145,675	171,333	189,108	205,567	384,763	224,762	231,599
AFPA	24,577	30,604	34,442	37,419	62,798	42,902	263,854	154,916

* Energy consumed during the pelletization process has already been subtracted

Appendix 19: Potential useful energy supply (in GJ) of the region's harvested crop residues in cooking devices with different biomass-to-useful heat conversion efficiencies

Unprocessed crop stalks at higher rates of field crop residue removal

	T1	T2	T3	T4	T5	T6	T7	T8
CEXP	205,142	215,814	226,486	237,157	247,829	258,501	269,173	279,845
FLAF	191,748	189,027	186,305	183,584	180,862	178,140	175,419	172,697
AFPA	202,987	211,504	220,020	228,537	237,054	245,570	254,087	262,604

Unprocessed crop stalks biomass at lower rates of field crop residue removal

	T1	T2	T3	T4	T5	T6	T7	T8
CEXP	198,576	202,683	206,789	210,895	215,002	219,108	223,214	227,320
FLAF	185,120	175,769	166,419	157,069	147,718	138,368	129,017	119,667
AFPA	197,255	200,040	202,825	205,610	208,396	211,181	213,966	216,751

Crop stalks' pellets at higher rates of field crop residue removal (Micro-gasifier) *

	T1	T2	T3	T4	T5	T6	T7	T8
CEXP	726,972	764,790	802,609	840,427	878,245	916,064	953,882	991,700
FLAF	679,509	669,864	660,219	650,574	640,929	631,285	621,640	611,995
AFPA	719,335	749,516	779,697	809,878	840,059	870,240	900,421	930,602

* Energy consumed during the pelletization process has already been subtracted

Crop stalks' pellets at lower rates of field crop residue removal (Micro-gasifier) *

	T1	T2	T3	T4	T5	T6	T7	T8
CEXP	703,705	718,257	732,809	747,360	761,912	776,464	791,015	805,567
FLAF	656,018	622,883	589,747	556,612	523,476	490,341	457,205	424,070
AFPA	699,023	708,893	718,762	728,632	738,502	748,371	758,241	768,111

* Energy consumed during the pelletization process has already been subtracted

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Marcos Jiménez Martínez

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