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Life cycle assessment of carbon and energy balances in Jatropha production systems of Burkina Faso

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ABSTRACT

Modern bioenergy offers several advantages to Burkina Faso, a country that is heavily dependent on imported fossil fuel and greatly relying on traditional biomass use. In this context, *Jatropha curcas* has been recently introduced as a low-maintenance energy crop with the potential to increase energy security while contributing to land rehabilitation and climate change mitigation. This study identified *J. curcas* cultivation systems practiced in Burkina Faso and analyzed their biomass dynamics and carbon (C) accrual over time as well as soil-C stocks. These data, together with the information on *J. curcas* seed transformation processes, were integrated in a life cycle assessment (LCA) of the greenhouse gas (GHG) emission and energy-saving potential of the complete biofuel production pathways.

The studied *J. curcas* systems include interplanting with annual crops, intensely managed plantations, afforestation of marginal land, plantings along contour stone walls, and traditional living fences. Destructive above- and below-ground biomass determination enabled the identification of growth stages and development of allometric equations relating total shoot and root biomass with the stem diameter that showed very good fits ($R^2>0.9$). Empirical growth models related woody biomass and tree age by a three-parametric non-linear logistic function. According to the model results, the biomass production of *J. curcas* plants peaked between the 10th and 15th year after planting, with intercropping and intensely managed systems showing the highest stock (21 t ha^{-1}). Afforestation systems on marginal land had the lowest biomass stocks (<0.1 t ha^{-1}), and could not be modeled due to drastic mortality at an early age in the absence of maintenance. Soil analysis did not reveal a clear trend of soil organic carbon (SOC) dynamics over time when comparing the soil carbon status in 4-year-old *J. curcas* sites with that in the reference cropland. Only *J. curcas* living fences exhibited significantly higher SOC stocks in the top 20 cm soil based on a chronosequence study covering 20 years of *J. curcas* cultivation.

All *J. curcas* production pathways showed GHG emission reductions and energy savings of up to 82% and 85%, respectively, as opposed to fossil fuel. Decentralized production of straight vegetable oil and its consumption in stationary diesel engines showed the best performance. However, *J. curcas* plantation systems had very low land-use efficiency (6.5-9.5 GJ ha^{-1}) and thus a high land-use replacement potential. Carbon-stock gains were attained when introducing *J. curcas* on croplands. However, the displacement of agricultural activities to other areas can indirectly result in C losses. Human energy accounted for 24% of the total energy balance, indicating high manual labor requirements in small-scale *J. curcas* systems. Monetary valuation of C offsets via carbon trading schemes showed returns below US$ 350 over 20 years.

Overall, *J. curcas* biofuel production can contribute to climate change mitigation and national energy independency. However, due to low land-use efficiency, high labor requirements and the unsuccessful cultivation on marginal land, *J. curcas* becomes a direct competitor with food crops and is a not viable option for smallholder farmers. Whereas *J. curcas* cultivation is yet to be intensified through improved plant material and optimized agronomic management, the traditional hedge systems are a preferable option for seed production as they offer additional benefits of erosion control and field protection to farmers' fields.

Analyse du cycle de vie du carbone et de l’énergie dans les systèmes de la production de Jatropha au Burkina Faso

RESUME

Les bioénergies modernes présentent plusieurs avantages pour le Burkina Faso, un pays fortement dépendant des hydrocarbures importés et s’appuyant largement sur l’utilisation traditionnelle de la biomasse. Dans ce contexte, le *Jatropha curcas* est devenu populaire, réputé comme une culture énergétique demandant peu de soins et ayant le potentiel de restaurer les sols marginaux, tout en contribuant à améliorer la sécurité énergétique et à atténuer les changements climatiques. Dans la présente étude, les systèmes de culture de *J. curcas* existants au Burkina Faso ont été identifiés et étudiés quant aux dynamiques de la biomasse et du carbone (C) dans les sols. Combinées à des informations sur la transformation des graines, ces données ont été intégrées dans une analyse du cycle de vie (ACV) pour calculer les émissions de gaz à effet de serre (GES) et le potentiel d'économie d'énergie de la chaine de production de biocarburants dans son ensemble.

Cinq systèmes de culture de *J. curcas* ont été identifiés: l’association avec des cultures annuelles, les plantations avec une gestion intensive, le reboisement de sols marginaux, les haies vives traditionnelles et les haies le long des codons pierreux. Des mesures directes de la biomasse aérienne et souterraine ont permis d’identifier les différentes phases de croissance et de développer des équations allométriques reliant la biomasse aérienne et souterraine au diamètre du tronc ($R^2>0.9$). En outre, des modèles de croissance empiriques ont été développés pour chaque système, prédisant la production de biomasse aérienne en fonction de l’âge. Les résultats de ces modèles montrent que la production de biomasse est maximale entre la 10$^{\text{ème}}$ et la 15$^{\text{ème}}$ année après la plantation. Les plus gros stocks de biomasse, jusqu’à 21 t ha^{-1}, sont observés dans les systèmes en association avec des cultures annuelles et dans les plantations intensives alors que le système de reboisement des sols marginaux présente la production de biomasse la plus faible (0.1 t ha^{-1}). A cause du taux de mortalité élevé des jeunes plants, ce système n’a pas pu être modélisé.

Les analyses de sol comparant les sols sous *J. curcas* depuis quatre ans avec les sols sous cultures annuelles n’ont pas montré de dynamique évidente du C dans le sol. Une chronoséquence de 20 ans pour une haie vive a cependant permis de mettre en évidence une augmentation significative du C dans les premiers 20 cm du sol.

Pour toutes les filières de production de *J. curcas*, l’analyse de cycle de vie a montré des réductions de GES jusqu’à 82% et une très haute efficacité énergétique par rapport aux carburants fossiles. La production locale d’huile végétale et son utilisation dans les moteurs stationnaires affiche la meilleure performance. Néanmoins, les plantations de *J. curcas* montrent une efficacité très faible en termes d'utilisation des terres (6.5-9.5 GJ ha^{-1}), augmentant ainsi le potentiel pour un changement d’utilisation du sol. Bien que les stocks de C augmentent lors de l’intégration du *J. curcas* dans les terres en cultures, le déplacement d’activités agricoles pourrait indirectement résulter

à un changement d’utilisation du sol et ainsi à une diminution du C. L’énergie humaine représentait 24% du bilan énergétique global, indiquant un besoin de main d'œuvre très élevé dans les systèmes de *J. curcas* à petite échelle. L'évaluation monétaire des crédits carbone pour le marché international ne promettait pas de recettes significatives.

Globalement, il a pu être démontré que la production de biocarburant de *J. curcas* pouvait contribuer à l’atténuation des changements climatiques et à l’indépendance énergétique. Cependant, l’inefficacité de l'utilisation de terres, le besoin de main d'œuvre très élevé et l’inaptitude des terres marginales pour la production de *J. curcas* mettent cette plante en concurrence directe avec les cultures alimentaires et la rendent donc non viable pour les petits agriculteurs. Tant que la culture de *J. curcas* n’est pas intensifiée grâce à des améliorations variétales et à une gestion agricole optimisée, les haies vives sont préférables: elles offrent divers bénéfices aux agriculteurs et contribuent à l’approvisionnement énergétique des régions rurales.

Ökobilanzierung der Kohlenstoff- und Energiebilanzen von Jatropha Produktionssystemen in Burkina Faso

KURZFASSUNG

Moderne Bioenergie stellt für Burkina Faso eine attraktive Alternative zu Erdölimporten und traditioneller Biomassenutzung dar. In diesem Kontext wurde *Jatropha curcas* bekannt als eine sehr anspruchslose Energiepflanze, dessen Anbau zur Rekultivierung von marginalen Standorten, zur nationalen Energieversorgung und zum Klimaschutz beitragen kann. Im Rahmen der vorliegenden Forschungsarbeit wurden existierende *J. curcas* Systeme in Burkina Faso identifiziert und auf ihre Biomasse- und Bodenkohlenstoff-Dynamik untersucht. Zusammen mit Informationen zur Weiterverarbeitung der Samen wurden alle Daten in einem Life Cycle Assessment (LCA) zur Berechnung der Treibhausgasemissionen und des Energieeinsparungspotenzials der *J. curcas* Bioenergie-Produktionssysteme zusammengeführt.

Insgesamt konnten fünf *J. curcas* Systeme identifiziert werden: Mischanbau mit einjährigen Kulturen, intensiv bewirtschaftete Plantagen, Aufforstung von marginalen Flächen, traditionelle Lebendhecken und Hecken entlang von Kontursteinmauern. Durch direkte Messungen von ober-und unterirdischer Biomasse der *J. curcas* Bäume konnten unterschiedliche Wachstumsphasen definiert und allometrische Modelle zur indirekten Biomassebestimmung entwickelt werden. Es zeigte sich eine sehr starke ($R^2>0.9$) allometrische Beziehung zwischen sowohl Holz- als auch Wurzelmasse und Stammdurchmesser. Des Weiteren konnten empirische Wachstumsmodelle zur Vorhersage der Holzbiomasse in Abhängigkeit des Alters erstellt werden. Entsprechend der Modelle erreicht die Biomasseproduktion ihren Höhepunkt zwischen dem zehnten und fünfzehnten Wachstumsjahr. *Jatropha curcas* im Mischanbau und in intensiv bewirtschafteten Plantagen erreichte die höchsten Biomassewerte (21 t ha^{-1}), während das Aufforstungssystem mit einer Biomasse von weniger als 0.1 t ha^{-1} die geringsten Werte aufwies. Aufgrund der hohen Mortalität der jungen Bäume auf den marginalen Standorten konnte das Biomassewachstum dieses Systems nicht modelliert werden. Vergleichende Bodenanalysen von vier Jahre alten *J. curcas* Standorten mit Flächen unter einjährigen Kulturen ergaben keine eindeutige Tendenz von Veränderungen des Bodenkohlenstoffs. Nur in einer Chronosequenz von Böden unter Lebendhecken über 20 Jahre konnte ein signifikanter Anstieg des Kohlenstoffs in den ersten 20 cm des Bodens festgestellt werden.

Für alle Produktionswege der *J. curcas* Bioenergie konnten eine bis zu 82% hohe Verringerung der Treibhausgasemissionen und bis zu 85% Energieeinsparungen im Vergleich zu fossilen Brennstoffen festgestellt werden. Die dezentrale Produktion von Pflanzenöl und dessen Verbrauch in stationären Dieselmotoren zeigte die besten Ergebnisse. Eine sehr geringe Landnutzungseffizienz (6.5-9.5 GJ ha^{-1}) der *J. curcas* Plantagensysteme erhöhen jedoch den Druck auf andere Landnutzungsformen. Auch wenn die Integration von *J. curcas* in landwirtschaftliche Systeme zu einer größeren Kohlenstoffspeicherung führt, kann die Verdrängung der Nahrungsmittel von den

Flächen zu indirekten Landnutzungsänderungen und dortigen Kohlenstoffverlusten führen. Zusätzlich bedarf die Kultivierung von *J. curcas* in kleinbäuerlichen Systemen einen sehr hohen körperlichen Arbeitsaufwand, der 24% der gesamten Energiebilanz konstituiert. Eine monetäre Bewertung der Kohlenstoffeinsparungen durch dessen Handel auf internationalen Märkten versprach nur geringfügige Erträge.

Zusammenfassend kann gesagt werden, dass *J. curcas* Systeme in Burkina Faso sowohl zum Klimaschutz als auch zur Energiesicherung beitragen können. Durch die sehr geringe Landnutzungseffizienz, den hohen Arbeitsaufwand und die fehlende Ertragsleistung auf marginalen Standorten wird *J. curcas* jedoch zu einer direkten Konkurrenz zu Nahrungsmitteln und stellt keine praktikable Option für Kleinbauern dar. Solange der Anbau von *J. curcas* durch verbessertes Pflanzmaterial und optimiertes Management nicht intensiviert werden kann, sollte der Anbau von *J. curcas* in Heckensystemen vorgezogen werden. Diese bieten vielfältige Vorteile für die Bauern während die Samenproduktion zur Energieversorgung in ländlichen Gebieten beitragen kann.

The Dissertation's Footprint

Dealing with carbon, bioenergy, and ecological sustainability over four years, I felt the need to know the carbon footprint of my dissertation. I summed up the miles spent in airplanes flying back and forth to Burkina Faso, the hours in a pick-up driving through the African bush, and all the Jatropha trees I cut.

I came up with a total 14 t CO_2 emitted to the atmosphere through my dissertation[1]. As you will understand after reading the dissertation, approx. 200 m of Jatropha living fence or half a hectare Jatropha plantation would be needed to offset this amount of carbon. Currently, I am not in the position to undertake the plantings and maintenance, therefore I decided to buy my way out. I donated € 322 from the *Dreyer research budget* to *atmosfair gGmbH* who is investing money in energizing projects worldwide. Now I can say that the preparation of my dissertation was almost carbon neutral!

However, the achievements resulting from my dissertation shouldn't be neutral but hopefully contribute to a sound policy of Jatropha biofuel production fulfilling most of the promises associated with Jatropha.

Enjoy reading this dissertation!

Sophia Emilia Baumert

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[1] Not included are daily food intake for brain activity, daily public transportation to ZEF, electricity and heating expenses in the office, paper paper paper, and thousands of mouse clicks browsing through the internet.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEZ	Agro-ecological zone
AGB	Above-ground biomass
BGB	Below-ground biomass
C	Carbon
CDM	Clean development mechanism
CED	Cumulative total energy demand
CH_4	Methane
CI	Confidence interval
CO_2	Carbon dioxide
D	Diameter at stem base
FGD	Focus group discussion
GHG	Greenhouse gas
GJ	Giga Joule
GWP	Global warming potentials
H	Height
iLUC	Indirect land-use change
JME	Jatropha methyl ester
K	Potassium
Kgoe	Kilogram(s) of oil equivalent
LCA	Life cycle assessment
LHV	Lower heating value
LUC	Land-use change
MJ	Mega Joule
N	Nitrogen
NER	Net energy ratio
NGO	Non-governmental organization
N_2O	Nitrous oxide
OM	Organic material
P	Phosphorus
PD	Plant density
RED	Renewable energy directive
RD	Relative difference
RHI	Relative height increment
RMSE	Root mean squared error
RSR	Root-shoot ratio
SE	Standard error
SOC	Soil organic carbon
SVO	Straight vegetable oil
SWC	Soil and water conservation
TOC	Total organic carbon

1 INTRODUCTION

1.1 Problem setting

Sub-Saharan Africa is home to the world's poorest population with 90% living in rural areas and depending on subsistence agriculture for their livelihoods (Bationo and Buerkert 2001). The high levels of poverty are, amongst others, reflected in the energy consumption pattern, with a very low share of modern energy and a high reliance on traditional biomass energy (Karekezi 2002) accounting for more than 80% of the primary energy supply (IEA 2006). With an annual population growth rate of 2.5% (World Bank 2012) the need for energy is constantly increasing, leading to highly unsustainable biomass consumption (Bugaje 2006; Tatsidjodoung et al. 2012). Trees, an essential element for the stability of ecosystems, are removed without providing the opportunity for re-growth (Rutz and Janssen 2012), and the energetic use of crop residues limits the re-cycling of soil nutrients, which leads to declining soil fertility (Lal 2006). Particularly in the low-input agricultural systems where productivity-enhancing technologies are largely out of reach, soil quality is key to agricultural production (Vlek 2005). Declining soil fertility and land degradation are among the major human-induced problems currently facing agricultural production throughout Sub-Saharan Africa (Katyal and Vlek 2000, Zida 2011).

Growing public awareness of the energy dilemma prevailing in Sub-Saharan Africa has directed international attention on the use of modern bioenergy[2] (Ndong et al. 2009). Particularly in Africa, where one-third of the total land is potentially available for biofuel production (Cai et al. 2010) and a large share of the population is involved in agriculture, biofuel production can offer many benefits to the rural poor (Blin et al. 2013). Biofuels could provide resource-poor countries with a means to invest in their own rural areas instead of exporting their capital to purchase fossil fuel. Moreover, the positive correlation between economic development and access to energy resources is long recognized (Karekezi 2002; Bugaje 2006). Internationally, energy crops can contribute to climate change mitigation through carbon sequestration in biomass and

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[2] Modern bioenergy is defined as bioenergy relying on sustainably used biomass as opposed to traditional biomass use depleting natural resources (Goldemberg and Coelho 2004).

soil and through substitution for fossil fuels or unsustainably harvested fuel wood (Bass et al. 2000). The carbon offsets can then be monetarily valuated via carbon trading mechanisms (e.g., Clean Development Mechanism (CDM), Voluntary Carbon Markets), which is often cited as an additional income opportunity for African farmers (Bryan et al. 2008). However, also in Sub-Saharan Africa, there are risks associated with bioenergy production such as negative impacts on ecosystems (Ndong et al. 2009), competition with food production, and increased food prices (von Braun 2008).

In this context, the tree species *Jatropha curcas* has become popular as an energy crop based on early claims of high productivity under low water, nutrient and management requirements. According to the claims, the crop can thrive on marginal land in semi-arid regions, contributes to land reclamation and does not compete with food crops for scarce resources (e.g., Heller 1996; Francis et al. 2005; Jongschaap et al. 2007; Henning 2009; Achten et al. 2010b; Contran et al. 2013).

1.2 *Jatropha curcas* and its relevance for Burkina Faso

Jatropha curcas Linnaeus has its origin in Central America and Mexico and was probably imported by the Portuguese seafarers to the Cape Verde Islands and Guinea Bissau in the 16th century and then distributed over wider parts of Africa and Asia (Heller 1996; Domergue and Pirot 2008; Henning 2009). *Jatropha curcas* belonging to the genus *Euphorbiaceae* is a small tree that produces fruits containing seeds with an oil fraction of 30 to 35% (Jongschaap et al. 2007; Achten et al. 2008). The oil is toxic and not edible for humans and animals, but it has a very good burning quality (Jongschaap et al. 2007; Blin et al. 2013). The tree is highly adaptable to a variety of growing conditions (the *J. curcas* belt is roughly situated between 30°N and 35°S (Jongschaap et al. 2007)) and is expected to yield over 50 years with a gestation period of 3 to 4 years (Jongschaap et al. 2007; van Eijck et al. 2010). Traditionally, *J. curcas* is planted as living fences protecting fields from animals and contributing to erosion control. The oil is originally used for the production of soap and for medicinal purposes. With the rising interest in biofuel, the use of the oily seeds as an energy feedstock has internationally come into focus. The oil can be mechanically extracted with a simple technology and used directly as straight vegetable oil (SVO) in diesel engines (Blin et al. 2013) such as in national power stations and can replace imported fossil fuel (Nonyarma and Laude 2010; Tatsidjodoung et al. 2012). Moreover, the use of SVO offers the possibility of decentralized production and consumption (e.g., for agricultural activities, power generation, rural industry, and cooking) avoiding long transportation distances and complicated transformation processes as is the case with biodiesel (FACT Foundation 2009; Blin et al. 2013). These decentralized schemes are particularly popular in West African countries with severe energy poverty in rural areas (Blin et al. 2013).

Owing to its great potential, *J. curcas* became idealized as a solution for energy-poor countries, and triggered large-scale investments (Achten et al. 2010b) with cultivation hotspots in India, Zambia, Madagascar, Tanzania, Brazil, Mexico and Ghana (Gao et al. 2011). However, most *J. curcas* projects were not scientifically grounded, but rather driven by over-optimistic claims leading to manifold project failures (van Eijck et al. 2010). By now, many lessons have been learnt showing that the full potential of this tree species is not easily exploitable and particularly not simultaneously applicable (Coltran et al. 2013). *Jatropha curcas* is still an undomesticated plant with a great variability in productivity (e.g., Achten et al. 2010c; Liyama et al. 2012; Contran et al. 2013). Under the current knowledge status, a definition of site-specific agronomic management regimes for optimal production levels is impossible (Singh et al. 2013) leading to sub-optimal management practices and low yields (Liyama et al. 2012, Singh et al. 2013). Moreover, it has been realized that trees grown on marginal soils with marginal inputs will produce marginal yields (Lal 2006; Elbehri et al. 2013), thus trading off marginal land restoration and biofuel production. Recent studies found out that *J. curcas* can survive in arid conditions due to its drought-avoidance strategy (Krishnamurthy et al. 2012; Rao et al. 2012). However, the highest productivity levels are reached under humid climates (Maes et al. 2009). Consequently, economically driven *J. curcas* cultivation takes place in regions with good soils and good rainfall conditions where it thus competes with food production (Tatsidjodoung et al. 2012). Finally, the contribution of *J. curcas* cultivation to rural development and rural energy access is not self-evident, and strongly depends on the applied production system and its integration of the rural population (Francis et al. 2005; Wani et al. 2006, Achten et al. 2010b; Dyer et al. 2012).

Since 2007, *J. curcas* has been one of the most strongly promoted biofuel crops in Burkina Faso (Tatsidjodoung et al. 2012). Studies assessing the land availability for biofuel production in semi-arid regions excluding agricultural land and land with high biodiversity (Cai et al. 2011; Wicke et al. 2011; Dauber et al. 2012) showed substantial land availability in Burkina Faso (Wicke et al. 2011). The contribution of *J. curcas* cultivation to the national energy supply and to the amelioration of the soil resources could thus be significant. Understanding the potential and challenges of *J. curcas*, the Burkinabe government began to design a national biofuel policy in 2009, prioritizing food security, environmental and biodiversity protection, and inclusion of small-scale farmers in biofuel activities (MMCE 2009; Nonyarma and Laude 2010; Tatsidjodoung et al. 2012). In order to avoid environmentally fatal land-use change and competition between food and energy, *J. curcas* should be preferably grown in combination with annual crops or on soils low in productivity (MMCE 2009). The allocation of land to large-scale plantations was regarded with caution (MMCE 2009).

1.3 Research needs

Overall, the productive capacity of *J. curcas* has been rarely studied in Burkina Faso (Sop et al. 2012), and the effects of different production models on people and environment have not yet been evaluated (Tatsidjodoung et al. 2012). It is generally agreed that sustainable bioenergy systems must provide net energy gains, have environmental and local socio-economic benefits, and produce bioenenergy in large quantities without impacting food supplies (Fritsche et al. 2005; Hill et al. 2006; Mangoyana 2008, Elbehri et al. 2013). Further, the association of *J. curcas* with carbon-neutral biofuel and climate change mitigation remains to be justified for the production systems in Burkina Faso in view of agro-inputs in energy crop production and impacts bound to land-cover change from ecosystems high in carbon stock to energy crops (Fargione et al. 2008). Carbon-offset calculations also provide evidence of the relevance of international carbon trading for Burkina Faso.

Life cycle assessment (LCA) is a common tool to evaluate environmental sustainability of biofuel production systems in terms of energy efficiency and carbon neutrality (Gnansounou et al. 2009). To date, no LCA has been conducted for *J. curcas* biofuel production in Burkina Faso, and *J. curcas* initiatives are proceeding without knowledge of case-specific environmental consequences. Ndong et al. (2009) presented a study for West Africa, but they did not include carbon stock changes in biomass and soil resulting from land conversion, and assumed more than 50% higher seed yields than actually observed in Burkina Faso. Over-optimistic *J. curcas* yield estimations were named by Gasparatos et al. (2012) as a major error source in LCAs. Achten et al. (2012) criticized the absence of carbon stock changes in biomass and soil in most LCA calculations, although bioenergy-induced land-use and land-cover changes are known to have high impacts on environmental sustainability (Fritsche et al. 2005). For *J. curcas* systems, this means that a better estimation of carbon stocks is needed as already called for by Reinhardt et al. (2007). Moreover, investigations of the soil carbon dynamics under *J. curcas* systems are important for the assessment of their claimed land rehabilitation potential.

Long-term observations of temporal biomass dynamics in *J. curcas* systems are out of reach, as most *J. curcas* systems are in their infancy. However, the development of empirical growth models by fitting chronosequences of trees differing in age could provide biomass predictions over time within a very short period of time (Walker et al. 2010). The establishment of allometric relationships between biomass and stem diameter in *J. curcas* could further facilitate non-destructive tree biomass estimation. The chronosequence approach is also widely applied for the detection of dynamics in soil organic carbon (Walker et al. 2010). Some studies have investigated allometric relationships and biomass dynamics in *J. curcas* (Ghezehei et al. 2009; Achten et al. 2010a; Behera et al. 2010; Rajaona et al. 2011; Hellings et al. 2012), albeit based on a modest sample size. No such research has been conducted in West Africa, and only few studies investigated changes in soil after afforestation with *J. curcas* (Ogunwole et al. 2008; Soulama 2008).

1.4 Research objectives

Considering the lack of scientific knowledge and the expanding cultivation of *J. curcas*, the aim of this dissertation is to assess the environmental sustainability of *J. curcas* biofuel production systems in Burkina Faso. To this end, the carbon- and energy-saving potential of existing *J. curcas* production systems is analyzed under consideration of carbon sequestration in biomass and soil. The findings are expected to support decision making for environmentally sound *J. curcas* production that can contribute to energy security, climate change mitigation and rural development, also beyond Burkina Faso's borders.

Accordingly, the main research objectives were to:

(i) Characterize and classify *J. curcas* cultivation systems prevailing in Burkina Faso;

(ii) Analyze the potential for carbon sequestration in above- and below-ground biomass stocks via allometric equations and empirical growth models;

(iii) Assess the soil carbon dynamics after afforestation with *J. curcas*;

(iv) Conduct a life cycle assessment for the calculation of the overall carbon and energy budget of *J. curcas* production pathways.

1.5 Outline of the thesis

The thesis comprises seven chapters. The general introduction gives an overview of the energy situation in Burkina Faso and the role *J. curcas* plays in this context. Chapter 2 describes the study region. In Chapter 3, the results of an extensive inventory study identifying the prevailing *J. curcas* management systems in Burkina Faso are presented. Through interviews with stakeholders involved in the *J. curcas* production chain, classification criteria for five management systems are developed. The findings of the inventory serve as basis for all further investigations. Chapter 4 presents the quantification of the carbon sequestration potential in standing biomass of the identified *J. curcas* systems. Allometric equations for non-destructive biomass stock estimations and empirical growth models demonstrating biomass growth of *J. curcas* stands over the years are developed and tested. The aspect of soil carbon sequestration under *J. curcas* systems is elaborated in Chapter 5. Data from a soil survey concentrating on soil organic carbon stocks and their changes under *J. curcas* systems relative to reference sites are presented. Chapter 6 integrates the results of Chapter 3, 4 and 5 in a life cycle assessment and presents different *J. curcas* production-transformation-consumption pathways in regard to their potential for carbon emission reduction and energy savings. Finally, in Chapter 7 the main findings of the study are summarized and discussed, and recommendations for exploitation of the potential of *J. curcas* and suggestions for further research are formulated.

2 STUDY REGION

Burkina Faso ("country of the honorable people") is a landlocked country situated in the heart of West Africa. It covers an area of 274,000 km² located between 09°20’ - 15°03’ N and 05°03 W - 02°20’ E and bordered by Niger, Mali, Ghana, Côte-d’Ivoire, Benin and Togo (CIA 2012). The country is divided into 13 regions and 45 provinces with Ouagadougou as the capital city. The population counts 17.813 million people (65 people km^{-2}) with a population growth rate of 3% (CIA 2012). More than 80% of the population resides in rural areas and is engaged in small-scale low-input agriculture (CIA 2012). Burkina Faso’s economy heavily relies on cotton and gold exports for revenues, as it has only few natural resources and a weak industrial sector. Overall, high population density, lack of natural resources, poor industrial development and low agricultural productivity are the main reasons behind the persisting poverty in Burkina Faso where 46% of the population live below the poverty line (World Bank 2013b).

2.1 Climate and vegetation

Burkina Faso is divided into three agro-ecological zones (AEZ), i.e., the Sudanian in the south (9°3’-11°3’N), the Sudano-Sahelian in the central region (11°3’-13°3’N) and the Sahelian in the north (13°5’-15°5’N). It has a tropical climate with two alternating seasons: a long dry spell from November to May with the continental trade wind (Harmattan) coming from northeast and a short rainy season from June to October with moist air coming from oceanic high pressure (Figure 2.1) (Thiombiano and Kampmann 2010).

Located in the transition zone between the Sahara Desert to the north and coastal rainforests to the south, Burkina Faso is prone to extreme weather events such as recurrent droughts, floods and wind storms (World Bank 2013a). Inter-annual and inter-decadal climate variability will likely increase; however a high level of uncertainty is associated with climate change projections for West Africa (IPCC 2001; World Bank 2013a).

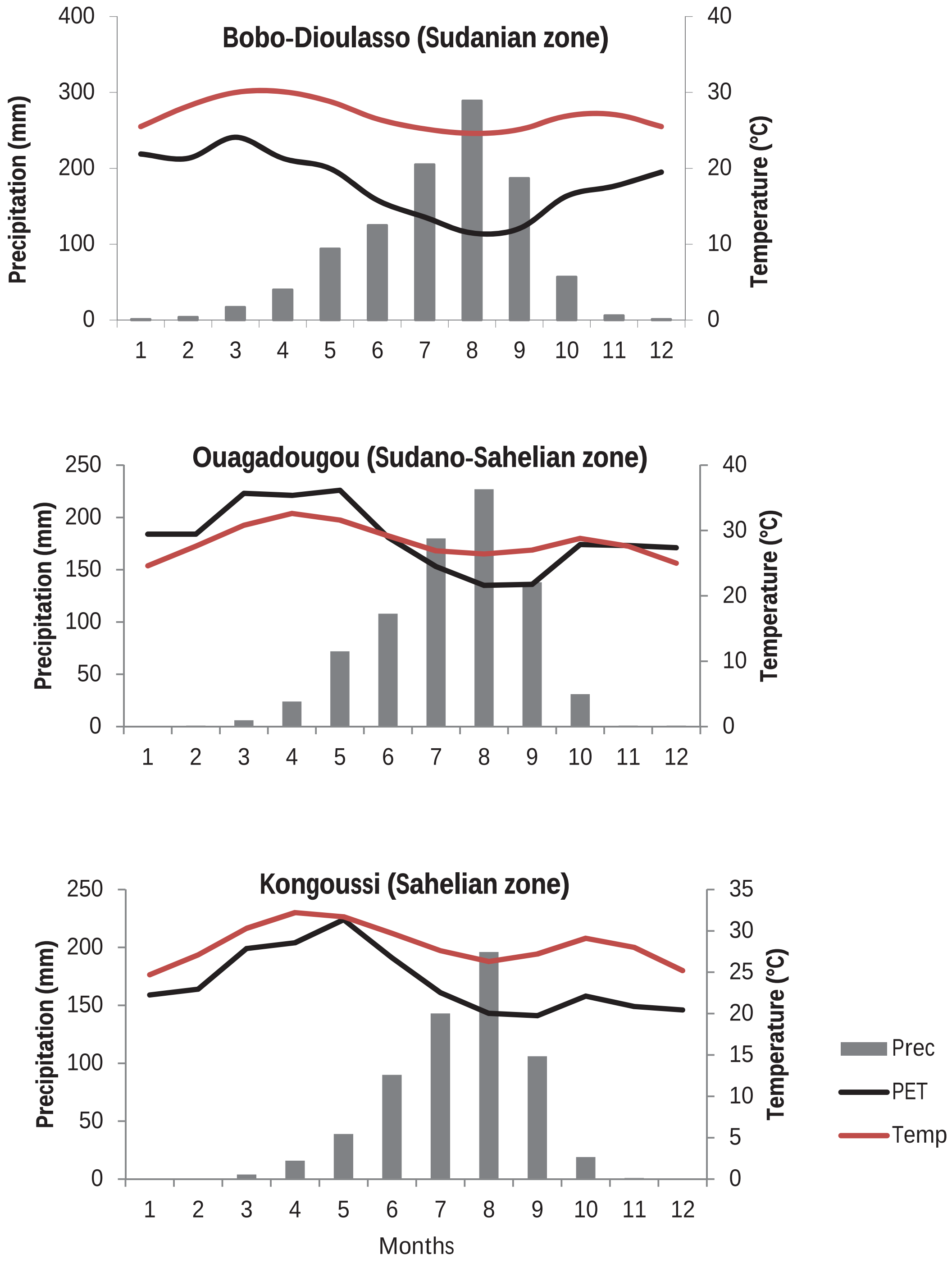

Figure 2.1 Long-term (1961-1990) average monthly temperature, rainfall and evapotranspiration (PET mm) (FAO 2013)

Table 2.1 Climatic conditions in the agro-ecological zones (AEZ) in Burkina Faso

AEZ	**Climatic zone**	**LGP (days)**	**Precipitation (mm)**	**% of national territory**	**No. of dry months**
Sudanian	sub-humid	180-269	900-1200	32.4	5-6
Sudano-Sahelian	semi-arid	90-179	700-900	38.9	6-7
Sahelian	arid zone	90	<700	28.7	>7

Source: Adapted from Kagone 2001 and Fontès and Guinko, 1995. LGP: length of growing period.

In the Sahelian zone the natural vegetation is composed of grassy and shrubby steppes in the north and shrubby savanna in the south (INSD, 2002; Thiombiano and Kampmann 2010). Tree species such as *Feidherbia albida, Sclerocarya birrea, Tamarindus indica, Balanites aegyptiaca, Ziziphus mauritiana, Lannea microcarpa,* and *Azadichta indica* are the most common in the agroforestry parkland systems. In the Sudano-Sahelian AEZ (North Sudan) annual rainfall ranges from 700 to 900 mm from north to south. Vegetation changes from grassy and shrubby steppes in the north to shrubby and woody savannas in the southern parts with parkland tree species such as *Vittelaria paradoxa, Feidherbia albida, Adansonia digitata, Tamarindus indica, Lannea microcarpa, Azadichta indica,* and *Bombax costatum* (Thiombiano and Kampmann 2010). The Sudanien zone (South Sudan) is characterized by mosaics of cropland, fallow areas in various stages of regeneration, and typical agroforestry parkland with the main tree species *Faidherbia albidia, Vittelaria paradoxa,* and *Parkia biglobosa* (Boffa 1999; Thiombiano and Kampmann 2010). Pressure on the natural vegetation is particularly high due to expanding cultivation of cotton, and high migration from the northern parts of Burkina Faso (Gray 1999) coupled with unsustainable firewood collection, annual bushfires, intensive pasturing and settlements (Commune Rurale de Boni 2009). Charcoal exploitation not only for local consumption but also for supplies to Ouagadougou is additionally triggering deforestation (1.45% annually) (Ouedraogo 2007; Ouedraogo et al. 2010).

2.2 Soils and land use

Most of Burkina Faso is covered by *ferric lixisols* (WRB 1998) *(leached ferruginous soils* (CPCS 1967)) and l*eptosols* or *lithisols (poorly evolved soils of erosion). Cambisols, vertisols, glysols* and *ferralsols* are of limited extent, and are found localized throughout the country (Thiombiano and Kampmann 2010). Generally, the soils are inherently low in soil fertility (organic carbon <1%), have low water holding capacity, and a tendency to develop soil surface crusting (Zougmoré 2003). Bush fires for land clearing make the soils susceptible to wind erosion during the dry season, and high rainfall intensities trigger water erosion at the onset of the rainy season (Zougmoré 2003). According to FAO (2009), 44% of the total land area in Burkina Faso is already affected by severe land degradation.

The land resources in Burkina Faso are divided as follows (World Bank 2008): 45% agricultural land (12 Mio ha) with 50% under cultivation (6.3 Mio ha) and 50% under permanent crops and pastures (including abandoned cropland and land not yet cultivated), 24% forest area, and 10% under settlement (other: 21%). High population growth and accelerating land degradation are key drivers behind cropland expansion with an annual rate of 0.2% (0.96% in southern Burkina Faso) at the expense of grazing area, forests and woodland (FAO 2001 in Ouedraogo et al. 2010).

2.3 Agriculture

The agricultural sector dominated by small family farms on rainfed land and characterized by low labor and input productivity (Breman et al. 2001 in Zougmoré 2003) provides income to more than 80% of the population (MED 2003). Millet (*Pennisetum glaucum*), red and white sorghum (*Sorghum bicolour*), maize (*Zea mays*), and cowpeas (*Vigna unguiculata*) are the main subsistence crops and cover 80% of the cultivated area. Cotton (*Gossypium herbarceum*), groundnuts (*Arachis hypogaea L.*), and sesame (*Sesamum indicum)* are the principal cash crops (Zougmoré 2003).). Extensive livestock production also plays an important role (cattle, small ruminants and poultry (INERA 2006)).

Crop production particularly suffers from poor native soil quality, surface crusting, low water-holding capacities, highly irregular rainfall patterns and high soil and air temperatures (Bationo and Buerkert 2001). Climate change projections show a further increase in climate variability and adverse effects on crop yields (IPCC 2001; World Bank 2013a). Small-scale agricultural systems are most vulnerable to these changes in climate due to their poor adaptive capacity (IPCC 2001; Mangoyana 2009). All in all, low agricultural productivity continues to impede poverty reduction. Therefore, major governmental efforts target agricultural intensification through mechanization, financial lending, water storage, crop diversification, and soil restoration (Hanff et al. 2011; World Bank 2013a).

2.4 Energy use pattern

Burkina Faso is facing a major energy crisis. More than 80% of the country's energy consumption is covered by traditionally used biomass such as fuel wood, dung and crop residues (Hanff et al. 2011). With its growing population and its increasing need for energy, the consumption of biomass exceeds the capacity of biomass re-growth (Bugaje 2006; Tatsidjodoung et al. 2012). Unsustainable use of biomass leads to soil erosion and land degradation, which are becoming the most serious environmental issues linked to energy consumption (Bugaje 2006; Toonen 2009; Sawe 2012). Moreover, indoor air pollution from open cooking fires is estimated to cause 16,500 deaths per year (WHO 2004). The remaining national energy need is covered by imported hydrocarbons used mainly for transportation and electricity production (Tatsidjodoung et al. 2012). As net importer of fossil oil, amounting to 50% of the national trade balance, Burkina Faso is heavily affected by rising oil prices (Hanff et al. 2011; Tatsidjodoung et al. 2012).

Overall, Burkina Faso has a very low level of energy consumption (234 kgoe per inhabitant compared with 1145 kgoe per inhabitant worldwide), and very poor access to electricity (<1% in rural and <15% in urban areas) (Blin et al. 2008; Hanff et al. 2011). It has long been recognized that energy poverty is directly linked to economic poverty (Karekezi 2002; Bugaje 2006). Therefore, the country's renewable energy sources urgently have to be harnessed (e.g., solar energy, biogas, biofuel) in order to supply the growing demand in energy to support the nation's development, increase the independency from imported fossil fuel, and reduce environmental degradation and health impacts associated with the traditional biomass use (Karekezi 2002; Bugaje 2006; Toonen 2009, Hanff et al. 2011).

3 JATROPHA IN BURKINA FASO

3.1 Introduction

Worldwide*, J. curcas* is long known as a multi-purpose tree with a large number of traditional uses (GTZ 2009). It is only since 2007 that *J. curcas* has attracted international attention as potential feedstock for biofuel production. The plant became particularly popular through its claimed potential to produce biofuel on marginal and degraded lands in semi-arid areas without high input requirements and to simultaneously contribute to socio-economic development (e.g., Heller 1996; Francis et al. 2005; Jongschaap et al. 2007; Henning 2009). Many projects were initiated; however, six years after the first hype, sobering conclusions can be drawn. Seed yields are very much lower than expected, knowledge of appropriate management is still lacking, seed harvest and dehusking are very labor intensive, most *J. curcas* plantation projects are economically not viable, and land availability and suitability for *J. curcas* production are not yet defined (e.g., van Eijck et al. 2010; Contran et al. 2013). Nevertheless, biofuel production from *J. curcas* continues to be hotly debated due to the numerous interesting characteristics of the tree species in terms of energy production and supply of environmental services (Contran et al. 2013).

In the case of Burkina Faso, *J. curcas* was traditionally planted in hedgerows demarcating property, protecting fields from roaming animals, and serving as windbreaks and for erosion control (Ayuk 1997; Soulama 2008; Sanou 2010). Besides, fruits were used for soap production and the plant sap for medical treatments (Heller 1996). Recently, also in Burkina Faso, *J. curcas* has become popular as a biofuel source and is seen as a valid alternative to alleviate the energy scarcity prevailing in the country. Realizing the potential of *J. curcas* and other energy crops for Burkina Faso, the government started to design a national biofuel policy in 2009. The government envisions biofuel production for the national market (electricity and transport), and is very prudent with the allocation of areas to the cultivation of *J. curcas* in large-scale monoculture plantations as it fears to compromise food security. According to the authorities, *J. curcas* should be predominantly cultivated in combination with annual crops and on degraded soils for their reclamation. A maximum of 500,000 ha land for bioenergy production is targeted so far (MMCE 2009). According to Wicke et al. (2011) an estimated 11% (1.6 million ha) of the arid and semi-arid areas in Burkina Faso, excluding agricultural land and land with high biodiversity, would be potentially available for energy crop production without negatively affecting food production. The suitability of such land for *J. curcas* production for social, environmental and economic reasons, however, remains to be investigated (Dauber et al. 2012). Life cycle assessment (LCA) is a common tool to evaluate environmental sustainability of biofuel production systems (Gnansounou et al. 2009), but needs location-specific data on the management of *J. curcas* cultivation systems in order to correctly show the environmental consequences.

Currently, several stakeholders are involved in *J. curcas* activities. Non-governmental organizations (NGOs) mainly work on the establishment of value chains for the local energy supply, whereas private investors aim at large-scale biofuel production. More than 80,000 ha are covered with *J. curcas* in form of newly planted mono- and intercropped plantations and traditional hedges (Nonyarma and Laude 2010; Ouedraogo 2012), and two biodiesel factories are already in place. Yet most projects do not fully operate along the entire value chain (Blin et al. 2008) due to low seed yields, high seed prices, high transportation costs, inferior quality of seeds (5 kg seeds needed for processing 1 l oil), immature markets and lacking regulatory policies (Laude 2011). In 2011, approximately 12,000 l *J. curcas* oil and 2,140 l biodiesel were produced (Ouedraogo 2012). Altogether, competition among the stakeholders for suitable land and knowledge on best cultivation and transformation management is high, as each claims its own pioneering position in *J. curcas* biofuel production. Thus, reliable information about the operational practices is not easily available. Besides, farmers' cultivation practices are not systematically reported and little is known about plant arrangement, plantation management, intercropping performance and land allocation. Conclusions about *J. curcas* systems and their productivity can hardly be drawn. Also, research on *J. curcas* cultivation and propagation in Burkina Faso remains scarce (Sop et al. 2012). The sound inventory and documentation of *J. curcas* activities in Burkina Faso is, therefore, the main objective of this exploratory study. Specific objectives are to (i) identify stakeholders involved in *J. curcas* production and to assess their operational practice, (ii) classify and characterize existing *J. curcas* cultivation systems in Burkina Faso, (iii) evaluate the effect on existing land-use patterns of introducing *J. curcas*, and (iv) based on the inventory results, to identify a sampling strategy for further analysis of productivity and carbon sequestration in biomass and soil in *J. curcas* systems.

3.2 Materials and methods

3.2.1 Sampling design and data collection

The sampling approach aimed to representatively illustrate the *J. curcas* scene in Burkina Faso. Using a mixture of snowball and random sampling, stakeholders involved in *J. curcas* activities and *J. curcas* cultivation sites were identified. Structured expert interviews were conducted with seven key stakeholders (BELWET, AGRITECH FASO, APROJER, Dreyer Foundation, ILARIA BF, APS and Terra-Verde) covering basic information on their organizational models and operational concepts, agronomic management in their nurseries and plantations, transformation steps, and marketing procedures. The *J. curcas* farmers in the project areas were visited, guided by an instructed person under the permission of the respective village leader. *Jatropha curcas* sites were then selected following the idea of theoretic sampling. According to this sampling approach, research sites are selected based on the new insights they may provide in regard to the overall objective (Neuman 2006). In this way, it could be guaranteed that the variability of *J. curcas* activities in terms of crop management, organizational practices, and environmental settings is covered. In case theoretic sampling was not suitable, *J. curcas* sites were selected randomly. In the regions where traditional *J. curcas* hedges were grown, 11 focus group discussions (FGD) were held, with the goal to identify appropriate research sites. Altogether, in-depth questionnaires were carried out with 111 *J. curcas* farmers at the selected sites (Table 3.1). Expert interviews were generally conducted in French, while questionnaires with farmers were translated by an assistant into the respective local language. The questionnaire consisted of factual questions for quantitative information, and of closed-ended and partially open questions in the categories motivation and reason for growing *J. curcas*, choice of land and land-use history, establishment and management of plantation, experienced limitations and workload, seed harvest, and sales. FGDs covered the same categories.

Table 3.1 *Jatropha curcas* research sites and sample size

Nearest city	**Village**	**System**[a]	**Farmer interviews**	**Participants in FGD**	**Sites with tree measurements**
Kongoussi	Sakou	Contour hedges	3	6	3
	Birou		3	7	2
Bagré	Kala Koudi	Living fence	6	11	4
	Yambo		5	10	5
	Guin-Galé		3	6	3
Mogdedo	Simtanga	Living fence	6	22	6
	Toéssin		6	6	6
	Tamosgo		4	12	4
	Zambanega		4	17	4
	Zam		5	11	6
Manga	Louré	Living fence	4	26	4
Ouaga-dougou	Gampela	Old trees integrated in young intercropping system	1		2
Dano	Dano	Intercropping/ Afforestation	9/ 3		5
Boni	Dossi	Intercropping/ Afforestation	8/ 1		5
	Badoun	Intensely managed	1		1
	Boni	Intercropping/ Afforestation	6/ 1		4
	Mamboué	Intercropping	6		3
	Minou	Intercropping	1		
	Moukounie	Intercropping	5		2
	Tounoun	Intensely managed	2		2
	Yenou	Intercropping	6		2
	Bansié	Intercropping	6		2
Banfora	Boulou	Intercropping	2		2
Orodara	Fon	Intercropping	1		1
	Tin		3		3
Total			111	134	81

[a] *System classification according to section 3.3.2. FGD: Focus group discussion.*

At 81 sites, measurements of selected trees (tree height, stem diameter, number of fruits) were undertaken (see section 4.2.3; Table 3.1). All sites were characterized and classified according to planting scheme, plantation management and cultivation purposes. The field work was carried out from July 2010 to March 2011.

In parallel, investigations were undertaken in regions where *J. curcas* cultivation for biofuel production had not yet expanded but will likely do so in the near future (Table 3.2). These investigations were particularly important to assess land-use management systems before integrating *J. curcas* and possible land allocation effects of expanding *J. curcas* cultivation. In the south-western part of Burkina Faso, *J. curcas* cultivation is likely to continuously expand due to the region's favorable climatic and pedologic conditions. In the central region, the close vicinity to Ouagadougou is likely to trigger the production of *J. curcas*-based biofuel as the fuel demand for transportation is constantly rising. In the northern part, soil degradation is an ongoing process, making soil conservation measures such as stone walls and *J. curcas* hedges attractive.

In these regions, 110 households were surveyed and 7 FGDs were conducted (Table 3.2), covering the categories land use and land ownership, crop production and maintenance, crop rotation, labor need and availability, and farmers' perception on or experience with *J. curcas*. A meeting with the chief of the respective village was arranged in advance in order to get permission for the survey and to get familiar with basic characteristics of the village such as household number. All households were then randomly selected. A high variation in terms of cropping patterns within one village was not expected, thus small sample sizes were deemed sufficient. In the last two villages no households were visited (Table 3.2) as most of the questions could be answered during the FGD. The questionnaire was pretested with a random sample of 20 farmers in order to ensure that the questionnaire was capable of collecting all information needed in an unambiguous and easily understandable way. The survey was conducted with the help of enumerators, who were instructed beforehand and supervised along the way. All questions were translated into the local language

(Dagara and Morré). This part of the field work was carried out from February to March 2011 (Table 3.2).

Table 3.2 Sample locations and sample size of household survey

Nearest city	Village	No. of selected households	% of total households per village	Participants in FGD
Dano	Pontieba	35	9	22
	Tambiri	20	16	14
	Bafor	20	20	43
Mogdedo	Zambanega	18	60	15
	Zam	17		8
Kongoussi	Sakou	/		12
	Birou	/		15
	Total	110		129

The overall challenge of a farmer survey for assessing quantitative information is the interpretation of traditionally coded units into standard weight, time, and area units, as local perception of time and space can greatly differ from standard norms (Harvey and Taylor 2000). Triangulation of methodologies aimed at the validation of the research findings by comparing data from different sources (Bryman 2008) such as from field observations, expert statements, informal communication with persons involved in *J. curcas* activities, and from secondary data such as from studies in Burkina Faso and national statistics.

3.2.2 Geographic distribution of the study sites

Investigations on *J. curcas* production were done throughout Burkina Faso in seven different regions spread over three AEZ (10°05’ - 13°18’ N and 04°58’ - 00°26’ W) (Figure 3.1).

In the region Centre-Nord, research was conducted in the province Bam around the city Kongoussi, where *J. curcas* is planted along contour stone walls (Figure 3.1). The construction of stone walls is a common soil conservation technique to control water erosion, and was initiated in the 1990s, particularly in the northern part of Burkina Faso (Zougmoré et al. 2002). In Bam, 1500 km² are already provided with these stone walls contributing to re-greening and restoration of large areas of land

(Landolt 2010). Bam has the largest natural lake, an important source for irrigation agriculture, yet 80-90% of the cultivated area is still covered by rain-fed crops such as millet and sorghum. Overall, the production of cereals is not sufficient for the local demand (MAHRH 2010).

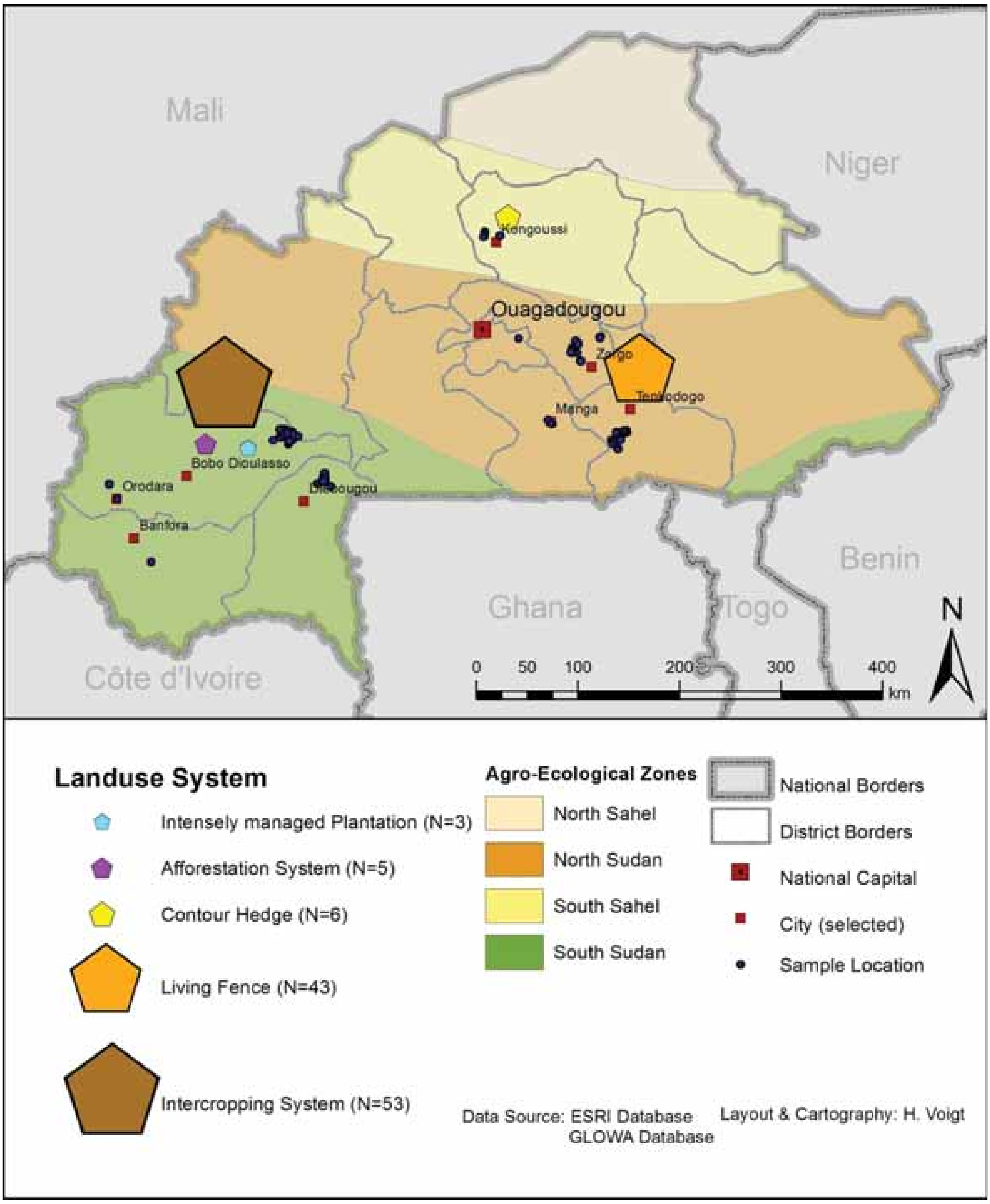

Figure 3.1 Sample sites and distribution of *Jatropha curcas* land-use systems in Burkina Faso. N: Number of sites visited.

On the Plateau Central in the province Ganzourgou, investigations took place in the municipality of Mogtedo, as numerous mature *J. curcas* hedges exist in this area. In the regions Centre-Sued (province Zoundwéogo, municipality of Manga) and Centre-Est (province Boulgou, municipality of Bagré), the research also focused on mature *J. curcas* hedges (Figure 3.1). The typical agrosilvopastoral land-use system integrates trees, crops and livestock in the same land management unit (Ayuk 1997). As a consequence, living fences are a common technique for controlling livestock movement to protect fields (Ayuk 1997). The emergence of live hedges on the central plateau of Burkina Faso dates back to the early 1980s, and they serve not only as protection against browsing animals but also as windbreaks and erosion control (Ayuk 1997). Altogether, the central region is one of the most highly populated in Burkina Faso (INERA 2006); the resource soil is thus under enormous pressure and exhibits the highest degradation rates in the country (Zougmoré 2003).

In the province of Ioba (region Sud-Ouest), research was conducted in Dano, where *J. curcas* is grown intercropped with annual crops on smallholders' land. In Tuy (region Hauts-Bassins), the heart of the cotton growing region (Gray 1999), larger scale *J. curcas* monoculture plantations, afforested marginal land, and intercropped *J. curcas* can be found around the village Boni. In Orodara and Banfora (region of Cascades, province of Comoé), investigations were conducted in small-scale *J. curcas* intercropping systems (Figure 3.1). All three study sites lie in the Sudanian zone with favorable rainfall patterns and relatively fertile soils (Gray 1999).

3.2.3 Shading effect of *Jatropha curcas* plantings

The shading effect of *J. curcas* plantings is an important indicator for the suitability of such plantings as an intercropping system. Under the assumption that the area permanently shaded by the tree canopy is not occupied by other plants, the canopy expansion can give information about the space occupation by *J. curcas* trees.

The shaded ground area is defined by the canopy expansion (CA in m²):

$$CA = \pi \cdot Cd^2/4 \tag{3.1}$$

where Cd is three single tree canopy diameter (m), measured with a measuring tape from one side of the canopy to the other (see section 4.2.3 for methodology).

The space occupation per hectare (CA_t m² ha^{-1}) over time t (years) was fitted by a three-parametric exponential model (STATA 12.0)

$$CA_t = b_1 + (b_2 \cdot b_3)^t \tag{3.2}$$

relating the shaded area per hectare CA_t with the respective age of the plantation. CA_t was calculated for different tree spacing types by multiplying the average tree canopy expansion with the respective plant density. It was assumed that the tree canopy growth is not affected by tree density as long as total canopy closure per hectare is not reached. In the case of living fences, a closed hedge surrounding a one-hectare field (400 m) was assumed and multiplied by the mean canopy diameter of 3 m. Models were developed for the spacing types 1 m x 4 m (2500 trees ha^{-1}), 2 m x 4 m (1250 trees ha^{-1}), 4 m x 4 m (625 trees ha^{-1}), 4 m x 6 m (417 trees ha^{-1}), and closed hedges (under the assumption of complete tree survival and no tree pruning). b_1, b_2, b_3 were the parameters to be estimated.

3.2.4 Statistical analyses

The data from the semi-structured interviews were coded and analyzed by STATA (12.0). Descriptive statistics (means, standard error and frequencies) were used for analyzing parameters. Nonlinear regressions were run for modeling the tree shading effects.

3.3 Results

3.3.1 Stakeholders in *Jatropha curcas* activities

Old *J. curcas* trees can be found throughout Burkina Faso, isolated on farmers' property for land demarcation or arranged in living fences protecting fields from roaming animals. Most of the farmers with *J. curcas* on their property were aware of the traditional utilization of the oil and the plant sap for soap production as well as for medical purposes such as against skin lesions, toothache and bacterial infections. In the language of the Mossi, *J. curcas* is called *Waben banguemeen* meaning *'If you eat me, you get to know me'*, which reflects the poisonous nature of this tree.

The promotion of *J. curcas* as feedstock for biodiesel only started in 2007. Campaigns were undertaken by private enterprises, politicians and NGOs to sensitize farmers regarding the potential of *J. curcas* and to convince them to integrate this plant into their agricultural activities (Table 3.3). It was also attempted to organize seed collection from mature *J. curcas* living fences, as this could substantially contribute to seed supply for biofuel production and economic revenues to the farmers. However, despite radio, newspapers and private extension services biofuel production still remains a niche in Burkina Faso; A Burkinabe scientist described the situation as follows: "Jatropha is in every mouth – many Jatropha trees can be found – some seeds are harvested – little oil is pressed – no oil is on the market" (Anonymous 2011; personal communication).

Based on stakeholder analysis in Burkina Faso, two organizational models could be distinguished: (1) Private investors aiming at industrialized oil production and transformation to biodiesel for use at the national level manage large-scale plantations on land they got from the government. The government, however, remains restrictive in allocating large areas to biofuel production, as it fears both a threat to food security and competition for land resources (Blin et al. 2011). Therefore, enterprises started to contract smallholder farmers for the cultivation of *J. curcas* in intercropping and living fence systems on their own land. Approximately 80,000 farmers are participating in this kind of outgrower scheme (Table 3.3). Farmers are given seedlings free of charge, training on plantation establishment, and given an oral guarantee of seed purchase. Two factories for oil extraction and etherification to biodiesel are in place. At the time of the field research (2011), there were the first seed harvests; however, the seed supply is not yet sufficient to tap the full capacity of the biodiesel plants.

(2) NGOs promote the integration of *J. curcas* in existing small-scale low-input agricultural systems intercropped with food crops or as hedgerows (Table 3.3) with the overarching goal of poverty reduction in rural areas. The aim of *J. curcas* afforestation is to combat soil degradation and to locally produce straight vegetable oil (SVO) for motive power and electricity generation at the village level. Alternative uses of SVO are further encouraged by pushing the development of adapted technologies such as plant oil cooking stoves and oil lamps. The planting of *J. curcas* as field borders is increasingly advertized in order to minimize the competition with food crops.

In Table 3.3 stakeholders involved in *J. curcas* production are listed as of January 2013. New *J. curcas* activities are constantly being initiated, but these cannot be easily identified in Burkina Faso.

Table 3.3 Overview of main Jatropha stakeholders in Burkina Faso (January 2013)

Private companies	Start of activities	Land area (ha)	*J. curcas* system	Province	Purpose	No. of farmers	Status	Source
AGRITECH Faso	2007	1,000	Small-scale intercropped (outgrower), intensely managed plantations (pilot), afforestation	Tuy	Biodiesel for national consumption	300	Biodiesel factory built, application for carbon credits, plans to grow high-yielding varieties	W. Kwendé 2010 interview; A.K. Sanou 2011 pc; http://www.agritechgroup.com/ 2013
BELWET	2007	67,000	Living fence, small-scale intercropped (outgrower), intensely managed plantations (pilot)	Zoundwéogo	Biodiesel for national consumption	62,000	Biodiesel factory built, only little seed transformation	A. Sawadogo 2010 interview, 2011 pc; Blin et al.2008
APROJER	2007	11,000	Small-scale intercropped, living fence (outgrowers)	Comoe, Kompienga	SVO for local and national energy supply	10,000	Oil press is installed, no seed transformation	H. Yaro 2010 interview, 2013 pc
Faso Biocarburant	2010	3,000	Small-scale intercropped, living fence (outgrower)	Nayala, Sissili	Biodiesel for national consumption, SVO for local energy supply, revenue for farmers	n.a.	First trees planted, application for carbon credits	O. Meier-Hahn 2012 pc,http://www.malibiocarburant.com/malibioen/fondation-faso-biocarburant 2013
ILARIA	2007	100	Intercropped	Boulgou	Biodiesel for national consumption	0	Jatropha activities stopped in 2010 (due to shortage in land)	G.P. v. Pezold and M. Kaboré 2010 interview
Genese SARL	2008	7,000	Living fence, small-scale intercropped (outgrower)	Houet, Comoe, Mouhoun	SVO for local and national energy supply	7,000	Little yield, no transformation	W.J. Simonse 2011 pc

Table 3.3 continued

NGOs	Start of activities	Hectare	*J. curcas* system	Province	Purpose	No. of farmers	Actual Status	Source
Terra Verde	2009	110	Hedgerow along erosion control contour walls	Bam	Stabilization of stone walls, SVO for local energy supply	80	No seed transformation	M. Landolt 2010 interview, 2011 pc
Tii Palga	2007	104	Living fence	Soum Kadiogo	Soil protection, revenues for farmers, SVO for local energy supply, soap production	350	Storage of seeds, no transformation	I. Ouedraogo 2011 pc
Dreyer Foundation	2009	250	Small-scale intercropped, afforestation	Ioba	Soil protection, afforestation, local use of SVO in cooking stoves and for motive power	46	Development of stove, storage of seeds, no transformation	P. Arnold 2010 interview, 2012 pc
Sustainable Energy(VE)	2013	n.a.	Living fence, small-scale intercropped	Tuy	SVO for local energy supply	n.a.	Project implementation phase	M. Sokona 2012 pc
APS	2009	n.a.	Living fence	Ganzourgou	Revenue for farmers, purchase of seeds from mature living fences for selling to factories	n.a.	No transformation	S. Lassane 2010 interview, 2011 pc

Data source: Hallensleben (2011), own investigations. SVO: Straight vegetable oil; n.a. not available; pc: personal communication.

3.3.2 System classification and characterization

With regard to the planting scheme, two main *J. curcas* systems were identified: the plantation and the hedge system, which were then further divided according to management practices and the cultivation purpose. This resulted in five *J. curcas* systems. The most widespread systems were small-scale *J. curcas* intercropping (47.7% of the surveyed sites) located in the south-western part and living fences (38.7%) in the central part of Burkina Faso. Intensely managed plantations (2.7%), afforestation plots on abandoned cropland (4.5%) and hedges along contour stone walls (5.4%) presented only niche systems (Table 3.1; Figure 3.1).

(1) Small-scale intercropping system

This system encompassed *J. curcas* cultivation combined with annual crops on land owned or managed by smallholder farmers. The plantations were usually less than 2 ha (1.8±0.15 ha) (n=53). The most common tree arrangements were 4 m x 4 m (inter-row distance x inter-plant distance) with 625 trees ha^{-1} (53%), 6 m x 4 m (417 trees ha^{-1}; 13%) and 3 m x 2 m (1667 trees ha^{-1}; 11%). Of the plantations visited 21% were established in 2007, 53% in 2008, and 26% in 2009. Accordingly, the research in 2010 and 2011 covered 1- to 4-year old trees.

The intercropping system (see Appendix 9.1 for picture) was predominantly located in the south-western region of Burkina Faso with favorable climate and soil conditions (section 2.1). Here, NGOs and private companies introduced *J. curcas* and its potential as an energy crop to small-scale farmers and promoted its cultivation. Seedlings free of charge were distributed among the farmers, and future purchase of the seeds was orally guaranteed. Regarding the transplanting of *J. curcas* seedlings, a planting depth of 30-50 cm with planting-hole dimensions of 50 cm x 50 cm was recommended. Planting was ideally scheduled prior to the rainy season in June. Seedlings originated from nurseries built up by the respective organization and were raised, for example, by AGRITECH from certified local seeds (certified in collaboration with the laboratory of 2iE in Ouagadougou). Seedlings were grown in polybags filled with a mixture of sand, manure and soil, watered regularly, and transplanted into the field 8 to 12 weeks after sowing. After the first year, as reported by the farmers, a seedling survival rate of 74-94% was observed.

In contrast, management techniques for *J. curcas* trees were not part of the sensitization campaign. Hence, *J. curcas* was generally grown as a rain-fed plant and was neither fertilized nor systematically pruned. Only 19% of the interviewed farmers temporarily irrigated their *J. curcas* trees during the first dry season. Mineral fertilizers were not applied, and only 24% of the farmers used mixed manure explicitly for their trees and 19% cut some of the branches. Regular pruning is named as an important practice to maximize productivity (Jongschaap et al. 2007). However, most farmers did not prune for fear of destroying the trees or reducing productivity. Overall, in the south-western region the practices of *J. curcas* plantation establishment were quite homogenous, as the same sensitization had taken place. Performance of plantations, however, differed depending on management practices such as rotation, fertilization and maintenance of intercrops. Thus, *J. curcas* mainly profited from the management of the intercrop.

Of the interviewed farmers (n=53), 67% had at least once combined *J. curcas* with sorghum, 38% with maize, 10% with cotton and 54% with legumes such as cowpeas or groundnuts. Looking at the share of annual crops frequently intercropped with *J. curcas* trees (Table 3.4) (investigated for 15 sites within the biomass study (see Chapter 4)), it can be observed that maize, sorghum and cotton were primarily grown in the first and second growth year of *J. curcas*, whereas leguminous plants were preferably integrated in older *J. curcas* stands. According to the farmers, 47% of the intercropped *J. curcas* fields were no longer intercropped three years after *J. curcas* planting. Although a high share of fields chosen for *J. curcas* plantations was previously cultivated with cotton, its cultivation decreased after introducing *J. curcas*. The replacement of cotton through *J. curcas* is probably a consequence of decreasing profitability of cotton cultivation (Commune Rurale de Boni 2009) and the expected productivity of *J. curcas*. Management interventions associated with the intercrops are listed in Table 3.4.

Table 3.4 Annual crops grown in *Jatropha curcas* intercropping systems and their recommended management

Intercrop	**Share (%) in crop rotation before and after introduction of *J. curcas* intercropping**					**Average fertilization**	**Recommended management of annual crops (INERA[3])**
	Before	**1st**	**2nd**	**3rd**	**4th**		
Maize	31	46	28	15	7	50-100 kg NPK 50 kg urea 0.5-1 t manure	Weeding & harrowing, seedling separation, ridging, fertilization
Sorghum	23	31	38	12	7	/	Weeding & harrowing, seedling separation, ridging
Cotton	38	15	8	0	6	100-150 kg NPK 50-100 kg urea	Weeding & harrowing, fertilization, ridging, herbicide application
Legumes	8	8	21	31	33	/	Weeding
No crop		0	5	42	47	/	/

All work is done ox driven or manually. NPK (14% N, 23% P, 14% K), urea (46% N).
Cropping pattern independent of J. curcas cultivation (Commune Rurale de Boni 2009): Cotton 30%; maize 43%; sorghum 22%; legumes 5%.

Based on the household survey (n=110, Table 3.2), 95% of the smallholders growing maize (n=105) stated to use a mixture of mineral (NPK and urea) and organic fertilizer (compost and manure) for their maize crop, 20% applied only organic fertilizer, and 5% left their crop unfertilized; 93% of the cotton farmers (n=68) applied NPK and urea but no organic fertilizer. The majority of farmers left other crops unfertilized. Most labor was allocated to the maintenance of maize and cotton through soil tillage, repeated weeding in the beginning of the growing period, harrowing, ridging, fertilizer application and, in the case of cotton, phytosanitary treatment. All field work was done manually or ox driven and in 67% of cases supported by seasonal labor. On average, a farmer undertook crop maintenance activities three times per crop and growing season, more frequently for maize and cotton and less frequently for sorghum and legumes. Consequently, frequent intercropping of cotton or maize with *J. curcas* indirectly benefits the biomass accumulation of the *J. curcas* trees.

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[3] INERA: Institut de l'Environnement et Recherches Agricoles de Burkina Faso

Insects (70%), animals and bushfires (39%) were named as the main factors limiting the growth of *J. curcas* trees. Termites, the multicolored beetle (*Scutellera nobilis)* and red beetles (*Aphtona species*) were the insects most frequently observed. Since *J. curcas* plantations were not directly treated with insecticides but only indirectly when combined with cotton, the insects could cause severe damage. Particularly during the dry season, *J. curcas* trees were threatened in several ways. Animals damaged trees by roaming through the plantations, and if no firebreaks had been cleared, bushfires could enter into the plantations and destroy the trees. Additionally, termite attacks mostly occurred during the dry season, the insects being attracted by the juicy wood of *J. curcas*. 23% of farmers mentioned a lack of water, weeds and soil infertility as limiting factors.

Two years after plantation establishment, most farmers harvested their first *J. curcas* fruits. Repeated harvest was necessary, as several fruit development stages occur at the same time. Farmers reported to harvest one to four times per month between July and December. Subsequently, seeds were sun dried (7-10 days under dry conditions) in front of the farmers' homesteads, manually dehusked if labor was available, packed into sacks and stored in a dry place. In 2011, some private companies started to buy *J. curcas* seeds paying 60 FCFA[4] for one kg dehusked and 40 FCFA for one kg non-dehusked seeds.

The amount of seeds harvested and stocked by the farmers was lower than the potential yield monitored over a growing period (section 4.3.2), indicating that farmers did not harvest all seeds. Reasons could be the time required for repeated harvests and for seed dehusking, and at the same time high workloads for other crops. Farmers usually refrained from sending their children to fruit picking due to the toxicity of the fruits. Besides, disappointment and frustration about low seed prices coupled with relatively low yields and high labor requirements were spreading among the farmers. The key motivation for *J. curcas* cultivation among all producers (100%) was the expected increase in income through the sale of the seeds. Environmental reasons such as erosion control and soil fertilizing effects through afforestation played

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[4] FCFA: Franc de la Communauté financière africaine; 60 FCFA=0.09€, 40 FCFA=0.06€ (15 May 2013).

a secondary role, and only few farmers (5 out of 53) used *J. curcas* explicitly to mark their property or for the traditional production of soap.

(2) Afforestation system on marginal land

Jatropha curcas planted on land abandoned from agricultural activities (see Appendix 9.2 for picture) because of low productivity was classified as 'afforestation system'. The sites surveyed had already been abandoned for several years and had started to be reclaimed by natural vegetation. The plantation size ranged from 1-300 ha (n=5). The trees were arranged in 4 m x 4 m spacing without prior field clearing. The transplanting of seedlings followed the same procedure as in intercropping systems. Subsequently, no management took place except for irregular weeding. Lacking management, competition with weeds, infertile soils and roaming animals were stated by the farmers as the main obstacles to plant growth. These factors coupled with soil constraints (section 4.2.2) visibly hindered plant development and productivity. Survival rate was 50-80% after the first and 20-70% after the second growing year. In 2009, the first plantations were established, but in 2011 fruits had not yet developed.

As the smallholders' main motivation to grow *J. curcas* was income generation through the sale of seeds, 64% (n=56) of them cultivated *J. curcas* on soils deemed as normal to very fertile. Badly performing afforestation systems did not carry economic incentives, and thus were practiced only by 3 out of 56 small-scale farmers. The government, however, preferred to allocate abandoned land to bioenergy production as, competition with food crops could thus be excluded and at the same time *J. curcas'* contribution to soil restoration could be exploited. Therefore, a company was provided with 300 ha of unused land for the expansion of their production area. Another afforestation site with 65 ha was held by a village community in Boni (Figure 3.1).

(3) Intensely managed plantation

This system comprised *J. curcas* plantations intercropped or as monoculture with a high level of maintenance (see Appendix 9.3 for picture). The plantations visited (n=3) were solely managed by the private company AGRITECH, which had obtained land from the government. Average plantation size was 59 ha with two tree arrangements of 4 m x 4 m and one 6 m x 4 m. The first plantation was established in 2007, the following two in 2008. Seedlings were grown in associated nurseries and transplanted in the same manner as taught for intercropping systems. Field preparation and soil tillage were motorized, plantations were drip irrigated during the dry season (15 l tree^{-1} two times a week over 12 weeks), soil fertilization took place on a regular basis (~150 kg NPK and ~100 kg urea ha^{-1} yr^{-1} and mixed manure), and pesticide and herbicide application was part of the management regime. Pruning was not carried out. All work was done by hired local labor.

The overall purpose of the intensely managed plantations was the production of high quantities of *J. curcas* seeds and their transformation to biodiesel. This cultivation system could still be considered as a pilot project for optimized *J. curcas* management. Also, the occasional cultivation of annual crops in the *J. curcas* plantations followed mainly experimental purposes (Tapsoba 2011). First fruits were harvested one year after plantation establishment.

(4) Living fence

In *J. curcas* living fences (see Appendix 9.4 for picture), trees were planted in single rows with a planting distance less than 1 m (84% of cases, n=43). Extrapolating the number of trees grown in a hedge section of 10 m on a per-hectare basis (assuming 400 m closed hedge surround a one-hectare field) resulted in an average planting density of 900±50 trees ha^{-1}. In reality, hedges did not surround one-hectare fields but were fragmented with an average hedge length of 98±31 m and a width of 3.2±0.1 m. 47% of the hedges surveyed were 10-25 years old, 30% 5-9 years and the remaining younger than 5 years. Self-propagation was common in the hedges resulting in a high variation of tree age within a hedge.

Living fences were generally not directly managed, but profited from the maintenance of adjacent crops. The main food crops such as maize (91% of interviewed hedge farmers), millet (98%), sorghum (77%) and rice (37%) were regularly grown in the fenced areas. Education pruning took place in all cases, but only to minimize the shading effect on the neighboring crop and not to maximize *J. curcas* seed production. 50% of farmers reported problems with weeds and pests (60% multicolored beetle, 40% termites). Damages in the hedge were commonly repaired by transplanting cuttings or young saplings found in the hedgerow. Farmers also stated that they distributed shootings among neighbors planning to establish *J. curcas* hedges because of their functionality and tradition. Originally, propagation took place through cuttings from wild *J. curcas* trees.

With the establishment of *J. curcas* living fences, farmers primarily aimed at protection of the crops from grazing cattle. Besides, all farmers chose *J. curcas* fences because of their longevity, low management requirements, property demarcation, and soil erosion reduction. Over 50% of the farmers stated that they had great problems with wind and water erosion, and planted *J. curcas* hedges for its control. According to their unanimous opinion, *J. curcas* hedges have contributed to soil fertility improvement through reduced topsoil losses and through organic matter input via leaf fall.

In contrast to the above-described systems, most living fences were in a mature state and widely distributed, thus they were already producing considerable amounts of seeds. However, no farmer had previously harvested the seeds because they were of no commercial value. In the context of the increasing popularity of *J. curcas* for biodiesel production, sensitization of hedge farmers also took place. The importance of the seeds and the revenues that can be gained by collecting seeds and bringing them to collection points for sale was explained to the farmers. Still, most fruits had not been harvested, but fell to the ground where they decomposed, germinated or were carried away by rain water. As reasons for why *J. curcas* cultivation for seed production was not thriving in their region, farmers named lacking infrastructure for seed collection, lack of markets, lacking knowledge about *J. curcas* cultivation, and no guidance. However, over 80% of the hedge farmers expressed interest in extended *J. curcas* cultivation, and mentioned income generation through the sale of seeds (65%), abundant space for *J. curcas* hedges (23%), benefits for soil (35%), and for their village through the collaboration with biofuel companies (37%).

(5) Contour hedge

This system describes *J. curcas* trees planted along erosion control stone walls (see Appendix 9.5 for picture) with 2-m planting distance, resulting in a planting density of 200 trees ha^{-1} (assuming a closed hedge surrounding a one-hectare field (400 m)). Average hedge length was 206±50 m (n=6). Hedges were established in June by transplanting 10-week-old seedlings. The trees were then only indirectly managed through low-intensity maintenance of adjacent crops. Sorghum, millet and maize were the main crops cultivated. Three of six farmers had done education pruning of the trees in order to minimize the competition with the adjacent crop. Termites and grasshoppers were named as the main threat to the trees.

In contrast to plantation systems, the motivation of the farmers to grow *J. curcas* along stone walls was of environmental rather than of economic nature. Wind and water erosion and poor soil fertility were stated as serious problems by all farmers in the northern region. All famers stated a high interest in *J. curcas* cultivation in view of its potential to reclaim degraded crop land. The planting of *J. curcas* trees along the contour stone walls aimed at stabilizing these and served as a complementary erosion control mechanism (windbreak, reduced run-off). The farmers experienced increase in soil fertility under *J. curcas* hedges due to the annual leaf shed, and they noticed that humidity remained longer in the soil. Additionally, the production of *J. curcas* seeds could generate alternative sources of income through seed sale or soap production. However, in their opinion, expanded *J. curcas* production is challenged by insufficient agronomic knowledge, weak infrastructure and lacking materials.

The planting of *J. curcas* was part of a pilot project initiated by the NGO Terra Verde in 2008. This NGO planned to buy all seeds, to press them in a locally installed pressing unit, and to use the vegetable oil for decentralized electricity supply such as motor pumps and multifunctional platforms. Two years after tree establishment, the first fruits were harvested, yet none were sold as the value chain beyond seed production was not yet in place. Table 3.5 provides a summary of the above-described systems.

Table 3.5 *Jatropha curcas* cultivation systems in Burkina Faso

Cultivation system	System characteristics	Agro-ecological conditions
Small-scale intercropping	*Jatropha curcas* combined with annual crops on a small scale (1.8±0.15 ha). Indirect, low-intensity management through maintenance of the intercrop, i.e., irregular fertilization (0-150 kg NPK and 0-100 kg urea ha^{-1} yr^{-1} for the intercrop), manual management, ox-plough, no pruning.	Sudanian agro-ecological zone (AEZ) with annual rainfall 950 mm from May to October. Main soil types *ferric lixisols* and *leptosols*.
Afforestation	No management. Land previously abandoned from agricultural activities.	
Intensely managed plantation	Intercropping or monoculture on a larger scale (50-70 ha). High-intensity management of *J. curcas* trees through regular fertilization (~150kg NPK and ~100kg urea ha^{-1} yr^{-1}), irrigation, motorized soil tillage, pesticide application.	
Living fence	Dense plantings around field for protection from browsing animals. Indirect, low-intensity management through maintenance of adjacent crop.	Sudano-Sahelian AEZ with annual rainfall 860 mm from May to October. Deep *lixisols.*
Contour hedge	Plantings along contour stone walls with wider spacing than in living fences. Indirect, low-intensity management through maintenance of adjacent crop.	Sahelian AEZ with average annual rainfall 650 mm from June to September. Mainly *cambisols.*

3.3.3 Land allocation to *Jatropha curcas* cultivation

In 89% of the visited *J. curcas* sites (n=111), *J. curcas* was integrated into existing cropping patterns as an intercrop or as hedge, thus not inducing immediate land-use change. The remaining 11% were established on savannah or fallow land. 95% of the interviewees cultivated *J. curcas* on their own property, with 56% using *J. curcas* trees for land demarcation. In 62% of all cases *J. curcas* was cultivated on normal to very fertile land with seed production and economic revenues as the main incentives.

Of the farmers not yet growing *J. curcas* systematically (n=110), 80% would start cultivating *J. curcas* for seed production in case of knowledge supply and financial support, 54% would then integrate *J. curcas* into their cropland, 27% would use fallow areas, and 19% would allocate the least fertile land to *J. curcas* cultivation.

Of the intercropping farmers (n=53), 49% stated positive effects of 2-year-old or younger *J. curcas* trees on the performance of the intercrop. However, 10 out of 12 farmers having plantations older than two years reported competition between expanding *J. curcas* trees and the annual crops. Seven farmers (with PD>1000 trees ha^{-1}) had therefore already stopped intercropping. In the end, yield reduction or total loss of annual crops could not be compensated by the revenues from *J. curcas* seeds sale. In 2011, some intercropping farmers intended to remove their *J. curcas* stands if seed prices were not to rise appropriately.

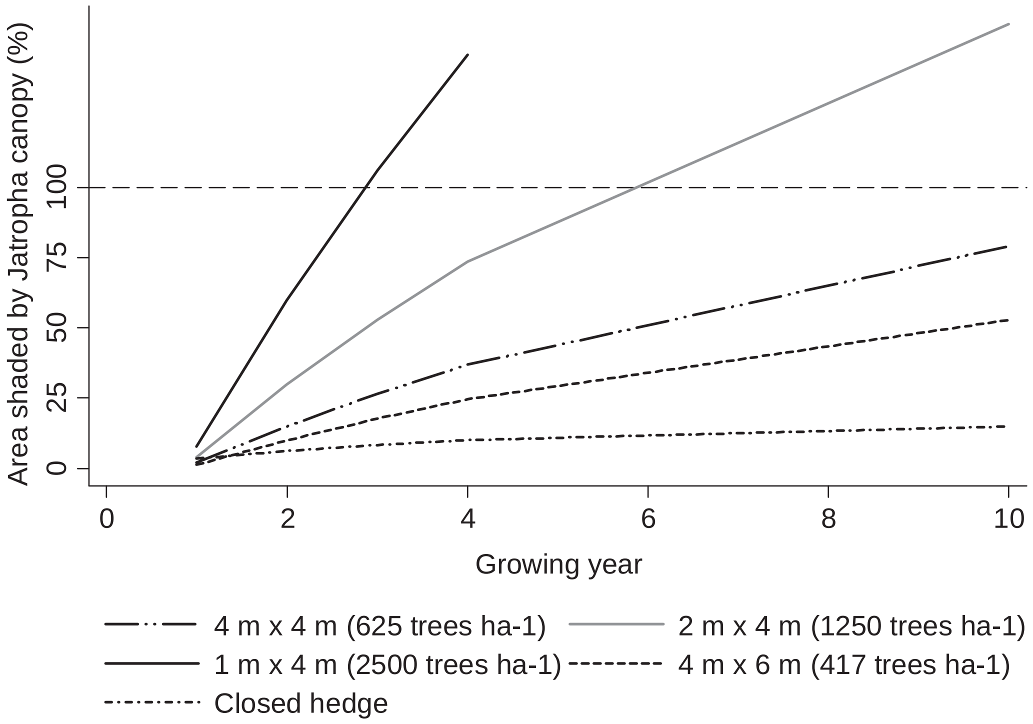

Figure 3.2 Canopy expansion area (% of one hectare) in *Jatropha curcas* systems with different spacing. Dotted line indicates total field coverage (100%) N=399.

With respect to the canopy expansion of *J. curcas* trees in the intercropping systems and the shading effect over the years (Figure 3.2; Appendix 9.7), it could be corroborated that, depending on the *J. curcas* planting density, food crops can be overshadowed and potentially crowded out from agricultural lands within few years of *J. curcas* cultivation. Plant density of more than 1000 plants ha^{-1} resulted in total shading in less than 6 years.

In the case of hedge systems, the shaded area was below 20%, and competition for space with annual crops was kept at a minimum through regular education pruning of the trees. Farmers stated unanimously that adjacent annual crops were benefitting from the surrounding *J. curcas* hedges.

3.1 Discussion

In Burkina Faso, as in other African countries, *J. curcas* has a long tradition as a species in living fences, and was only recently promoted as feedstock for biodiesel. Private companies working with local small-scale farmers in combination with managed large-scale plantations, and NGOs aiming at rural development are the main drivers of the newly arising *J. curcas* scene (e.g., in Madagascar (Uellenberg 2007), Kenya (GTZ 2009), Tanzania (van Eijck et al. 2010)). Although many stakeholders have been involved in *J. curcas*-related activities in Burkina Faso since 2007 (Table 3.3), none of them has yet reached seed production on a large scale, as also reported by Laude (2011).

3.1.1 Management practices in *Jatropha curcas* systems

Jatropha curcas is still an undomesticated plant about which systematic knowledge of input responsiveness and environment-dependent management optimization is scarce (e.g., Achten et al. 2010c; van Eijck et al. 2010; Singh et al. 2013). However, beyond the first claims that *J. curcas* can thrive on almost all soils with low input requirements (Jongschaap et al. 2007), it was learnt that when aiming at seed production, *J. curcas* trees need to be maintained, e.g., by weeding, fertilization, pesticide application, pruning, and clearing of firebreaks (van Eijck et al. 2010). Reviewing management recommendations given in literature, it becomes obvious that management of the systems identified in Burkina Faso is far from optimal. Weeding is the most important measure during the initial phase of tree growth (Heller 1996; van Eijck et al. 2010), as the competitive influence of fast growing weeds hinders young *J. curcas* trees in their development (Andersson et al. 2012; Everson et al. 2012). Competition between *J. curcas* and grasses was particularly experienced in unmanaged afforestation systems, leading to slower growth and additionally to higher susceptibility to bushfires during the dry season when the grasses die off. In seed-producing *J. curcas* stands, the application of fertilizer should at least cover the amount of nutrients withdrawn through seed harvest. Based on the nutrient contents of seeds (Reinhardt et al. 2008), 28 kg N, 12.4 kg P_2O_5, and 8.8 kg K_2O per ton of seeds are withdrawn from the soil at harvest, thus requiring the application of approximately 50 kg NPK and 50 kg urea fertilizer to the trees. Regular pruning was not done by most farmers, but is named as an important practice when aiming at maximizing productivity (Jongschaap et al. 2007; van Eijck et al. 2010; Rajaona et al. 2011). However, studies published recently indicate significant yield reduction after pruning (Everson et al. 2012; Singh et al. 2013). According to the farmers, pests such as beetles and termites were a threat to *J. curcas* growth, thus the application of pesticides should be considered in case of severe insect infestation. Termite attacks especially during the dry season can totally destroy young *J. curcas* stands (Sop et al. 2012). In general, *J. curcas* is not eaten by animals due to its toxic compounds (Heller 1996; Openshaw 2000; Henning 2009). However, cattle were reported to cause serious damages by roaming through the plantations and breaking branches. Bushfires commonly occurring during the dry season were also named as a threat to the trees. Although trees belonging to the *Euphorbia* family are likely to survive bushfires (Henning 2009), damage can still be substantial. Therefore, it is recommended to establish firebreaks during the dry season to protect the *J. curcas* stands. Overall, Singh et al. (2013) concluded that management recommendations have to be site specific, as the performance of plants is highly interconnected with soil and climate conditions.

Optimal management is only applicable by smallholder farmers if sufficient guidance via extension services is offered (Dyer et al. 2012; Liyama et al. 2012). This was not the case in the small-scale intercropping systems beyond plantation establishment. Consequently, smallholder farmers were only able to apply sub-optimal management, which can lead to the total failure of community-based *J. curcas* production (Bos et al. 2010). In line with Bos et al. (2010), it could be observed that following poor *J. curcas* performance, the farmers' disappointment in *J. curcas* production increased, partly leading to the removal of the plantations for the production of other crops.

Regarding competition for labor between *J. curcas* and food crops, results from literature show both competition for labor and compatible labor schemes (van Eijck et al. 2010). In line with studies showing that households with children, women and elderly people with little land do not have enough labor to work their land in a productive manner (Watson and Diaz-Chavez 2011), the majority of the interviewed smallholders had to employ seasonal farm workers in order to cope with the workload. The farmers described repeated seed harvests and seed dehusking as particularly labor intensive. Postponing these activities to low activity times by leaving the fruits on the plant for several weeks as proposed by Nielsen and de Jongh (2009 in van Eijck et al. 2010) could ease the workload, yet at the risk of fruit loss. However, in order to make *J. curcas* production a viable option for smallholders, markets have to be able to absorb a very low production of seeds (Bos et al. 2010), and prices for seeds should at least cover the opportunity costs of labor time spent on *J. curcas* cultivation.

Intensively managed large-scale *J. curcas* plantations are rare in Burkina Faso, and this is likely to remain so until the government sets up an energy policy defining the areas which can be allocated to energy crop production. Even if the system can be described as intensive in terms of maintenance, such management practices are still in an experimental stage. All private enterprises in Burkina Faso are currently operating on a limited scale (Laude 2011), probably due to knowledge gaps in agronomic management, lacking long-term funding, land acquisition problems, and unpredictable yields as reported by van Eijck et al. (2012) and Dyer et al. (2012) for Tanzania and Malawi.

The cultivation of *J. curcas* in living fences has a long tradition in Burkina Faso (Soulama 2008), fulfilling both productive and service functions (Young 1989 in Ayuk 1997). So far, the service functions soil and crop protection are regarded as most important. Only recently, in the course of the biofuel debate, have productive aspects received more attention. According to Bako (2011), approximately 754 million *J. curcas* trees have been planted in hedge systems throughout Burkina Faso. Irrespective of the enormous challenge and costs to collect all seeds from remote areas, the study concluded that 146% of the national petrol consumption could be covered (Bako 2011) without compromising food production through competition for labor and land. However, as long as no functioning seed market or seed collection system exists, fruits will remain unpicked in the field.

The planting of *J. curcas* along contour stone walls exists only as a pilot project. Nevertheless, it can be assumed that tree plantings along stone walls pose a win-win situation, with stone walls being stabilized and trees profiting from the sedimentation which takes place along the walls and the humidity which remains longer in the soil (Zougmoré et al. 2002). Local usage of *J. curcas* oil for motive power would act as an economic incentive to grow *J. curcas*.

Despite the persistent claim that *J. curcas* is suitable for dry areas and marginal soils (Heller 1996; Jongschaap et al. 2007; Achten et al. 2008) and the vision of the Burkinabe government to reclaim degraded areas through plantings of *J. curcas*, afforestation of poor soils plays a negligible role in Burkina Faso. Explanations can be seen in the lacking incentive to allocate time and money in an activity which is not promising high revenues. Low survival rates, bad plant performance and absence of fruit production are underlining the need for intensified management. However, it remains unclear whether the production of *J. curcas* on marginal soils can be an economically viable option (Dauber et al. 2012). Consequently, if marginal soils are to be used for biofuel production in Burkina Faso, it first has to be known at which expense this can be done successfully and second, which tools are needed to guide the biofuel production in these areas.

3.1.2 The land use dilemma

It was observed that most of the projects aiming at industrial production have located their plantations in the south-western part of Burkina Faso on more fertile lands (Blin et al. 2008) (Figure 3.1). With the integration of *J. curcas* as intercropping in existing agricultural systems, companies argued that they do not threaten food crop production or induce land-use change while producing biofuel. Data on tree density per hectare, spacing, and canopy shaded areas (Figure 3.2) show, however, increasing competition for space between annual crops and developing *J. curcas* trees. This competition eventually led to land-use change, reflected by the high proportion of intercropping plantations left as *J. curcas* monoculture plantations beyond the second growing year (Table 3.4). In this way, particularly productive land was converted into monoculture plantations, indicated by the farmers' allocation of more fertile land to *J. curcas* cultivation. Although farmers' perceptions may be subjective and location specific, the fact that a high share of land was previously used for cotton production and frequently intercropped with maize and *J. curcas* thereafter (Table 3.4) is an indication for the choice of fertile land. The use of prime agricultural land for *J. curcas* cultivation was also observed by Sop et al. (2012). Although no clear evidence regarding the negative impacts of *J. curcas* production on food security has yet been found in literature (van Eijck et al. 2010), reduced cultivation of sorghum and maize is likely to affect food production. The frequently observed replacement of the fiber crop cotton with *J. curcas* plantations (Table 3.4) could indirectly affect food production as soon as the profitability of cotton rises again and farmers restart cotton cultivation on land previously used for food crop production (Ndong et al. 2009). Nonetheless, the integration of *J. curcas* into existing smallholder agroforestry systems is in many cases documented as an opportunity for rural development (e.g., Francis et al. 2005; Wani et al. 2006; Achten et al. 2010b; Dyer et al. 2012) where the extent of *J. curcas* cultivation should be based on its compatibility with the existing cultivation systems (Achten et al. 2010c). In this regard, *J. curcas* hedge systems currently show the highest compatibility.

According to a study by Wicke et al. (2011), 11% (1.6 million ha) of the semi-arid area in Burkina Faso is potentially available for energy crop production while excluding agricultural land. However, the true availability might be much lower considering hardly assessable land-use forms such as livestock grazing, hunting and gathering (Dauber et al. 2012). Moreover, the productivity of non-irrigated *J. curcas* on semi-arid lands is questionable. Contrary to the common statement that *J. curcas* originates from arid and semi-arid zones (Jones and Miller 1992 in Heller 1996, Domergue and Pirot 2008; Henning 2009), Maes et al. (2009) found the natural distribution in areas with a humid climate and high temperatures. Also, findings from Krishnamurthy et al. (2012, p.250) on the basis of a root system analysis show that under drought *J. curcas* is rather “a good survivor” than “a good producer”. Within this context, land allocation to *J. curcas* biofuel production remains the key challenge for the Burkinabe government, which has to find a balance between marginal land reclamation and profitable biofuel production without affecting food security.

3.2 Conclusions and recommendations

In the most widely distributed small-scale intercropping system, *J. curcas* trees were not directly maintained but indirectly benefited from the management of the intercrop. Here, choice of intercrop and spacing of *J. curcas* trees have to be optimized in order to allow concurrent cultivation. However, as a result of low seed prices, labor-intensive harvest and dehusking, and yield losses of intercrops due to inadequate tree spacing, small-scale farmers should rather grow *J. curcas* in hedges on field boundaries than in sub-optimally managed plantation systems, which are leading to land-use change and might compromise their food production. Living fences offer a variety of benefits to the farmers, such as erosion control and protection against damage by animals, and can be established and maintained with relatively little effort. With a functioning collection system in place, hedges could contribute substantially to the national seed supply. The planting of *J. curcas* trees as contour hedges along erosion control walls in northern Burkina Faso is still in the pilot phase, but promises the same benefits as living hedges. Afforestation systems on nutrient-poor abandoned cropland were not maintained, and showed very poor growth performance with no seed production in the first years. If seed production is aimed for, the trade-off between the cost of intensified management and seed production should be considered. Intensively managed large-scale *J. curcas* plantations are not common in Burkina Faso, and this is likely to remain so until the government decides in favor of allocation of land for large-scale bioenergy production.

For all systems, the management regime needs to be improved and intensified if seed production is the main purpose. As management optimization is reported to be highly site specific, experimental research on *J. curcas* cultivation in Burkina Faso is extremely relevant. Research targets should particularly comprise selection of improved varieties, input responsiveness of *J. curcas,* and management optimization of intercropping systems. It also has to be ensured that optimized management packages are transferred to the *J. curcas* farmers.

4 DYNAMICS IN ABOVE- AND BELOW-GROUND BIOMASS

4.1 Introduction

The lack of biomass and seed estimations precludes adequate life cycle analyses (LCA) of *J. curcas* production pathways. To date, the assessments have either relied on default biomass values (Dehue and Hettinga 2008; Paz and Vissers 2011) and rough estimates (Struijs 2008) or did not account for C sequestration in biomass at all (Ndong et al. 2009; Whitaker and Health 2009; Gmünder et al. 2010). In the absence of reliable yield estimations, many LCAs used overoptimistic yield scenarios (Gasparatos et al. 2012). Incomplete data on key parameters lead to flawed predictions and prevent decision makers from formulating the right strategies for biofuel policies. Information on biomass dynamics and carbon (C) sequestration through various growth phases of the different *J. curcas* cultivation systems is required to quantify the potential of this perennial biofuel crop as a local energy source and for CO_2 emission reduction via C sequestration in woody biomass, as well as via substitution for fossil fuels. Although the tree species has been cultivated in Burkina Faso since 2007, its productive capacity remains rarely studied (Sop et al. 2012).

Repeated destructive measurement of tree biomass is time and labor consuming, and can be avoided once allometric relationships between height or diameter and tree biomass are defined (Pilli et al. 2006). The robustness of allometric relations between biomass and stem diameter has been proven in numerous studies covering different tree species (Niklas 1994; Ketterings et al. 2001; Pilli et al. 2006; Zianis 2008). The relationships developed for particular species applied to a wide range of growing conditions and tree development stages (Landsberg and Sands 2011). Nonetheless, biomass growth depends on site and age factors (Pilli et al. 2006), and therefore the accuracy of biomass estimates greatly relies on the adequacy of the applied equation (Zianis 2008).

Some site-specific studies have investigated allometric relationships with respect to the tree species *J. curcas* (Ghezehei et al. 2009; Achten et al. 2010a; Rajaona et al. 2011; Hellings et al. 2012), albeit based on a modest sample size. Achten et al. (2010a) determined the relation between stem diameter and total above-ground biomass (AGB) based on data from 41 potted seedlings and using a common power function. Ghezehei et al. (2009) revealed strong relationships between various AGB fractions and basal diameter of twelve 16-26-month-old trees grown in a plantation in South Africa, while Hellings et al. (2012) applied a power model on 15 trees aged 2.5 to 7 years in semi-arid Tanzania. Both Achten et al. (2010a) and Rajaona et al. (2011) reported failed allometric relations in pruned trees.

Below-ground biomass (BGB) represents an important part of the ecosystem carbon budget (Gill and Jackson 2000; Brunner and Godbold 2007; Konôpka et al. 2010). Allometric relations for BGB of mature trees are less commonly reported given that few studies have attempted time consuming root excavations. Razakamanarivo et al. (2012) accurately predicted BGB in *Eucalyptus* spp. via regression with stump circumference, while Landsberg and Sands (2011) confirmed allometric relations between stem diameter and root mass of the species. However, allometric relations for estimating BGB in *J. curcas* are yet to be developed.

Biomass dynamics in *J. curcas* over time have been addressed by Achten et al. (2010a), Behera et al. (2010), and Rajaona et al. (2011), although no such studies have been conducted in West Africa. Projections of biomass and C accrual over time are important for selecting an optimal rotation length of tree plantations (Liski et al. 2001) and calculating their C offset potential (Dean et al. 2003; Masera et al. 2003; Shoch et al. 2009).

Seed yield is the most important parameter for economic viability of biofuel production and its CO_2 reduction potential via fossil fuel substitution (van Eijck et al. 2010). Yet the factors affecting productivity are not well understood (Achten et al. 2008; Liyama et al. 2012) partly owing to the fact that *J. curcas* is still a wild plant with great variability in productivity between individual plants (Francis et al. 2005; Contran et al. 2013). Moreover, yield estimations of *J. curcas* trees are extremely difficult to obtain due to year-round ripening of fruits and long-term developments (Liyama et al. 2012). This uncertainty is reflected in yields reported in literature ranging from 1.5 to 7.8 t ha^{-1} (e.g., Heller 1996; Francis et al. 2005; Jongschaap et al. 2007; Achten et al. 2008).

This chapter aims to fill this knowledge gap by (i) establishing allometric equations for a non-destructive estimation of above- and below-ground biomass in *J. curcas* production systems in Burkina Faso, (ii) developing an empirical model for simulating biomass growth and C stock over time, and (iii) collecting data for seed yield prognoses of *J. curcas* stands in Burkina Faso.

4.2 Materials and methods

4.2.1 Sample design and control for confounders

Given the perennial nature of *J. curcas* and the lack of long-term observations on cultivated *J. curcas* in Burkina Faso, the biomass growth over time was studied in an observational research setting constructing age chronosequences of *J. curcas* trees grown in same management systems. The nature of observational studies is the impossibility of controlling all influencing factors; thus the data are subject to confounding (Gail 2005). Here, a design-based approach to control for confounding was used where all covariates are stratified into homogenous groups, as a covariate within an internally homogenous stratum no longer has a confounding effect (Greenland 2005).

The sampling sites for the biomass studies were selected based on the inventory study (Chapter 3) following a two-stage sampling approach. First, *J. curcas* stands were stratified according to the defined management systems found in different agro-ecological zones (AEZ). The *J. curcas* systems adapted to the particular AEZ were assumed to represent homogenous strata with similar management and environment (Table 3.5). Well-performing plantations with homogeneous *J. curcas* stands and unpruned trees were selected to avoid the influence of random factors such as improper maintenance, insect attacks or fire incidents. This selection could not be achieved for afforestation systems on marginal land where plants performed poorly due to lack of maintenance.

The second step of the sampling methodology was the selection of available age classes within each system type. In the following table, the number of investigated sites is listed separately according to the age of plantation and the system type.

Table 4.1 Number of plantations visited and plants measured (N(n)) according to management system and time since *Jatropha curcas* planting

Management system/ years since planting	**1**	**2**	**3**	**4**	**5-10**	**11-25**	**Total**
Small-scale intercropping	3(25)	15(113)	14(128)	2(11)	0	0	34(277)
Afforestation	4(40)	2(30)	0	0	0	0	6(70)
Intensely managed plantation	0	0	3(30)	1(10)	0	0	4(40)
Living fence	3(9)	1(3)	5(13)	0	20(63)	11(60)	40(148)
Contour hedge	0	4(32)	2(23)	0	0	0	6(55)
Total	10(74)	22(178)	24(194)	3(21)	20(63)	11(60)	**90(590**)

Data adopted from the inventory study (Hallensleben 2011) and own investigation in 2010 and 2011.

Interest of investigation was rather the comparison of the different *J. curcas* systems than of intra-system management interventions and their effects on biomass dynamics. Thus, all possible confounders were included in the system factor, while all other influencing factors that can contribute to variation within the observations were at random and could not be defined.

4.2.2 Study sites

Basic characteristics of the study regions are given in Chapter 2. Based on soil sampling (see section 5.2 for methodology), the study sites could be described pedologically; evaluation was done according to BUNASOL (1990).

In south-western Burkina Faso, in the Sudanian AEZ, *J. curcas* was introduced in small-scale, low-input intercropping systems and in larger-scale, more intensely managed plantations. These sites were predominantly characterized by shallow (53±7 cm) *ferric lixisols* (WRB 1998) corresponding to *leached ferruginous soils* (CPCS 1967), with sandy loamy texture in the topsoil and clay content increasing with depth. Agricultural activities seemed to be mainly constrained by low plant-available nutrients, restricted soil depth (<60 cm) and high gravel content in the topsoil.

Table 4.2 Location of investigated *Jatropha curcas* sites (Figure 3.1) and their average soil parameters

AEZ	**Nearest city to study site**	**Precipitation**	**Soil type**	**pH**	**P**	**K**
		mm			Ppm	
Sudanian	Boni	850	ferric lixisols and leptosols	6.1±0.1	3.0±1.2	24±5.3
	Dano	950				
	Banfora	1040		6.3±0.2	1.0±0.1	21±5.0
Sudano-Sahelian	Mogdedo	860	Lixisols	6.3±0.1	1.5±0.3	61±18
	Manga					
	Bagré					
Sahelian	Kongoussi	650	cambisols	6.0±0.1	1.0±0.1	58±5.1

AEZ: Agro-ecological Zone. Soil types classified according to the International World Reference Base for Soil Resources (WRB 1998 and 2006). Plant available phosphorus (K) and potassium (K).

Afforestation plots were found on very shallow (<40 cm) *leptosols* (WRB) (*poorly evolved soils of erosion,* CPCS) and *endo-plinthic ferric lixisols* containing over 20% of ferruginous gravel. Sandy loamy in upper horizons and more clayey in depth, these soils were particularly poor in plant-available phosphorus (P) and potassium (K), and agricultural activities on these sites had been abandoned several years before *J. curcas* planting owing to low productivity. The mean annual rainfall (2007-2010) at the nearest meteorological stations in Houndé, Dano and Banfora was 850, 950 and 1040 mm, respectively.

Within the Sudano-Sahelian AEZ, living fences of *J. curcas* are traditionally planted to protect farm fields from animals. The hedges contained *J. curcas* shrubs of varying age (due to self-propagation), growing on 120-cm deep *lixisols* with a sandy or silt-loamy texture. The presence of *fluvisols* and *regosols* was an exception. The average annual rainfall (2007-2010) at the nearest meteorological station in Mogdedo was 860 mm.

Further to the north, in the Sahelian AEZ, *J. curcas* was planted along the stone walls established 20 years ago against wind and water erosion. This area is characterized by >100-cm deep *cambisols* (WRB) or *brown eutrophic soils* (CRCS), clay-loamy in texture with clay content increasing in deeper horizons. The average annual rainfall was 650 mm.

Soil concentrations of plant-available P and K in the top 40 cm ranged between very low and medium (0.5-5.5 ppm P; 12-35 ppm K) across all sites, while the soil reaction varied from moderately acid to neutral (pH=5.6-6.6). Low concentrations of total nitrogen (N_t=0.06-0.08%) and total organic carbon (TOC=0.76-1.04%) prevailed in all examined sites. The average observed soil bulk density was between 1.33 and 1.53 g cm^{-3} (below the average 1.7 g cm^{-3} for Burkina Faso (BUNASOL 1990)).

4.2.3 Measurements of tree dimensions and dry matter production

Ten plants per plantation were chosen randomly – poorly developed trees were excluded - and marked with paint. Stem height (H) and canopy diameter (CD) were measured with a measuring tape; diameter at the stem base (D) was measured with a caliper. In case of ramification at stem base, D (cm) and basal area (BA, cm^2) were computed as follows:

$$D = \sqrt{\sum_{i=1}^{n}((Di)^2)} \tag{4.1}$$

$$BA = \sum_{i=1}^{n}((Di)^2/4\pi) \tag{4.2}$$

where *i* represents the number of ramified stems measured at stem base.

Subsequently, 2-5 of the measured trees were felled and separated into stem, branches, leaves and fruits. However, permission was not given for cutting trees in intensely managed plantations, and thus only H and D were measured. As ramification starts near the basis of the stem, branches were considered to be all woody parts starting at the second ramification (Figure 4.1).

Roots were completely excavated with hand tools and washed free of soil. Root length and root diameter were measured with a measuring tape and a caliper, respectively. Next, the root systems were separated into four categories according to the diameter, i.e., ∅ <3 mm, 3-10 mm, 10-30 mm, and >30 mm. The fresh weight (FW) of all fractions was determined in the field; subsamples (sFW*)* were taken to the laboratory, dried at 103°C until constant weight and weighed for dry mass (sDW) determination. The amount of total dry matter per tree (DW, g) was calculated.

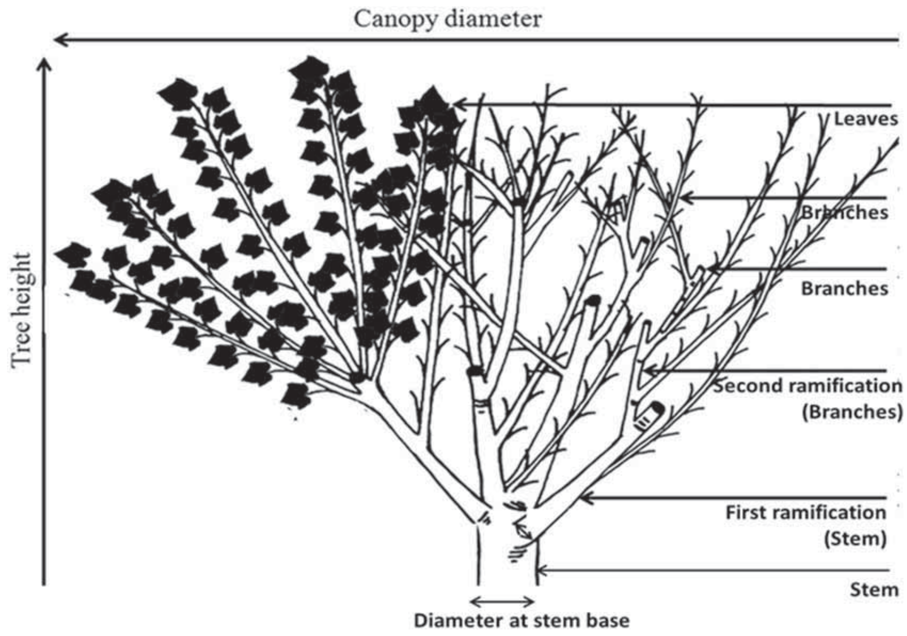

Figure 4.1 Tree layout (modified according to Rajaona et al. 2011)

The total biomass per hectare was calculated by multiplying tree weight with plant density per hectare (PD), with the latter estimated for plantations by determining the inter- and intra-row distance between trees. The PD in living fences was estimated by extrapolating the number of trees growing in a 10-m long hedge section to a hedgerow surrounding a one-hectare field (400 m). The intercropping, afforestation and intensely managed plantation systems counted 625 trees ha^{-1} (spacing 4 m x 4 m), living fences 900±50 trees ha^{-1} (intra-row spacing ~0.5 m), and contour hedges 200 trees ha^{-1} (intra-row spacing 2 m) (section 3.3.2).

To capture the growth dynamics of *J. curcas* over the entire growing period, the shoot and root biomass of sixty 4-week-old, nursery-grown seedlings and the stem dimensions of twenty 15-20-year old trees growing in two sparse plantations in central Burkina Faso were additionally measured. A total of 670 trees were measured, including 158 harvested for AGB and BGB determination. All measurements were conducted during November in 2010 and 2011, after the rainy season.

4.2.4 Fruit yield observations

Continuous harvest of ripe *J. curcas* fruits was undertaken in 45 *J. curcas* stands for two trees each (90 trees in total) during the fruit-bearing season from August 2010 to February 2011. Fruit and seed characteristics (seed-shell ratio, number of seeds per fruit, thousand-seed weight) as well as total yield were determined. The fruit picking was done by the farmers; in the case of managed systems once a week, and for living fences twice per season.

4.2.5 Statistical analyses

Statistical analyses were performed using STATA (12.0). All data sets were tested for normal distribution and homogeneity of variances. In case of heteroscedasticity, the data were logarithmically transformed and checked for robustness. Influential points according to Cook's D (>1) and DFITS were excluded using robust linear regression with log-transformed data. Tests for significance were conducted using linear regression and multiple Bonferroni-adjusted comparisons (all at 0.05 level) unless indicated otherwise. All regressions were adjusted for nested design (trees nested in plantations), and scatter plots of the residuals were checked for any systematic error in estimates. The mean values ± standard errors are reported unless indicated otherwise. Further statistical methods used are described in the following sections.

Growth stages

The commonly used Chapman-Richard and Weibull function for height-diameter modeling failed to converge owing to the large sample size (Huang et al. 1992; Zhang 1996; Pilli et al. 2006). Therefore, the Gompertz function was used, with its asymmetric sigmoid shape allowing greater flexibility than a logistic function (Winsor 1932):

$$H = \beta_1 \cdot exp(-exp(-\beta_2(D - \beta_3))) \tag{4.3}$$

where $\beta_{1,}\ \beta_{2,}\ \beta_3$ are the parameters to be estimated, with β_1 presenting the asymptote, β_2 the shape of the curve, and β_3 the inflection point; H is the total tree height (m) and D the diameter at stem base (cm).

The temporal pattern of the HD ratio was analyzed in order to identify the different growth stages (Niklas 1994; Bond 2000; Pilli et al. 2006). The relative height increment (RHI=δH/δD) and its first partial derivative f'(RHI) were obtained accordingly. The presence of an inflection point indicated a complete dataset where it is possible to distinguish a juvenile, adult and mature growth stage (Pilli et al. 2006). The juvenile phase is commonly associated with increasing RHI, the adult stage (maturity) with decreasing growth increments is placed between the maximum and the point of inflection of the RHI, and the subsequent mature phase (senescence) is characterized by stagnating growth (Brack and Wood 1997; Pilli et al. 2006). The different stages were thus distinguished according to the stem diameter thresholds identified.

Allometric equations

Jatropha curcas is a semi-deciduous species, shedding its leaves during the dry season. The deciduousness cannot be captured by an allometric relation, thus the inclusion of foliage into biomass prediction can generate misleading results (Ghezehei et al. 2009). In this study, only dry woody above- and below-ground biomass (excluding fruits) was considered by the allometric models. The empirical relationships between biomass and the predictive variables (diameter and height) were established for 141 *J. curcas* plants (16 cases with missing data were excluded) aged 0-20 years and showing a stem diameter range from 0.7 to 21 cm. A set of equations was tested to identify the most appropriate model for the biomass estimation of *J. curcas* trees.

First, AGB and BGB were estimated by a power function according to Niklas (1994):

$$M = \alpha D^{\beta} \tag{4.4}$$

where M is total dry woody above- or below-ground tree biomass (kg), D is tree diameter at stem base (cm), and α and β are scaling coefficient and exponent, respectively.

Ketterings et al. (2001) proposed a site-specific refinement of the power function by including height measurement into the equation, as they hypothesized that the scaling exponent between M and D depends on the relationship between H and D. They suggested the form:

$$M = \alpha \cdot D^{2+c} \tag{4.5}$$

where c=0.55 as estimated from the site-specific relationship between D (cm) and H (m) with k=0.58:

$$H = k \cdot D^{c} \tag{4.6}$$

The traditional allometric approach by fitting a linear model to logarithmically transformed data is recommended when the standard deviation of M at any D increases in proportion to the value of D, meaning that values of M can be measured more precisely at low than at high diameter levels (Zar 1996 in Zianis and Mencuccini 2004). Additionally, log transformation normally results in homoscedasticity of the variables, which is prerequisite for least square regression (LQR) models:

$$lnM = ln\,\alpha + \ \beta \cdot lnD \tag{4.7}$$

The linear model was then back-transformed to a power function using a correction factor CF. This factor adjusts the bias in logarithmic regression estimates and accounts for the back-transformation of regression error when transforming linear models to power functions (Baskervielle 1972 in Mascaro et al. 2011; Razakamanarivo et al. 2012).

$$M = \alpha D^{\beta} \cdot CF \qquad \text{and} \qquad CF = exp^{(\frac{MSE}{2})} \tag{4.8}$$

where MSE is mean squared error of the regression.

As the rate of height growth relative to the rate of growth in trunk diameter decreases with increasing tree size and age, allometric equations were established for each growth stage (Niklas 1995) as determined by the D classes (section 4.3.3), using equation 4.7 and 4.8. For BGB estimation the root-shoot ratio (RSR) was also considered.

The performance of all models was tested with the following three criteria: 1) coefficient of determination R^2, 2) standard deviation of residual error RSE (where a smaller RSE indicates a smaller unexplained part in the observed biomass and an overall better fit of the model), and 3) relative difference (RD, %) between the observed (M_o) and predicted (M_p) biomass value:

$$RD = \frac{|Mp - Mo|}{Mo} \cdot 100 \tag{4.9}$$

RD values were compared using panel regression with repeated measurement and multiple, Bonferroni-adjusted comparisons. To check for statistically significant differences between the model parameters, their confidence intervals (CI) were compared following van Belle (2008, p. 38): “confidence intervals associated with statistics can overlap as much as 29% and the statistics can still be significantly different”.

$$0.29 = overlapping\ CI/(\frac{CI1}{2} + \frac{CI2}{2}) \tag{4.10}$$

Growth models

Based on the developed allometric equations, AGB and BGB were predicted for all measured trees in a diameter range of 0.7-35 cm. A nonlinear model was subsequently fitted to the complete data set, relating biomass accumulation with tree age (years) for the different systems. A three-parameter logistic function was selected, which is one of the most useful models for fitting sigmoid responses (Ratkowsky 1990 in Tjorve 2003):

$$AGB = \beta_1/(1 + exp(-\beta_2 \cdot (Age - \beta_3))) \tag{4.11}$$

where β_1 is the asymptote, β_2 determines the shape of the curve, and β_3 is the inflection point. The model was fitted to data from individual trees (kg tree^{-1}) and total stands (t ha^{-1}). The latter was calculated by multiplying single tree weight with the common plant density per hectare for the respective system.

Due to the recent introduction of *J. curcas* in Burkina Faso, only the traditionally practiced living fences were older than four years. Therefore, mature trees (section 4.2.3) were used for the model calibration for intercropping and intensely managed systems. J*atropha curcas* plantings along the contour stone walls were assumed to follow a similar growth pattern to sparse living fences (PD <700 trees ha^{-1}). No mature counterparts were found for the young plants in the afforestation system.

The model parameters were compared according to Eq. 4.10. Inter-system difference in biomass accumulation was tested by a two-tail Student’s t-test and mixed-effects multilevel linear regression (two levels: plantation and tree) with postestimation Wald test; intra-system comparison was conducted using linear regression and multiple Bonferroni-adjusted comparison (all at 0.05 level). Influence of soil properties (gravel content and soil depth) and fertilization (kg N applied on *J. curcas* plantation since planting) on biomass accumulation was tested with mixed-effects multilevel linear regression (three levels: system, plantation and tree).

4.2.6 Model validation

An independent dataset (Fondation Fasobiocarburant 2011) used for the model validation contained 100 cases, including 21 one-year old trees, 76 two-year olds and three 20-year olds with D ranging from 2.5-27.5 cm. The trees were grown in intercropping systems and living fences in the west Sudano-Sahelian and north Sudanian AEZ of Burkina Faso. Amongst these cases, 18 observations with known AGB and BGB (9 intercropping systems, 9 living fences) and D range of 7-14 cm were compared with values simulated by the log-transformed Eq. 4.7 and the general allometric Eq. 4.4 for the adult and mature growth phase, respectively. AGB and BGB of the remaining intercropped trees were estimated by the equations 4.7.1, 4.7 and 4.4 respectively for the juvenile, adult and mature growth stages (Table 4.6), and then taken for growth model validation. Only the cases with known biomass values were considered for living fences, as the allometric relationships did not hold sufficiently for hedge systems (section 4.3.7). Mean prediction error $\bar{e} = \sum(y - \bar{y})/N$ (y is independent data, $\bar{y}$ predicted data and N number of cases) and RD were used to evaluate the quality of the model fit.

4.2.7 Carbon stock estimation

Samples of stems, twigs, and roots (n=42) were analyzed for total C and N content by dry combustion with a EuroEA Elemental Analyzer in the soil laboratory of the University of Bonn; all samples had been dried at 103°C until the constant weight and ground to pass a 0.2-mm sieve prior to the analyses. Carbon storage in woody biomass (t ha^{-1}) was calculated based on modeled AGB and BGB stocks and measured wood-C concentrations.

4.3 Results

4.3.1 Morphological and physiological attributes of *Jatropha curcas* trees

Mean H, D and AGB values of *J. curcas* trees of different ages are given in Table 4.3. A 3-year-old *J. curcas* tree had a mean height of 206 cm, a diameter of 11 cm, a woody above-ground dry weight of 3.5 kg, rooting depth and radius of 52 cm and 150 cm respectively, and a root-shoot ratio (RSR) of 0.45. The RSR decreased with increasing diameter from 0.53±0.3 in the juvenile stage (corresponding with findings of Achten et al. (2010a) showing a mean RSR of 0.50 for *J. curcas* seedlings), over 0.41±0.2 in the adult to 0.35±0.4 in the mature stage. The water content of leaves and woody above- and below-ground parts were 78%, 74% and 71%, respectively. Nitrogen and C content in the plant parts are displayed in Table 4.4.

Table 4.3 Observed grow parameters diameter at stem base (D), tree height (H) and above-ground biomass (AGB) of *Jatropha curcas* trees of different ages over all plantation systems

Years since planting	**D (cm)**		**H (cm)**		**AGB (g)**		**No of trees measured N and cut n**
	Mean	**SE**	**Mean**	**SE**	**Mean**	**SE**	**N(n)** [b]
0[a]	1.2	0.1	63	4.9	3.6	0.2	60(60)
1	5.3	0.4	119	11	265	78	74(23)
2	8.6	0.5	174	11	1511	470	178(42)
3	10.8	0.5	206	7.2	3494	608	194(23)
4	13.3	0.8	233	6.1	5590	227	21(3)
5-10	17.4	1.5	298	9.5	n.o.	n.o.	63(0)
11-25	21.1	2.5	340	8.0	11992	1473	80(7)

[a] *4-week-old seedlings from a nursery;* [b]*outliers excluded;*
SE: standard error of the mean adjusted for nested design. n.o.: no observations. Data from the inventory study (Hallensleben 2011) and own investigation in 2010 and 2011.

Table 4.4 Nitrogen and carbon content (%) in plant parts, their coefficient of variation (CV) and standard error (SE)

	N (%)	**SE**	**CV (%)**	**C (%)**	**SE**	**CV (%)**
Wood	1.19	0.07	37.8	43.1	0.23	3.55
Leaves	2.06	0.06	19.9	43.6	0.20	3.03
Roots	0.66	0.02	18.2	41.0	0.28	4.70
Press cake	3.60	0.06	3.33	47.7	0.63	2.64
Hull	0.79	0.02	3.80	49.1	0.71	2.51
Shell	0.90	0.02	8.89	42.1	0.56	1.33
Seed	2.61	0.04	5.00	54.4	0.28	1.64

A high coefficient of variation (CV) for N contents in wood, leaves and roots led to the assumption that site characteristics might influence the nutrient content. However, statistical tests did not show significant effects of site, age and N content in soil (see section 5.2 for methodology) on the N concentration of plant components. Nitrogen in seed components and C concentrations in all plant components seemed stable over all site conditions.

4.3.2 Fruit characteristics and seed yield

Average thousand-seed weight (TSW) lay between 702 and 732 g with an increase over age. Trees in the adult phase (5.5 cm ≤ D < 12.3 cm) had a significantly lower TSW of 694±9.7 g than mature trees (D ≥ 12.3 cm) with a TSW of 735±10.5 g. Seed-shell proportion increased significantly over age with 0.2% per year, starting with 67% in the first year and arriving at 73% in the 25th year. The mean dry seed yield over the fruit-bearing season August 2010 to February 2011 is displayed in following table:

Table 4.5 Average dry seed yield (kg ha^{-1}) and standard error over *Jatropha curcas* systems and observed age

Jatropha **system**	**Age**	**Seed yield**	**PD (trees ha^{-1})**	**n**
Intercropping	2 years	764±86.2	625	22
	3 years	813±204		8
Living fence	>7 years	721±64.7	900	58
Contour hedge	2 years	111±18.2	200	2

PD: plant density. n: Number of observed trees.

Two-year-old afforestation systems did not yet start producing seeds; the yield structure of intensely managed plantations could not be monitored due to logistical obstacles but was reported to range between 1 and 2 kg $tree^{-1}$ (625-1250 kg ha^{-1}) (A.K. Sanou 2011; personal communication).

In all systems, significant correlation (Pearson correlation p=0.001) was observed between the number of fruits counted in August and stem diameter and tree height of the respective tree. This correlation also applied to total seed yield and stem diameter ($p<0.05$) in plantation systems, but was not apparent in living fences. This led to the assumption that seed yields monitored in living fences might be underestimated due to infrequent harvest and consequential fruit loss.

4.3.3 Growth stages

The HD relation described by the Gompertz function yielded

$$H = 3.59 \cdot exp\left(-exp\left(-0.14(D - 5.51)\right)\right)$$

where β_1 with 3.59 presents the asymptote, β_2 with 0.14 the shape of the curve and β_3 with 5.51 the inflection point.

The inflection point fell within the D range of 5.2-5.8 cm, indicating the transition from the juvenile to adult growth phase. Maturity was reached with D=12.3 cm, where the second partial derivative f'(RHI) (negative) reached its minimum (Figure 4.2).

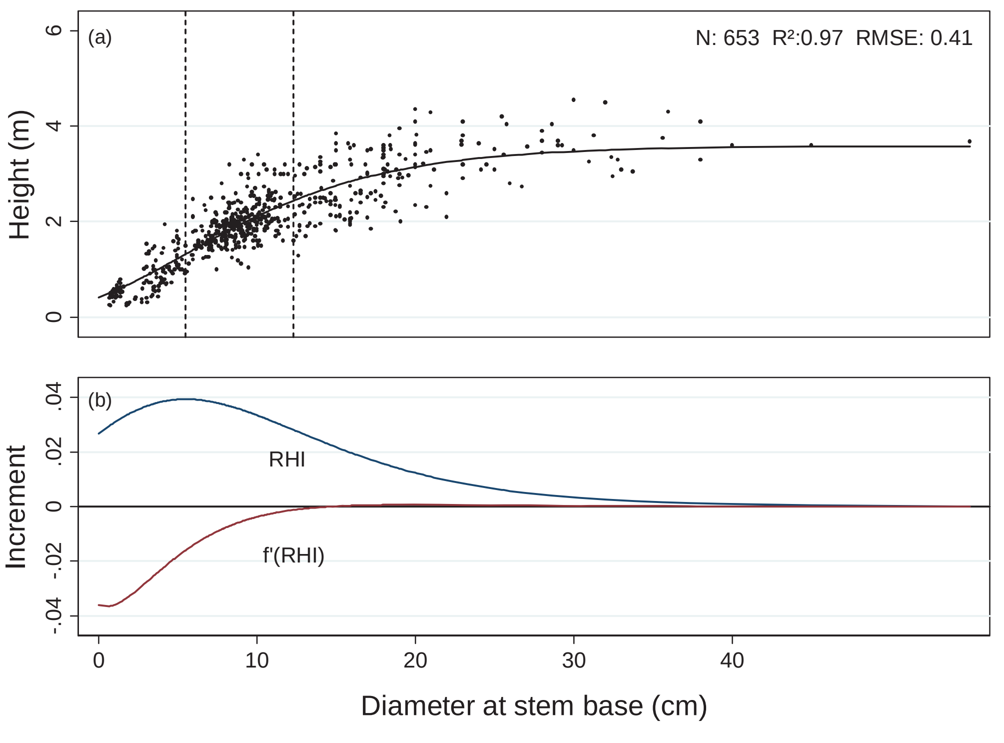

Figure 4.2 (a) Scatter plot and curve fitting of height (H) against diameter at stem base (D); (b) relative height increment (RHI=δH/δD) and its first partial derivative f'(RHI). Dotted lines indicate thresholds from juvenile phase to adulthood, and from the adult to mature growth stages. N=653 (one outlier and 16 trees with missing data excluded).

Relating the D threshold (D <5.5 cm) with age allocated 66% of the one-year-old plants and 12% of the 2-year-old plants to the juvenile phase. The adult stage commenced at latest when trees reached D ≥5.8 cm, as detected in 79% of the 2-year-old and 72% of the 3-year-old trees. The remaining 9% of the 2-year-olds and 28% of the 3-year-olds were found to have already reached the mature stage. Almost all 7-year-old trees had left the adult phase of fast growth and entered the senescence.

4.3.4 Allometric relationships

Above-ground woody biomass

Strong allometric relationships between AGB and D were revealed by fitting a power model, a power model including the H-D relationship, and a linear model back-transformed to a power function (Eq. 4.4, 4.5, 4.7, Table 4.6). All three models accounted for more than 90% of the variance, and had significant parameter estimations.

Table 4.6 Parameters and properties of allometric relationships of above-ground biomass (M, kg tree^{-1}) and diameter at stem base (D, cm)

Allometric relationship	**n**	**D range**	**A**	**P**	**β**	**p**	**RMSE**	**R²**	**Eq.**
$M = \alpha D^{\beta}$	141	0-21	0.016	0.07	2.31 a	0.00	1.04	0.92	4.4
$M = \alpha D^{2+c}$	141	0-21	0.008	0.00	2.55^{a} a		1.07	0.91	4.5
$\mathrm{LnM} = \ln\alpha + \beta \cdot \ln D$	141	0-21	0.003^{b}	0.00	3.03 b	0.00	0.43	0.98	4.7
LnM_1	76	0-5.5	0.003^{b}	0.00	2.74 ab	0.00	0.39	0.96	4.7.1
LnM_2	54	5.5-12.3	0.001^{b}	0.00	3.68 b	0.00	0.40	0.68	4.7.2
LnM_3	11	12.3-21	0.003^{b}	0.01	2.93 ab	0.00	0.33	0.75	4.7.3

[a] *$\beta = 2 + c$ with $H = 0.58 \cdot D^{0.55}$;*

[b] *corrected $\alpha = \exp(CF + \ln a)$(Eq.4.8);*

α and β are parameters to be estimated. RMSE: root mean squared error. n: Number of trees, R²: coefficient of correlation. Different letters indicate statistically significant difference at p<0.05. Robust cluster estimation.

The log transformation of diameter and biomass data in Eq. 4.7 normalized the biomass error structure along the range of D values and accounted for multiplicative errors and heteroscedasticity, yielding the linear regression model illustrated in Figure 4.3.

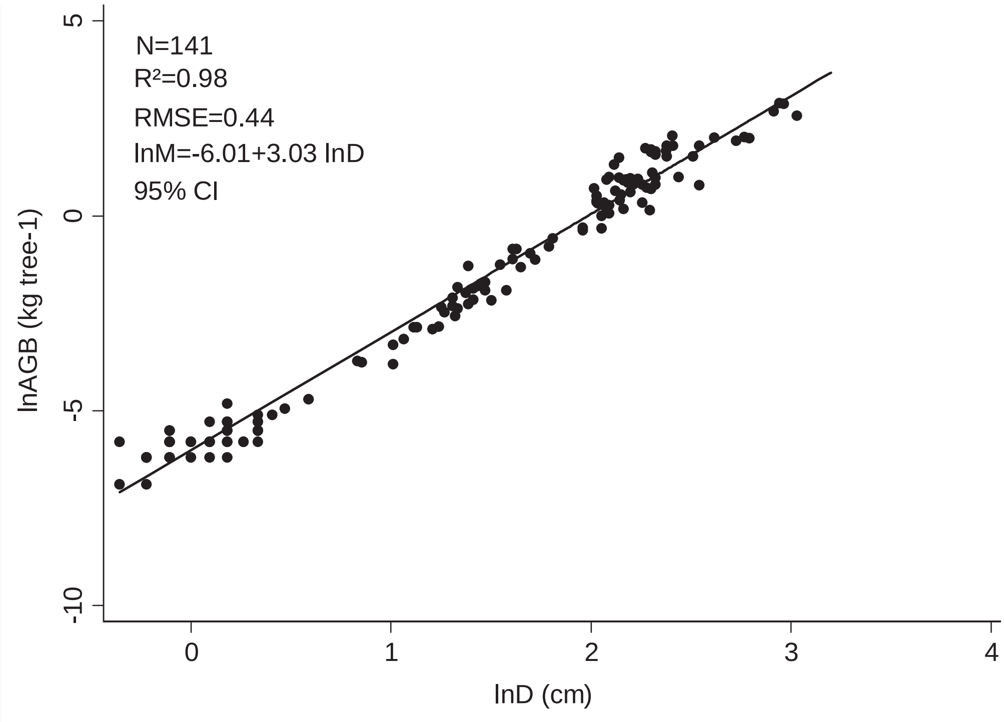

Figure 4.3 Logarithmically transformed diameter (lnD) versus woody above-ground biomass (AGB). N: number of trees, RMSE: Root Mean Squared Error

The parameter β with 3.03 was significantly higher than that of the models 4.4 and 4.5. The back-transformation with the application of the correction factor CF: 1.103 (Eq. 4.8) resulted in $\mathrm{M} = 0.003 \cdot \mathrm{D}^{3.03}$, which showed a higher R² and lower RMSE in comparison to the first two main models (Eq. 4.4, 4.5). The linear model (Eq. 4.7), run separately for the growth stages as defined by the diameter classes, showed a good fit for the juvenile stage, yet poorer fits for the adult and mature stages.

High R² values and low values of the standard error of the estimate *per se* did not guarantee the precision of the estimates, as revealed by the relative difference (RD) (Figure 4.4). The error associated with the power function (Eq. 4.4) exceeded 600% for the diameters below 3 cm. The AGB estimated by Eq. 4.4, 4.5, 4.7 showed RD ranges of 196-280%, 99-139%, and 37-48%, respectively.

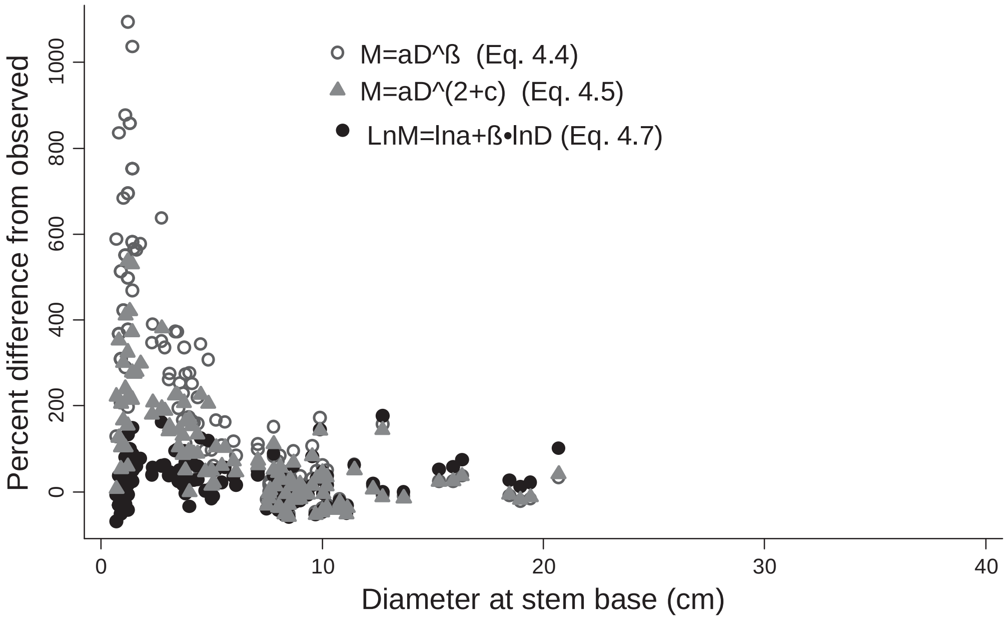

Figure 4.4 Percent error in allometric models predicting above-ground biomass based on diameter at stem base (cm)

Separating the growth stages showed highly significant differences between the RD values of the model for the juvenile phase, with the power function having highest errors (Table 4.7).

Table 4.7 Relative differences (RD) between observed biomass values and as estimated by allometric equations for growth stages defined by stem diameter (D) classes

Allometric relationship	**Juvenile stage (D=0-5.5 cm)**		**Adult stage (D=5.5-12.3 cm)**		**Mature stage (D=12.3-21 cm)**		**Eq.**
	Mean RD (%)	**SE**	**Mean RD (%)**	**SE**	**Mean RD (%)**	**SE**	
$\mathrm{M}=\alpha\mathrm{D}^{\beta}$	404.4 a	27.3	46.6 a	5.6	32.4 a	12.9	4.4
$\mathrm{M}=\alpha\mathrm{D}^{2+\mathrm{c}}$	190.0 b	13.7	37.7 a	3.9	30.9 a	11.8	4.5
LnM=lnα+β·lnD	48.2 c	4.1	34.4 a	3.3	49.4 a	16.0	4.7
LnM$_1$	36.6 c	3.4	/	/	/	/	4.7.1
LnM$_2$	/	/	37.4 a	5.2	/	/	4.7.2
LnM$_3$	/	/	/	/	28.4 a	8.8	4.7.3

SE: Standard error of the mean; CI 95%. Different letters indicate significance at p<0.05. RD values were compared using panel regression with repeated measurements, and multiple, Bonferroni-adjusted comparisons.

The model based on the data of trees with D <5.5 cm (Eq. 4.7.1) showed the smallest RD, indicating that its predictions were most precise for the juvenile phase, while no significant differences were observed for the adult and mature stage. However, with regard to absolute values, the overestimation in the juvenile phase did not lead to significant differences in model prediction (Figure 4.5). In contrast, a relatively small RD in the mature phase (i.e., RD 49% for Eq. 4.7) translated into a significant biomass overestimation.

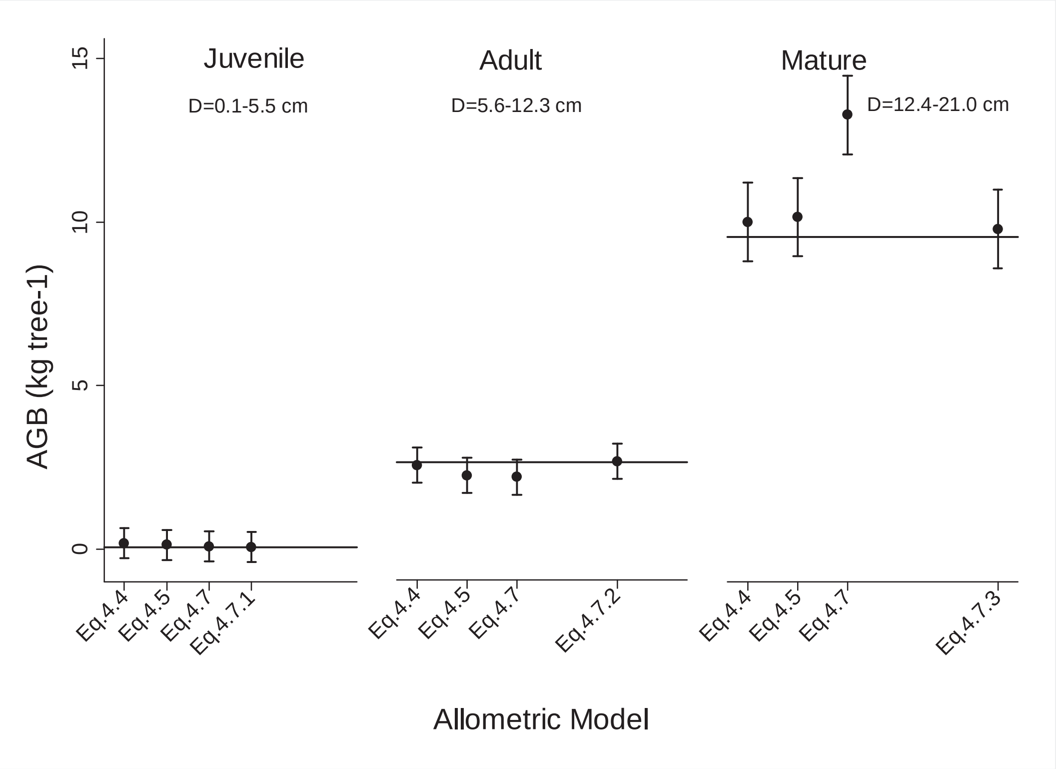

Figure 4.5 Average values and CI (95%) of AGB estimated by allometric relationships for three growth stages. Horizontal line indicates average value of observed biomass over respective growth stage. Panel regression with repeated measurements and multiple, Bonferroni-adjusted comparisons.

The increasing uncertainty in biomass predictions with increasing tree size is also illustrated by the diverging CI for the larger D classes (Figure 4.6). For instance, the model developed for mature trees (Eq. 4.7.3) showed highly uncertain predictions for

D >21 cm (Figure 4.6D). Eq. 4.4 and Eq. 4.5 yielded the most conservative estimates of RD (Table 4.7) and CI (Figure 4.6) within the higher D classes.

The RD values per model and growth stage did not differ significantly among the *J. curcas* cultivation systems.

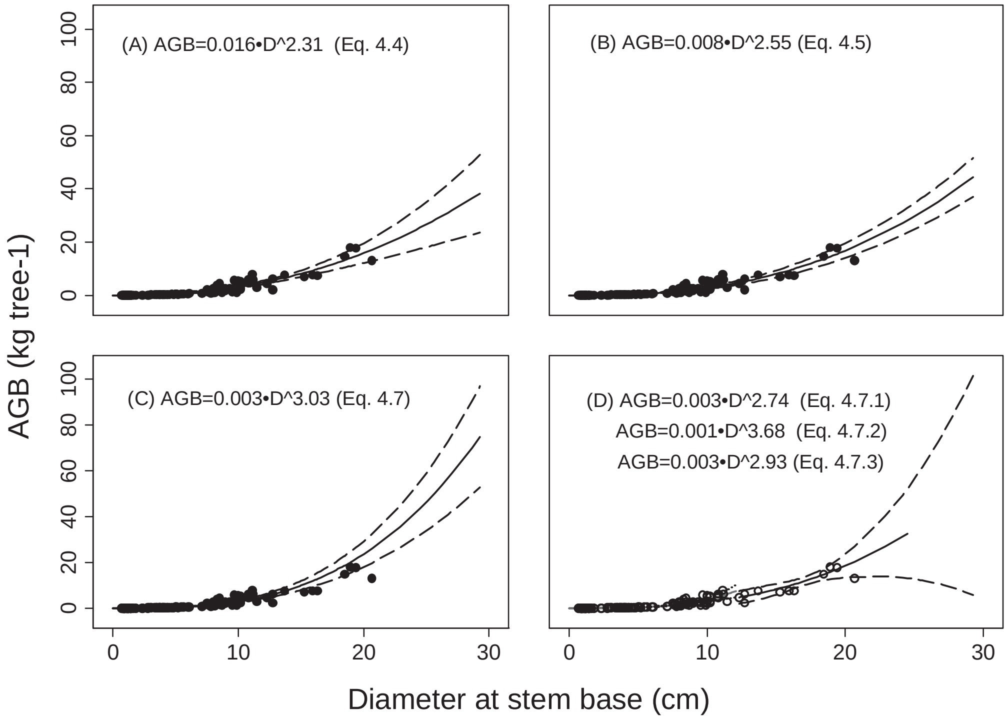

Figure 4.6 Allometric relationships between AGB and D. Dashed lines indicate confidence intervals (95% CI).

Below-ground biomass

The model application for the estimation of BGB resulted in slightly different parameters, but revealed the same tendency regarding R^2 and RMSE as in the AGB predictions (Table 4.8). The drawback of the common power function remained the overestimation of biomass in the juvenile growth phase (RD>800%) (Eq. 4.4). Similar to the model fitting for AGB prediction, the model derived from the logarithmically transformed data (Eq. 4.7) did not deliver reliable results for large trees, as indicated by a mean RD of 103% for the mature growth stage (D ≥ 12.3 cm). In absolute terms, this deviation measured around 2 kg tree^{-1} above the observed mean of 2.8 kg BGB tree^{-1} (Appendix 9.8).

Table 4.8 Parameters and properties of allometric relationships of below-ground biomass (M, kg tree^{-1}) and diameter at stem base (D, cm)

Allometric relationships	**N**	**D range**	**α**	**P**	**Β**	**P**	**RMSE**	**R²**	**Eq.**
$M = \alpha D^{\beta}$	141		0.016	0.00	1.88 a	0.00	0.37	0.89	4.4
$M = \alpha D^{2+c}$	141		0.002	0.00	2.55^{b} b		0.44	0.85	4.5
$\mathrm{Ln}M = \ln\alpha + \beta \cdot \ln D$	141		0.001^{a}	0.00	2.92 c	0.00	0.49	0.97	4.7
$\mathrm{Ln}M_1$	76	0-5.5	0.001^{a}	0.00	2.71 bc	0.00	0.49	0.93	4.7.1
$\mathrm{Ln}M_2$	54	5.5-12.3	0.001^{a}	0.00	3.11 bc	0.00	0.42	0.59	4.7.2
$\mathrm{Ln}M_3$	11	12.3-21	0.003^{a}	0.04	2.48 abc	0.02	0.49	0.48	4.7.3

[a] *$\beta = 2 + c$ with $H = 0.58 \cdot D^{0.55}$;*
[b] *$\alpha = \exp(CF + \ln a)$(Eq 4.8);*
Robust cluster estimation.

Equation 4.7.1 (RD 48±5.8%), Eq. 4.7 (36±5.4%) and Eq. 4.4 (46±18.1%) showed lowest RDs for the juvenile, adult and mature growth stages, respectively. In Figure 4.7, the allometric relationship between D and BGB is depicted for the models (Eq. 4.4, 4.5, 4.7).

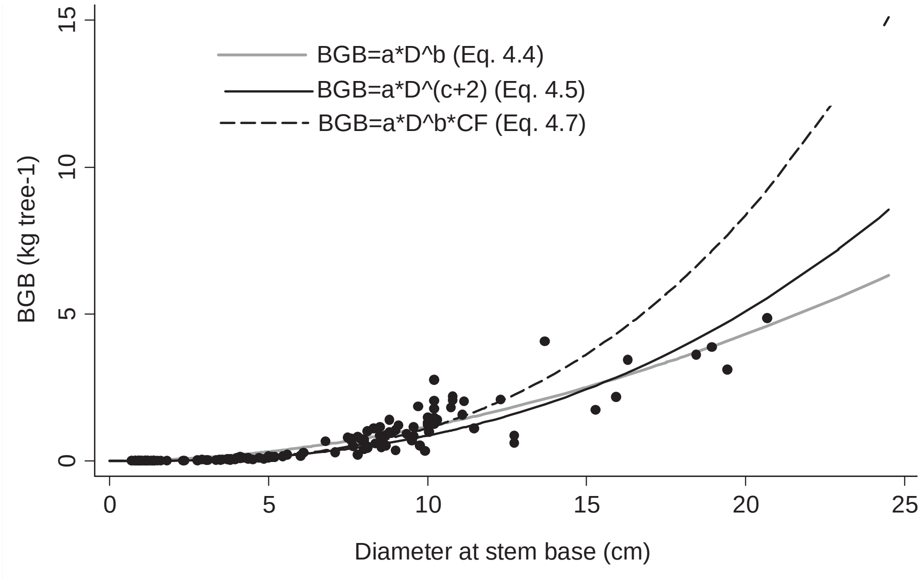

Figure 4.7 Predictions of total below-ground biomass (BGB) provided by empirical regression models

The prediction of BGB by applying the derived mean root-shoot ratio (RSR) of 0.45 was relatively accurate given the mean RD of 38±3.5%. However, distinguishing the predictions according to the growth stages revealed an overestimation of up to 82±31% for older trees, because RSR tended to decrease along with increasing diameter (section 4.3.1).

4.3.5 Empirical growth models

Inter-system comparison

The three-parametric non-linear logistic model (Eq. 4.11) showed good fits for the relationships between AGB and age for all *J. curcas* cultivation systems, except for afforestation. All estimated model parameters were significant ($p<0.05$) with an R^2 above 0.6. Comparing the parameters and their CI revealed significant differences among the systems (Table 4.9).

Table 4.9 Parameters and their confidence intervals (CI) in AGB (kg tree^{-1}) growth models for *Jatropha curcas* production systems in Burkina Faso: $\mathrm{AGB} = \beta_1/(1+\exp(-\beta_2 \cdot (\mathrm{Age}-\beta_3)))$

System	β_1	90% CI	β_2	90% CI	β_3	90% CI	R^2	n
Intercropping	33.61 a	30.99 36.24	0.50 ab	0.29 0.71	7.37 a	5.10 9.64	0.84	356
Afforestation	0.14 c	0.11 0.18	21.83 c		0.11 c	0.14 0.18	0.65	130
Intensely managed	33.10 a	30.85 35.36	0.91 a	0.34 1.49	4.80 b	4.37 5.24	0.87	119
Living fence	13.63 b	10.06 17.20	0.56 ab	0.16 1.00	4.23 ab	1.97 6.59	0.62	202
Contour hedge	27.92 a	18.19 37.63	0.36 b	0.17 0.55	8.29 ab	4.26 12.31	0.74	153

Age is expressed in years. β_1 represents the asymptote, β_2 the shape and β_3 the inflection point. Different letters indicate significant differences among the systems ($p<0.1$). Robust cluster estimation. n: number of trees for model fitting.

No satisfying model could be fitted to predict biomass accumulation in the afforested plots. Despite a statistically significant biomass growth ($p<0.00$) observed during the first growing year (based on the data of seedlings and one-year-old trees), the biomass stocks decreased in the second year, with the plants showing visible damage and mortality due to roaming animals, termite attacks and fire. The afforestation model is omitted in the following. For living fences, the large CI and relatively low R² (Table 4.9; Figure 4.8) can be explained by heterogeneous per-tree biomass within stands owing to self-propagation.

Pairwise comparison (Student's t-test) of the predicted biomass values (kg tree^{-1}) per age and system resulted in significantly higher tree biomass in intercropping and in intensely managed plantation systems compared to living fences onwards from the 12th and 8th growing year, respectively ($p<0.1$). All other pairwise comparisons did not show any significant difference. However, when looking at the observed data in the first four growing years, linear regression analyses revealed significantly higher biomass stocks per tree in intensely managed plantations than in contour hedges and intercropping systems. Afforestation systems showed significantly lower biomass values than all other systems ($p<0.05$). Figure 4.8 illustrates the fitted models with their CI and the observed data points.

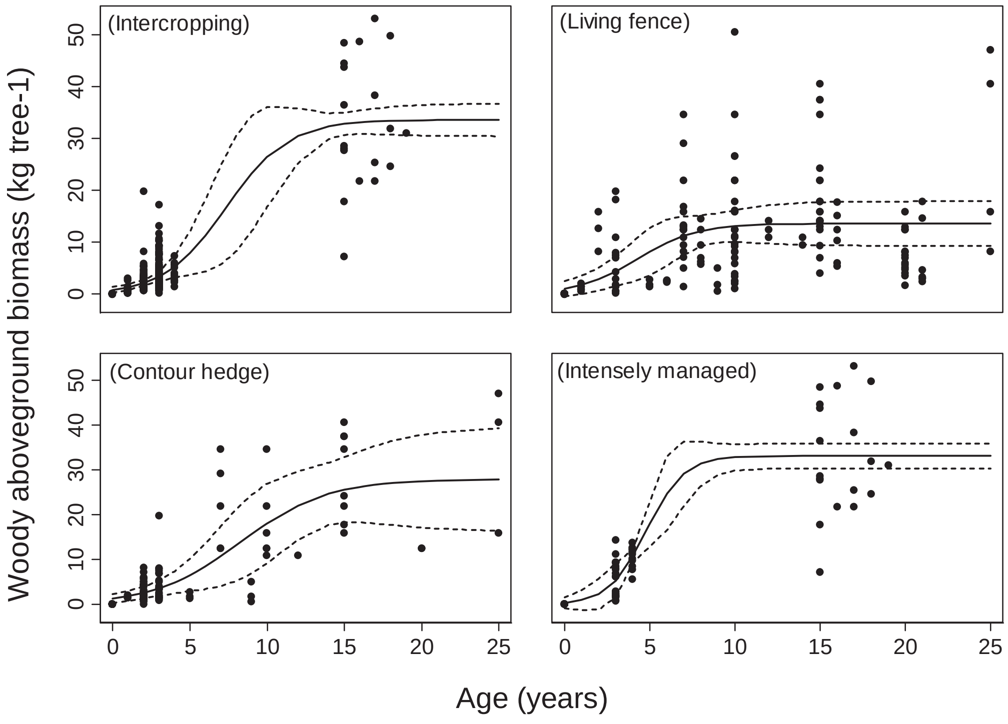

Figure 4.8 Empirical growth models predicting AGB (kg tree^{-1}) for *Jatropha curcas* cultivation systems in Burkina Faso. Afforestation system is omitted due to insufficient model fit. Dashed lines mark the lower and higher limit of the CI (90%); dots and straight lines respectively indicate observed points and the fitted model: $AGB = \beta_1/(1+\exp(-\beta_2 \cdot (Age-\beta_3)))$.

The earliest inflection point, namely between the 4th and 5th year, occurred in the intensely managed plantations (CI=4.37-5.24), whereas the transition from the juvenile to adult stage occurred between the 5th and 10th year in the low-input intercropping systems characterized by more heterogeneous management practices. This contrasts with results of the HD function (section 4.3.3), which showed that almost all 2-3 year-old trees reached adulthood irrespective of the management system. Gompertz functions generally have an early inflection point. In addition, the diverging CI between the 5th and 15th year in the growth models of intercropping and intensively managed systems (Figure 4.8) indicates the uncertainty in localizing β_3 due to the lacking observations. Therefore, the growth stages distinguished from the HD function are likely to be more accurate.

Modeling the biomass growth at a stand level (Table 4.10) indicated the same growth rates over the years (β_2) and inflection points (β_3) as simulated for individual trees. The maximal potential biomass accumulation indicated by the asymptote β_1 was highest in the intercropping and intensely managed systems (21 t ha^{-1}), significantly lower for the living fences (12.3 t ha^{-1}), and lowest for the contour hedges (5.6 t ha^{-1}). When considering biomass production per m^2 and assuming a ground cover of 1200 m^2 ha^{-1} by hedges (3 m width and 400 m length, surrounding 1-ha field), the living fences accumulated the most biomass (~10 kg m^{-2}). The maximal biomass stock was defined as being reached when the relative growth increment (i.e., δAGB/δAge) dropped below 0.2. Accordingly, AGB climaxed in the 10th year in the intensively managed and living fence systems, and in the 15th and 14th year in the intercropping and contour hedge systems, respectively (Appendix 9.9).

Pairwise comparison (Student's t-test) of the predicted biomass values (t ha^{-1}) per age and system showed significant lower biomass stands for contour hedges than for intercropping systems (from 10th growing year onwards) and intensely managed plantations (from 6th growing year onwards) ($p<0.1$). All other system comparisons showed no significant difference. In the linear regression with the observed data, significantly lower biomass values for contour hedges appeared already in the first four growing years. Living fences had significantly higher biomass than the other systems in the first two growing years. Afforestation systems again showed the lowest biomass values ($p<0.05$).

Table 4.10 Parameters and their confidence intervals (CI) in the AGB (t ha^{-1}) growth models at stand level for *Jatropha curcas* cultivation systems in Burkina Faso: $\mathrm{AGB} = \beta_1/(1+\exp(-\beta_2 \cdot (\mathrm{Age}-\beta_3)))$

System	β_1	90% CI	β_2	90% CI	β_3	90% CI	R^2	n
Intercropping	21.01 a	19.37 22.65	0.51 ab	0.29 0.71	7.34 a	5.09 9.64	0.84	356
Intensely managed	20.69 a	19.28 22.10	0.91 a	0.33 1.49	4.80 b	4.27 5.24	0.87	119
Living fence	12.26 b	9.05 15.48	0.58 ab	0.16 1.00	4.28 ab	1.97 6.59	0.62	202
Contour hedge	5.58 c	3.64 7.52	0.36 b	0.17 0.54	8.23 ab	4.26 12.31	0.74	153

Age is expressed in years. β_1 represents the asymptote, β_2 the shape and β_3 the inflection point. System planting density is 625, 625, 900, and 200 trees ha^{-1}, respectively. Different letters indicate significant differences at $p<0.1$. Robust cluster estimation. n: number of trees for model fitting; afforestation system is omitted due to insufficient model fit.

Similar to the AGB model, the BGB models showed significant parameter estimation and good fits ($R^2>0.7$). However, growth rates (β_2) were slightly higher and inflection points (β_3) insignificantly earlier, and thus the BGB maximum was reached some years before. Maximal potential BGB (β_1) varied significantly, from 3.6 kg tree^{-1} in living fences to 7.8 kg tree^{-1} in intercropping systems and intensely managed plantations (Table 4.11).

Table 4.11 Parameters and their confidence intervals (CI) in the BGB (kg tree^{-1}) growth models for *Jatropha curcas* cultivation systems in Burkina Faso: $\mathrm{BGB} = \beta_1/(1+\exp(-\beta_2 \cdot (\mathrm{Age}-\beta_3)))$

System	β_1	90% CI	β_2	90% CI	β_3	90% CI	R^2	n
Intercropping	7.84 a	7.47 8.20	0.54 ab	0.33 0.75	6.08 a	4.60 7.55	0.86	356
Intensely managed	7.79 a	7.40 8.19	0.92 a	0.43 1.41	4.40 b	4.13 4.67	0.91	119
Living fence	3.60 b	2.86 4.32	0.65 ab	0.18 1.11	3.64 ab	1.71 5.57	0.70	202
Contour hedge	6.53 c	4.71 8.36	0.37 b	0.15 0.58	7.16 ab	3.64 10.68	0.79	153

Age is expressed in years. β_1 represents the asymptote, β_2 the shape and β_3 the inflection point. Different letters indicate significant differences at $p<0.1$. Robust cluster estimation. n: number of trees for model fitting. Afforestation system is omitted due to insufficient model fit.

Intra-system comparison and management factors

No significant differences were detected in biomass accumulation between plantations of the same system and age. Over all systems, a mixed-effect multi-level linear regression model with the predictor variables soil depth, soil gravel content and fertilization (total N applied since plantation establishment) was applied for the description of differences in biomass accumulation between plantations (1-4 years). The model showed significant effects of all factors on biomass accumulation, except for the second growing year. However, when the factors were categorized into three groups (0-30, 30-70, >70 kg N) (0-35, 35-60, >60 cm soil depth) (0-10, 10-30, >30 % soil gravel) it became clear that no model could yield reliable results due to unbalanced data and the subsequent risk of biased predictions.

4.3.6 Carbon storage in *Jatropha curcas* systems

The C stock at the maximum biomass accumulation ranged from 2.8 to 10.6 t ha^{-1} among the systems, with around 24% of the C stored in the roots. Annual C sequestration rates, given as a range from the first growing year until maximal relative growth is reached, were highest in the intensely managed plantations, followed by the intercropping systems (Table 4.12).

Table 4.12 Carbon stocks in AGB and BGB (t ha^{-1}) and annual C sequestration rate (t ha^{-1} yr^{-1}) in *Jatropha curcas* cultivation systems in Burkina Faso

System	**Stand density** trees ha^{-1}	**C sequestered in AGB** t ha^{-1}	**C sequestered in BGB** t ha^{-1}	**C sequestration rate** t ha^{-1} yr^{-1}
Intercropping	625	8.6	2.1	0.3-1.3
Intensely managed	625	8.6	2.1	0.3-2.3
Living fence	900	5.0	1.4	0.1-0.9
Contour hedge	200	2.1	0.5	0.1-0.3

C sequestered at age when relative growth increment drops below 0.2, as calculated by the growth models. Max. C sequestration rate reached at the inflection point of growth models (Table 4.9; Table 4.11). Biomass contained 42.5±0.17% C.

4.3.7 Model validation

The RD between the values predicted by the allometric equations (Table 4.6) and the observed independent data for the adult (n=15) and mature (n=3) growth stages was not significantly different from the RD reported (Table 4.7; section 4.3.4). Distinguishing between production systems showed no influence on model performance. However, separating the independent dataset into intercropping system and living fence led to precise predictions for the intercropped *J. curcas*, whereas AGB in living fences was overestimated (RD=74%) (Table 4.13). Consequently, the allometric relations should not be uniformly applied for all hedge systems that show high variability.

Table 4.13 Observed and predicted values of AGB and BGB (kg) used for the validation of the allometric models

System	n	Observed AGB	Predicted AGB	RD	Observed BGB	Predicted BGB	RD
Intercropping	9	32.34	35.15	26.0±9.5	13.25	9.47	27.7±4.9
Living fence	9	23.94	35.55	74.1±21.4	8.99	9.56	35.0±8.3

Observed AGB/BGB calculated as sum of single observed tree/root biomass. Predicted AGB/BGB calculated as sum of single tree/root biomass predicted by Eq.4.7 if D 5.5-12.3 & by Eq. 4.4 if D ≥12.3. Displayed RD (%) is the mean of single RD values ± standard error. n: Number of trees. Independent data from Fondation Fasobiocarburant.

When applied to the independent dataset, the growth models developed for the intercropping systems and living fences showed $\bar{e}$ values within the observed mean at 95% CI. According to Huang et al. (2003), this indicates an acceptable quality of model fitting, except for two-year-old intercropped trees with significantly higher observed AGB and BGB than predicted (Table 4.14). Therefore, the intercropping model is less precise for the early growth phase when plant performance is highly responsive to management, yet is robust in biomass projections for older trees (RD=12% for AGB and 9% for BGB).

Table 4.14 Mean values and prediction error ($\bar{e}$) for predicted and independently observed AGB and BGB (kg tree^{-1})

System	Age	n	Observed AGB	Predicted AGB	$\bar{e}$	Observed BGB	Predicted BGB	$\bar{e}$
Inter-cropping	1	15	2.37±1.51	1.33±0.28	1.03	0.71±0.47	0.47±0.09	0.24
	2	32	3.86±0.42	2.14±0.27	1.72	1.17±0.15	0.78±0.08	0.39
	20	3	30.2±1.95	33.5±1.16	-3.29	7.41±0.48	7.84±0.20	-0.43
Living fence	2	9	2.66±0.39	3.04±1.09	-0.38	1.05±0.15	0.92±0.32	-0.13

Observed data based on measurements and for intercropping system additionally on allometric extrapolation (Eq. 4.7 if D=5.5-12.3 cm; Eq. 4.4 if D ≥12.3 cm). Values predicted by respective growth model (Table 4.9; Table 4.11). Standard error adjusted for nested design. Independent data from Fondation Fasobiocarburant.

4.4 Discussion

4.4.1 Seed productivity of *Jatropha curcas* trees

Seed yields ranged between 0.1 and 1.2 t ha^{-1} (0.5-1.3 kg tree^{-1}) dependent on the management system. Yields were observed in two- and three-year-old trees (except living fence) and will probably increase till the fifth year (van Eijck et al. 2010) reaching approximately 1.5 kg tree^{-1} as observed for adult trees in Burkina Faso (M. Ouedraogo (2010, personal communication). It has to be noted that the presented yields were achieved under sub-optimal management conditions but on comparatively fertile soils (section 3.3.3). Afforestation systems on abandoned land did not yield at all. Avoiding competition for fertile land and with reasonable seed yields, *J. curcas* hedgerows showed the best performance. The actual yield of *J. curcas* living fences most probably lies above the monitored yield, as infrequent harvests led to fruit loss during the monitoring period.

A study conducted by Liyama et al. (2012) interviewing 211 Kenyan smallholder farmers about *J. curcas* seed yields resulted in comparably low yields with <0.1 kg tree^{-1} for up to 4-year-old trees and <0.8 kg tree^{-1} for trees older than 7 years. However, such results based on the memory of the farmers (Liyama et al. 2012) need to be treated carefully as shown in the present study, where yields reported by the farmers were far below the yields monitored over a season (section 4.3.2). Here again, the technical challenge with respect to yield assessment in smallholder farming systems became obvious.

Altogether, *J. curcas* is still considered an undomesticated plant for which agronomic properties are poorly understood. This leads to a high variability in productivity and uncertain yield predictability (e.g., Francis et al. 2005; Achten et al. 2010c; Contran et al. 2013). This uncertainty is also reflected in literature where seed yields in a range from 1.5 to 7.8 t ha^{-1} are reported (e.g., Heller 1996; Francis et al. 2005; Jongschaap et al. 2007; Achten et al. 2008). Most figures are given without any further information about the management system and ecological conditions in the study area. A report by van Eijck et al. (2010), combining *J. curcas*-related studies and filtering out overoptimistic yield prognoses, concluded that current seed productivity could be expected to be 1 t ha^{-1} with variations according to the input system. This corresponds to the findings of the present study. The development of genetically improved *J. curcas* planting material accompanied by best management practices is precondition for enhanced productivity (e.g., Achten et al. 2010c; van Eijck et al. 2010; Liyama et al. 2012).

4.4.2 Allometry of *Jatropha curcas*

In accordance with many previous studies (Niklas 1994; Ketterings et al. 2001; Pilli et al. 2006; Zianis 2008), the allometric equations using basal stem diameter as predictor for AGB and BGB of *J. curcas* provided acceptable outcomes (R^2>0.9). This facilitates the non-destructive biomass estimation of *J. curcas*, which is particularly important with regard to large trees. The accuracy of biomass estimates improved by distinguishing three growth stages based on the height increment relative to diameter at the stem base (Pilli et al. 2006). The respective D thresholds, i.e., 5.5 cm and 12.3 cm, marking the transition from the juvenile to adult and then to the mature growth stage, made it possible to develop adequate allometric equations for the biomass prediction for each ontogenetic phase. The inclusion of H in the power equation (Eq. 4.5) did not significantly improve its explanatory power, neither for AGB nor for BGB estimates, owing to the close relationship between D and H (Ketterings et al. 2001; Zianis 2008) retained in different *J. curcas* systems.

Regression diagnostics with RD as an indicator showed that the power model, commonly seen as the ideal of tree allometry (Niklas 1995), was not automatically appropriate across the entire range of stem diameters sampled. The high RD was reduced by considering ontogenetic stages when applying allometric equations, thus confirming that different scaling relationships apply for trees differing in size and/or age (Niklas 1995; Pilli et al. 2006). The statistical evaluation and comparison of absolute values highlight that both criteria must be considered in assessing the model fitness, particularly for the large diameter classes. The caution necessary when applying allometric equations on stem diameter data outside the range developed for (Rothman 2002) is indicated by diverging CI and overestimation of the allometric functions for trees with D >21 cm.

Along with the influence of the ontogenetic stage on the biomass-diameter relation, this is evidenced by applying the existing *J. curcas* allometric models to our data (Figure 4.9). The model developed by Ghezehei et al. (2009) with 16-26-month-old *J. curcas* trees showed similar parameters and predictions for the adult growth stage (RD=34%) compared with the values obtained from Eq. 4.7.2 (α=0.01; β=3.68±0.41). However, the equation severely overestimated AGB in the mature growth stage (RD=110%). Similarly, the model developed solely with seedlings in a study by Achten et al. (2010a) offered reasonable predictions for the juvenile trees (RD 41%), thus matching our results for this growth stage (Eq. 4.7.1: α=0.003; β=2.74±0.14). However, their model underestimated the biomass of trees with larger stem diameters. The model of Hellings et al. (2012), based on data of trees ranging from 4-16 cm in diameter, showed very good fit irrespective of the growth stage (RD 32%), and parameters corresponding with those in Eq. 4.7 (α=0.003±0.001; β=3.03±0.08). In predicting the biomass for D >16 cm, the function showed a similar fast incline as in Eq. 4.7, and hence risked overestimating the biomass of large trees. Overall, within the respective growth stage, our models corresponded well with those of Ghezehei et al. (2009), Achten et al. (2010a), and Hellings et al. (2012). Given that all equations were developed for trees grown in different environments, the influence of the environmental factors on the parameters α and β is likely minimized when analysis is performed according to growth stage as defined by the stem diameter classes.

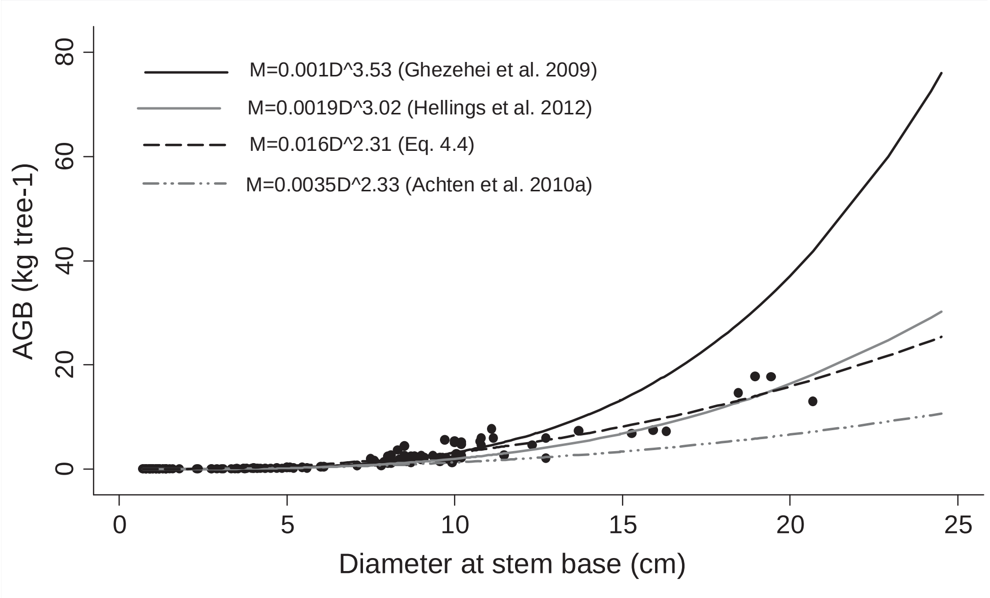

Figure 4.9 Allometric relationships of AGB and D developed by Ghezehei et al. (2009) (α transformed to express biomass in kg tree^{-1} and stem diameter in cm); Hellings et al. (2012) and Achten et al. (2010a) (α transformed as indicated above and corrected for the excluded leafy biomass[5]) compared to Eq. 4.4. Dots indicate observed points, and lines signify the fitted models.

Based on the regression diagnostics (RD, R² and CI), the most reliable predictions for the juvenile stage were obtained from Eq. 4.7.1, i.e., $AGB=0.003 \cdot D^{2.74}$ and $BGB=0.001 \cdot D^{2.71}$. The overall logarithmic function (Eq. 4.7) with $AGB=0.003 \cdot D^{3.03}$ and $BGB=0.001 \cdot D^{2.92}$ was suitable for the adult stage predictions. The biomass growth in the mature stage was most adequately predicted by the general power model (Eq. 4.4) with $AGB=0.016 \cdot D^{2.31}$ and $BGB=0.016 \cdot D^{1.88}$; the conservative estimates were appropriate considering the high uncertainty for predictions within the large-diameter class. The allometric models could be validated for *J. curcas* trees from plantation

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[5] The share of leaves (43% of the total above-ground dry biomass (Achten et al. 2010a)) was subtracted from the biomass estimates using the original allometric equation, with the resultant values used to develop the new equation (Hellings et al. 2012).

systems, whereas the variability apparent in living fences was shown to also result in changing D-BM relationships. The validity range of the equations could be further improved by sampling trees with larger diameters.

Estimation of BGB from the root-shoot ratio could be a valid alternative to the developed allometric equations provided that RSR is specific for each growing stage, as RSR decreases with increasing plant size. Given the responsiveness of RSR to changing growth conditions (Bray 1963), and the fact that BGB is usually underestimated due to excavation methods resulting in errors up to 40% for larger trees (Robinson 2004), more empiric validation of RSR is needed for estimation of *J. curcas* root biomass.

4.4.3 Biomass growth modeling

The widely accepted sigmoid function for tree growth (Winsor 1932; Niklas 1994; Landsberg and Sands 2011) adequately described the AGB and BGB growth of *J. curcas* as a function of time, thus forming the basis for a reliable LCA of the *J. curcas* production systems prevailing in Burkina Faso. While the large confidence intervals, particularly for the growth years with insufficient observations, indicated uncertainty in the biomass modeling, the applied three-parametric logistic model generally had a good predictive power. Overall, the validity of the growth models was also confirmed through comparison of the predicted values with the observations independent of those used for the model fitting, despite the management-induced deviations in biomass growth observed in the early growing phase.

The appropriateness of the chronosequence approach, i.e., fitting one curve to trees originating from different sites, required the assumption of similar management regimes and environmental conditions within each cultivation system. However, this represents the only available option for the estimation of *J. curcas* biomass over a longer growing period. Through the stratification of *J. curcas* sites according to their management system, confounding effects commonly dealt with in observational studies (Gail 2005) could be minimized and statistical analyses could be conducted.

Commonly known, traditional empirical growth models are site specific and fail to indicate mechanisms underlying growth. Nevertheless, the predictions for the sites they are developed for are usually considerably accurate (Landsberg and Sands 2011). The research setting as an observational study did not allow precise conclusions about optimal growing conditions of *J. curcas* stands. Multivariable analyses with soil and management properties as predictor variables provided significant results, but factoring of these variables showed false cause-effect relations owing to the uneven data distribution (Rothman 2002). The inconclusive results might also stem from the wild characteristic of *J. curcas*, where productivity does not proportionally respond to management intensity (Achten et al. 2008). Overall, the goal to develop a simple model for reliable biomass predictions based on low-cost measurements and usable for stakeholders interested LCA was reached.

4.4.4 Carbon sequestration potential in *Jatropha curcas* systems

Reasons for the failed model fitting for the afforestation systems on marginal cropland are beyond the methodological drawbacks. Sop et al. (2012) evidenced drastic mortality (70-95%) of *J. curcas* seedlings grown on degraded shallow *leptic-luvisol* in Burkina Faso without conservation management. The early mortality and damage by animals, insects and fire were similarly encountered in the present study in afforestation systems on shallow *lepto-* and *luvisols*. These observations underline the necessity of adequate maintenance of *J. curcas* plantings on marginal land, if production and soil amelioration goals are to be realized.

The developed growth models enabled estimating the C sequestration potential in *J. curcas* plantations. Regarding the C sequestration purpose, the appropriate rotational length of *J. curcas* plantations would be between the year with the maximum sequestration rate (4-8 years depending on cultivation system) and the year of biomass climax (10-15 years). However, fruit yields and economic cost effectiveness of *J. curcas* cultivation options (Liski et al. 2001) need to be considered in harvest decisions.

The presented sequestration rate of 0.2-1.9 t C ha^{-1} yr^{-1} for plantation systems (sequestration in roots excluded) falls in the lower range of the rates derived from empirical data reported in other semi-arid regions: 0.4-2.2 t C ha^{-1} yr^{-1} in plantations of up to 25 years old (Hellings et al. 2012) in Tanzania, and 1.4 t C ha^{-1} yr^{-1} in a 3-year-old plantation in India (Reinhardt et al. 2008). However, low planting densities (as opposed to the 1667 trees ha^{-1} reported) could be responsible for the lower sequestration rates in the present study. The above-ground C sequestration rate of 0.1-0.7 t C ha^{-1} yr^{-1} for living fences is in line with the 0.3 t C ha^{-1} yr^{-1} reported for hedges (918 trees ha^{-1}) in Tanzania (Struijs 2008), while all observed sequestration rates are lower than the 1.8-4.9 t C ha^{-1} yr^{-1} in 3-year-old plantations in humid regions (Firdaus et al. 2010). Besides low precipitation (<1000 mm), possible explanations include poor natural fertility of West African soils and relatively low management intensity in terms of irrigation, fertilization, hand tillage, and weeding.

4.5 Conclusions and recommendations

All allometric relationships between stem diameter and biomass showed very good fits. This permits the non-destructive estimation of *J. curcas* biomass above- and below-ground. Distinguishing different growth stages by analyzing the height-diameter function of *J. curcas* trees was essential for developing robust regressions covering the entire growth cycle of *J. curcas*. Statistically robust sigmoidal growth models for the *J. curcas* cultivation systems prevailing in Burkina Faso were developed and validated, and provide a low-cost tool for carbon stock estimation and potential use in LCAs. Owing to the only recent introduction of *J. curcas* in the crop production systems in Burkina Faso, model development largely relied on a dataset from younger trees. Accordingly, the projections for the mature growth stage can be further improved by including data from adult and mature trees when available. As no previously known growth model studies have been carried out for *J. curcas*, the results provide a critical starting point, helping to develop more precise models in future that can include functional relationships in plant growth processes.

The results of the study highlight the low productive potential of *J. curcas* plantings on marginal land in Burkina Faso, indicating the necessity of improving their management. Altogether, *J. curcas* systems showed low seed-yield and C sequestration potentials comparable to those reported in small-scale projects in East Africa. The development of domesticated *J. curcas* breeds accompanied by a clear portfolio of best management practices is prerequisite for enhanced productivity. Till then, the traditional living fences appeared to be a robust system due to self-regeneration, lower competition for the cropland area, reasonable yields under low-input regimes, and the additional benefit of field protection from animals and erosion.

5 DYNAMICS OF SOIL ORGANIC CARBON

5.1 Introduction

The quantification of any agroecosystem carbon (C) stocks is incomplete without accounting for the soil pool, as it is the largest of the terrestrial C pools (Young 1997; IPCC 2000; Montagnini and Nair 2004; Smith 2008) and represents a potential sink for atmospheric CO_2 (Lal and Kimble 1997). Increasing C sinks in vegetation and soil are thus contributing to climate change mitigation and can be, in the context of the Clean Development Mechanism (CDM) of the Kyoto Protocol, monetarily valued. Soil organic carbon (SOC) also plays a vital role in soil-based environmental services, soil fertility and the productivity of an ecosystem (Vlek 2005; Bationo et al. 2006). Consequently, soil carbon dynamics following land-use changes should be part of any Life Cycle Assessment (LCA). However, due to lacking data, LCA studies of *J. curcas* production pathways did not integrate changes in soil carbon following afforestation (Reinhardt et al. 2007; Achten et al. 2012).

Soil organic carbon dynamics are determined by the balance of inputs from litter and roots (humification) and output by decomposition (oxidation) (Cheng and Kimble 2000; Tiessen 2009). Accumulation of C in soil can be reached by increased annual inputs through plant net primary production and lower decomposition rates (Paul et al. 2002). In West Africa, organic material left in annual cropping systems for mulching is low due to low productivity levels, biomass burning in the field, livestock grazing and biomass use for energy purpose or as construction material (Bationo et al. 2006). Frequently, the C returned to the soil is only that of the below-ground biomass (Tiessen et al. 1998). On the other hand, soil carbon loss is accelerated by microbe-, termite- and temperature-induced rapid mineralization and decomposition rates of organic material, leaching and erosion (e.g., Bationo and Buerkert 2001; Batjes 2001). Average annual losses in topsoil organic C at continuously cultivated sites were estimated to range between 2 and 6.3%, depending on soil properties and management practices (Bationo et al. 2001; Zougmoré 2003). Thus, the SOC concentrations in West African soils, inherently low in fertility and under increasing anthropogenic pressure, range only between 1 and 8 g kg^{-1} (Bationo and Buerkert 2001).

The shrub species *Jatropha curcas L.* has been repeatedly claimed to have the potential for improving the soil fertility and erosion control (e.g., Heller 1996; Francis 2005; Jongschaap et al. 2007; Henning 2009). In Burkina Faso, where the declining soil fertility represents a main threat to agricultural production (Vlek et al. 2008), the contribution of *J. curcas* cultivation to an amelioration of the soils through increased residue inputs (leaves are shed annually) and erosion control could be significant. However, scientific evidence on land rehabilitation by *J. curcas* is scarce (Gasparatos et al. 2012). Experiments carried out so far show evidence of improved soil structure and potential for C sequestration in degraded soils under a 30-month old *J. curcas* plantation (Ogunwole et al. 2008) and increased C stocks under *J. curcas* hedgerows as opposed to neighboring soils (Soulama 2008). Long-term soil C sequestration rates of *J. curcas* systems are not known, neither directly determined by soil sampling, nor estimated by an organic material input-output balance.

Studies of long-term changes in soil carbon in same location are rarely feasible due to long-term follow-up required. Therefore, comparisons of soils under plantations with those under previous land use and under plantations of different age are valuable methods for the detection of SOC change due to afforestation. The latter “space-for-time substitution” approach implies a soil chronosequence as a series of soils which develop on similar geological positions with comparable site factors, except the plantation age (Jenny (1980) cited in Richter and Markewitz (2001)). Stable C isotopic studies can furthermore help to detect subtle SOC changes per annum due to contribution of trees to soil organic matter in systems where the ^{13}C signature of the C inputs from afforested plots (C_3 plants) is different from the ^{13}C signature of the previous land use with C_4 plants (Nyberg and Högberg 1995; del Galdo et al. 2003). Using the mass balance of stable isotope contents, the relative contribution of the new system to SOC can be detected (Balesdent et al. 1987).

This chapter presents the quantification of the SOC dynamics in *J. curcas* systems as opposed to annual crop cultivation using different approaches: (i) by means of comparing paired *J. curcas*-cropland sites in a chronosequence approach, and (ii) through application of ^{13}C natural abundance technique, where the land-use history allowed ^{13}C discrimination. (iii) The annually produced leaf litter and its decay rate were determined giving insights about annual litter accumulation and its potential contribution to SOC changes.

5.2 Materials and methods

5.2.1 Soil sampling

The *J. curcas* plots investigated for their biomass dynamics (section 4.2.2) were also studied in regard to their SOC dynamics (Figure 5.2). At 20 *J. curcas* sites, soil pits between the tree rows were dug to the bedrock, or to a maximum depth of 120 cm. Soil horizons were described following the standardized FAO field description (FAO 1977 and FAO 1994), and soil classification was based on the French classification scheme (CPCS 1967) and the international World Reference Base for Soil Resources (WRB 1998, 2006). In the soil pits, samples were taken from the three upper horizons for the analysis of pH, texture, and phosphorus (P) and potassium (K) concentrations. In each of the horizons, three undisturbed soil cores (diameter 5.3 cm, height 4.0 cm) were extracted for the calculation of soil bulk density. Samples from the pit in 0-10, 10-20, 20-40, 40-60, 60-100 cm soil layers were collected for the determination of carbon (C) and nitrogen (N) concentration. Additionally, soils for the C and N analysis were sampled with a soil auger to a maximum depth of 60 cm (0-10, 10-20, 20-40 and 40-60 cm) according to the microsite sampling approach (Ellert et al. 2001). Thus, in two microsites per plantation, samples were auger-collected at three points with an increasing distance to the tree stem (40 cm, 120 cm, 200 cm) and bulked according to the sampling depth (Figure 5.1). This approach aimed to account for differences in soil C dynamics caused by spatially variable rooting and leaf-fall patterns of *J. curcas* trees.

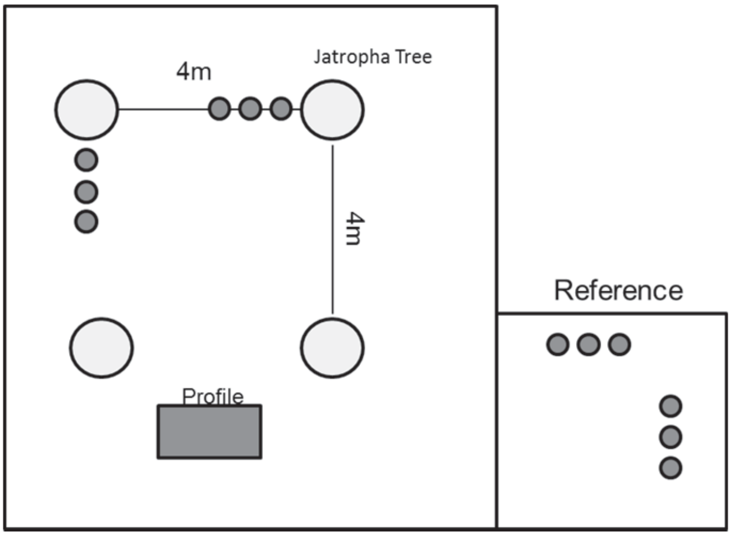


Figure 5.1 Microsite sampling design for *Jatropha curcas* plantations and reference sites

As reference sites, croplands with similar soil types in the immediate proximity of the *J. curcas* systems were sampled to present the previous land use. These sites cropped with cotton, maize, sorghum, millet, and legumes (Table 5.1) were sampled with a soil auger to a maximum depth of 60 cm. However, soil auger sampling beyond 40 cm soil depth was hardly possible, due to compacted or gravelly soil. The reference cropping sites next to contour hedges were protected with stone walls. The abandoned croplands in the vicinity of afforestation sites were not sampled because *J. curcas* plants survived poorly; hence no SOC accrual was expected. All samples were collected in the beginning of the dry period in October and November of 2010 and in 2011. The sampling locations were geo-referenced.

5.2.2 Chronosequence study

Short-term soil chronosequences were selected for introduced *J. curcas* systems, covering previous land use (cropland) and plantations with 1, 2, 3, and 4 years of age (Table 5.1). For traditional living fence systems, the long-term effect of *J. curcas* could be investigated in a chronosequence of two cropland sites representing year 0 and two *J. curcas* living fences aged 15 and 20 years. The mean annual change of SOC following the transition from annual cropping to *J. curcas*-based agroforestry was calculated by dividing the total change by 20.

5.2.3 ^{13}C natural abundance technique

Topsoil (0-20 cm) and plant (leaves) samples from four sites where *J. curcas* was established on land former cropped with sorghum were analyzed with respect to their ^{13}C signature (expressed as δ^{13}C). Adjacent sorghum cropped sites, representing the situation before afforestation were also analyzed for δ^{13}C. The proportion of newly derived C from *J. curcas* plots f_{new} was calculated according to the mass balance equation (del Galdo et al. 2003; Christensen et al. 2011):

$$f_{new} = \frac{\delta_{new} - \delta_{old}}{\delta_{veg} - \delta_{old}} \tag{5.1}$$

where δ_{new} is δ^{13}C of *J. curcas* system, δ_{old} is that of the reference soil, and δ_{veg} is that of *J. curcas* leaves.

5.2.4 Leaf fall and leaf decomposition

Jatropha curcas is a semi-deciduous species, shedding its leaves during the dry season. Leaf litterfall and its decomposition were observed in a 2-year-old intercropping system (11°08’ N, 3°04’ W, 330 m asl) and a 4-year-old intensely managed plantation (11°32’ N, 3°18’ W, 305 m asl) in the south-western region. Leaf litterfall was additionally measured in two mature living fences in the center region (12°12’ N, 0°48’ W, 300 m asl). Six nets were installed under tree crowns in plantation systems, and six litter traps 1 m² were put under the closed canopy in living fences. The litter was collected monthly over the course of one year and monthly leaf fall and annual leaf production were calculated.

For the calculation of leaf and shell decomposition rates, in the two plantations 12 bags filled with 5 g air-dry *J. curcas* leaves and shells were placed randomly underneath three trees. The mesh size (1 mm) was large enough to allow free entry of meso- and microfauna and small soil animals. Every three months over the course of one year (day of exposure: December 5, 2010), three bags per tree were recovered and the remaining weight was recorded after drying at 75°C. The weight (W) of all samples was corrected (cW) for adherent soil material by estimating the posterior ash concentration (PAC) after burning the samples in a muffle oven at 500 °C. The initial ash concentration (IAC) in the *J. curcas* leaves was determined by burning reference samples in a muffle oven.

$$cW = W - (W \cdot PAC) + (W - (W \cdot PAC)) \cdot IAC$$

(adapted by Martius 2004) (5.2)

The decomposition rate *k* was derived from the first-order exponential decay function (Olson 1963):

$$\frac{M_t}{M_0} = e^{-kt} \tag{5.3}$$

where M_0 is the initial mass of litter and M_t the remaining mass after time t (days).

According Olson, time required for 50% mass loss was calculated as t50=0.693/k and for 95% mass loss as t95=3/k (Olson 1963).

5.2.5 Soil analyses

Analyses for soil reaction (1:2.5 soil:water), soil texture and total P and K were done in Burkina Faso in the National Soil Bureau (BUNASOL) in Ouagadougou. Total P was determined spectrophotometrically by the Murphy & Riley method (1962) following soil digestion in a hot (340° C) mixture of sulfuric acid and salicylic acid. Total K was determined by flame emission spectrophotometry. All other analyses were conducted in the soil laboratory of the University of Bonn. Soil samples were analyzed for plant-available P and K, the first spectrophotometrically and the second by flame emission spectrophotometry, both after CAL extraction (VDLUFA Methodenhandbuch 1991). Total carbon (Ct % of the <2mm fine earth fraction), nitrogen (Nt %) and total organic carbon (SOC %) were analyzed by dry combustion with a EuroEA Elemental Analyzer. For SOC analysis, the soil was treated with 20% HCl beforehand. Samples of roots, leaves, wood, seeds, fruit shell and press cake were also analyzed for total C and N. Analysis of $^{13}C/^{12}C$ was done using a mass spectrometer (SerCon 'Callisto CF-IRMS'). Prior to chemical analyses, all samples were dried at 103°C for 24 hours and ground to pass a 0.2-mm sieve. For soil bulk density (ρ_b) determination, the soil taken with the soil corer was weighed, separated from coarse fragments (>2 mm), oven dried at 105 °C and weighed again. Soil ρ_b was then computed as the ratio of water and gravel content corrected mass to volume (g cm^{-3}). For the sites where it was not possible to measure bulk density due to high gravel contents, it was calculated according to a linear regression model relating ρ_b and soil gravel content ($R^2=0.5$; $p<0.001$; $n=60$). The soil C concentration (Conc %) was converted to C stock (C_t t ha^{-1}) for a fixed soil depth increment d (0-10, 10-20, 20-40 cm):

$$C_\mathrm{t} = Conc \cdot \rho_b \cdot d \tag{5.4}$$

Carbon stocks for the entire soil profiles were calculated by summing up C stocks of individual layers to the bedrock.

Considering that the soil bulk density can change over time due to crop choice or soil tillage, the SOC content should be related to the unit of mass rather than volume (Ellert et al. 2001), e.g., if SOC content increases in older *J. curcas* plantations, the soil will likely have a lower bulk density thus requiring sampling to a greater depth. To account for unequal soil masses or densities among the sites, SOC was calculated in successive layers of a soil mass corresponding approximately to the mass of the depth increments (~ 14 g cm^{-2} for 10 cm increment). The thickness of the additional soil layer ($\mathrm{T_{add}}$) required to attain the equivalent soil mass ($\mathrm{M_{equiv}}$) was then computed by the Equivalent Soil Mass Calculation proposed by Ellert et al. (2001, 2002)

$$T_{add} = \frac{M_{equiv} - M_{layer}}{\rho_b} \tag{5.5}$$

with $\mathrm{M_{layer}}$ as the actual soil mass of a 10-cm increment and ρ_b as soil density.

5.2.6 Soil carbon budget

Based on the primary data, organic C input-output dynamics were described for *J. curcas* systems. The basis for calculation was: (1) The C contributed by leaf fall was calculated according to the estimation that leaf production accounts for 20% of above-ground biomass (section 5.3.5) with a mean C content of 43%. Using the biomass models presented in section 4.3.5 (Table 4.9), the average annual leaf production of the different systems could be derived. (2) An average fruit yield of 2.2 kg tree^{-1} was assumed from which the fruit shells constituted 30% of the total fruit (section 4.3.2) are left in the field after harvest. (3) Decay rates were k=0.0026 for litter and k=0.005 for fruit shells (section 5.3.5). (4) Other inputs which could contribute to increasing soil C stocks are press cake and pruning residues, which are currently withdrawn from the systems. Therefore, their estimation is omitted in the presented case. (5) C input by fine-root turnover and C losses by erosion or leaching can be substantial but could not be accounted for due to lacking data.

5.2.7 Statistical analyses

Statistical analyses were performed using STATA (12.0). All datasets were checked for normal distribution and homogeneity of variance. Least square linear regression models were tested for significance. In case of overall significant results, differences between means were tested by pairwise comparison with Bonferroni-adjustment. For comparison among the cultivation systems, regression analyses were adjusted for nested design (*J. curcas* plantations nested in system). The analyses were performed at P=0.05 significance level. Relationships among measured soil properties were determined using Pearson correlations. Mean values ± standard error (adjusted for nested design) are reported except when indicated otherwise.

5.3 Results

5.3.1 Soil properties

Study sites and their soils are briefly described in section 4.2.2. Further characteristics and regional distribution of the sample sites are shown in Figure 5.2 and Table 5.1.

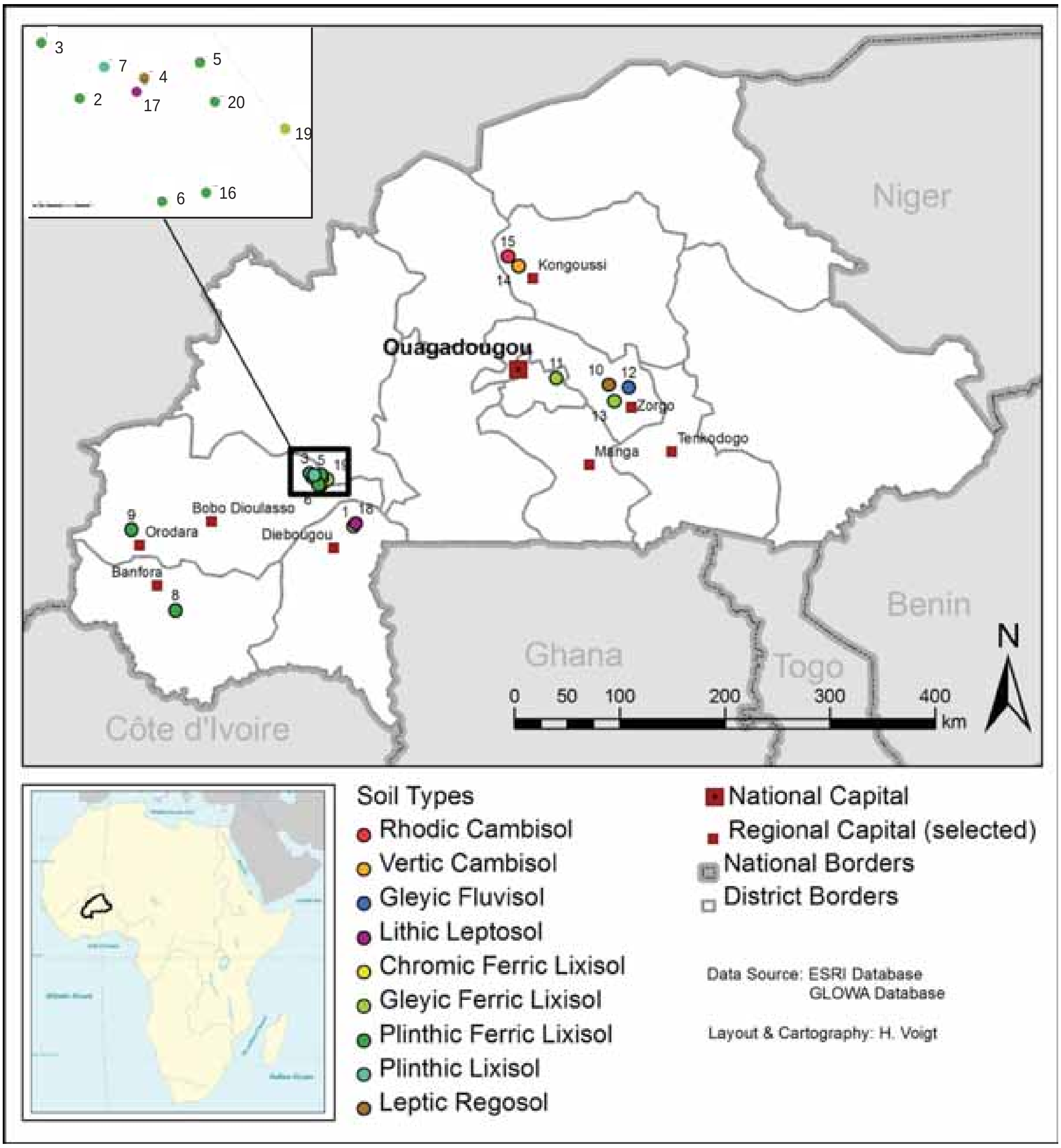


Figure 5.2 Location of 20 paired *J. curcas*-cropland sample sites and their soil types. Numbers indicate sample sites listed in Table 5.1.

Table 5.1 Main site characteristics and soil properties (topsoil 20 cm) of different *Jatropha curcas* systems and reference sites

Sample site	**Texture**	p_d	**pH**	**Gravel content**	*J. curcas* **age (Intercrop and/or previous crop)**	N_t	**SOC**	**C/N**	**n**
		g cm^{-3}		**%**		**g kg^{-1}**			
Intercropping system; (Prior) land use: annual crops									
1	Sandy clay loam	0.6	5.9	50	1 (Maize)	1.0	11.7	13.8	6
					2 (Maize)	0.9	11.5	13.6	4
					0 (Maize)	1.0	14.2	14.1	4
2	Loam	1.4	6.2	10	3 (Maize)	0.5	6.8	18.8	6
					4 (Maize)	0.8	7.8	11.5	4
					0 (Cotton)	1.3	15.0	12.2	3
3	Silt loam	1.7	6.3	0	2 (Legume)	0.3	4.7	13.8	6
					3 (Legume)	0.3	4.7	13.6	4
					0 (Cotton)	0.4	5.1	13.4	4
4	Sandy loam	1.5	6.4	60	2 (Sorghum)	1.1	14.5	13.4	6
					0 (Sorghum)	1.0	12.9	12.6	4
5	Sandy loam	0.8	6.8	40	2 (Sorghum)	1.2	19.0	16.6	6
					3 (Cotton)	0.9	13.5	15.9	4
					0 (Legume)	1.0	13.9	15.0	8
6	Sandy loam	0.9	6.3	40	3 (Legume)	0.8	11.0	13.9	6
					4 (Fallow)	0.9	12.6	14.7	4
					0 (Sorghum)	1.0	12.8	13.3	8
7	Sandy clay loam	1.3	6.4	15	2 (Millet)	0.7	9.1	12.1	6
					3 (Fallow)	0.9	11.2	12.7	6
		0.8	6.0	20	0 (Sorghum)	1.2	18.9	15.5	4
8	Loamy sand	1.5	5.9	5	3 (Fallow)	0.7	8.4	14.7	6
					0 (Fallow)	0.5	6.6	12.6	4
9	Loamy sand	0.5	6.2	70	3 (Fallow)	1.0	15.2	15.5	2
		0.7	5.7	60	3 (Legume)	1.0	15.6	15.5	2
10	Sandy loam	1.6	6.3	15	2 (Maize)	0.5	4.7	10.0	6
11	Sandy loam	1.9	6.2	0	15 (Fallow)[5]	0.8	6.2	9.1	4
					16 (Fallow)[6]	0.5	6.5	12.5	4
					1 (Fallow)	0.3	4.0	13.0	2
					0 (Sorghum)	0.4	5.8	13.0	4

[6] Sparse plantation integrated with a young *J. curcas* intercropping system.

Table 5.1 continued

Sample site	**Texture**	p_d	**pH**	**Gravel content**	*J. curcas* **age (Intercrop and/or previous crop)**	N_t	**SOC**	**C/N**	**n**
		g cm^{-3}		**%**		**g kg^{-1}**			
Living fence; (Prior) land use: annual crops									
12	Silt loam	1.6	6.1	0	15	0.9	13.4	14.6	6
					0 (Sorghum)	0.7	9.0	13.4	4
13	Loam	1.6	6.2	0	20	0.7	9.7	15.0	6
					21	0.9	13.1	14.7	4
					0 (Sorghum)	0.5	7.7	14.8	8
Contour hedge; (Prior) land use: annual crops									
14	Sandy clay loam	1.6	6.0	5	2 (Sorghum)	0.4	4.7	12.9	6
					3 (Sorghum)	0.4	5.3	12.2	4
					0 (Sorghum)	0.4	5.4	12.7	8
15	Loam	1.3	6.1	0	2 (Millet)	0.6	7.4	13.9	6
					3 (Cotton)	0.6	6.9	11.8	4
					0 (Cotton)	0.6	8.3	14.1	8
Afforestation system; (Prior) land use: abandoned cropland (fallow)									
16	Sandy loam	1.1	5.7	15	1	0.8	9.6	12.5	6
17	Loam	0.9	6.5	45	1	1.1	9.5	9.0	5
					2	0.8	9.0	12.6	4
					0 (Sorghum)	0.7	6.8	10.6	6
18	Sandy loam	1.2	6.5	30	1	1.1	14.7	13.5	6
		1.2	5.9	30	1	0.9	13.5	14.6	6
		1.4	6.6	15	1	0.5	7.8	15.7	6
Intensely managed plantation; (Prior) land use: annual crops (19) and fallow land (20)									
19	Sandy loam	1.6	5.6	0	3	0.4	4.7	13.6	6
					4	0.5	4.7	10.5	4
					0 (Sorghum)	0.6	7.9	15.5	8
20	Sandy clay loam	1.4	6.0	5	3	1.0	11.1	11.7	6
		1.2	5.6	10	3	1.2	16.5	13.4	6
					0 (Fallow)	1.4	17.1	11.9	4

Mean values of top two depth increments (0-10; 10-20 cm). n: number of composite samples. Age 0 stands for a reference site representing the land use before J. curcas *introduction. Geographic distribution of sample sites is shown in Figure 5.2.*

The predominant soil type is *ferric lixisol* with a sandy loam texture. The average observed soil bulk density over all sites falls between 1.33 and 1.53 g cm^{-3}, typically increasing with depth. The soils are moderately to slightly acid (pH 5.9 - 6.3) and are very low in plant-available phosphorus (P) (2.2±0.7 ppm) and low in plant-available potassium (K) (28±4.9 ppm) (BUNASOL 1990). Total N and C concentrations, ranging between 0.06-0.08% and 0.76-1.04%, respectively, decreasing with depth, also reflect poor soil fertility. The C/N ratio averaged 13.8±0.68.

5.3.2 Soil organic carbon dynamics

The SOC pool to 60 cm soil depth ranged from 33 to 66 t ha^{-1} (50±7.5) over all cropland and *J. curcas* sites with ~40% of the C residing in the top 20 cm. SOC made up 97±0.7% of the total C pool with no significant variation among systems. Average SOC concentrations lay between 0.73 and 1.01% across all sites and depths.

Table 5.2 Significance of (a) soil depth factor on SOC in paired sites of Jatropha curcas and reference cropland, and (b) differences in topsoil SOC concentrations (20 cm) among Jatropha curcas systems

System	**(a) Depth**				**(b) System**			
	J. curcas **(n)**		**Reference (n)**		**2**	**3**	**4**	**5**
1. Intercropping	<0.001	(147)	0.002	(65)	1.00	0.13	1.00	1.00
2. Living fence	0.138	(31)	0.872	(19)		**0.00**	1.00	1.00
3. Contour hedge	0.969	(36)	0.446	(24)			**0.03**	1.00
4. Afforestation	0.239	(45)	n.o.					1.00
5. Intensely manag.	0.112	(37)	0.390	(16)				
Prob>F	<0.001	(296)	<0.001	(131)		<0.001 (183)		

Linear regression model adjusted for nested design (p<0.05). Multiple comparisons were Bonferroni-adjusted.n: sample size. n.o.=not observed.

Three-factorial linear regression showed significant overall effects of the system (for 0-20 cm horizon) and depth factors (Table 5.2) and their interactions (p<0.001) on SOC concentrations. The factor microsite within one plantation was not significant; however, subsoil samples taken from soil pits tended to have lower C values than samples taken with the soil auger. The inclusion of the age factor in the overall regression model did not show interpretable results because of the unbalanced data distribution (Table 5.1). Over all sites and systems, SOC concentrations significantly decreased with increasing soil depth (Table 5.2), measuring 0.9-1.2% in the topsoil and 0.2-0.5% below 60 cm. Testing the depth factor separately for each system (Table 5.2) showed significant decrease of SOC over soil depth in intercropping systems. The depth effect was statistically insignificant for intensely managed plantations and associated cropland due to high SOC variability observed in these sites. Living fences with their associated cropland sites and afforestation systems, showed statistically insignificant variations in SOC concentration over sampled soil depths. Contour hedges exhibited a constant SOC concentration over all soil depths (0.61±0.03%).

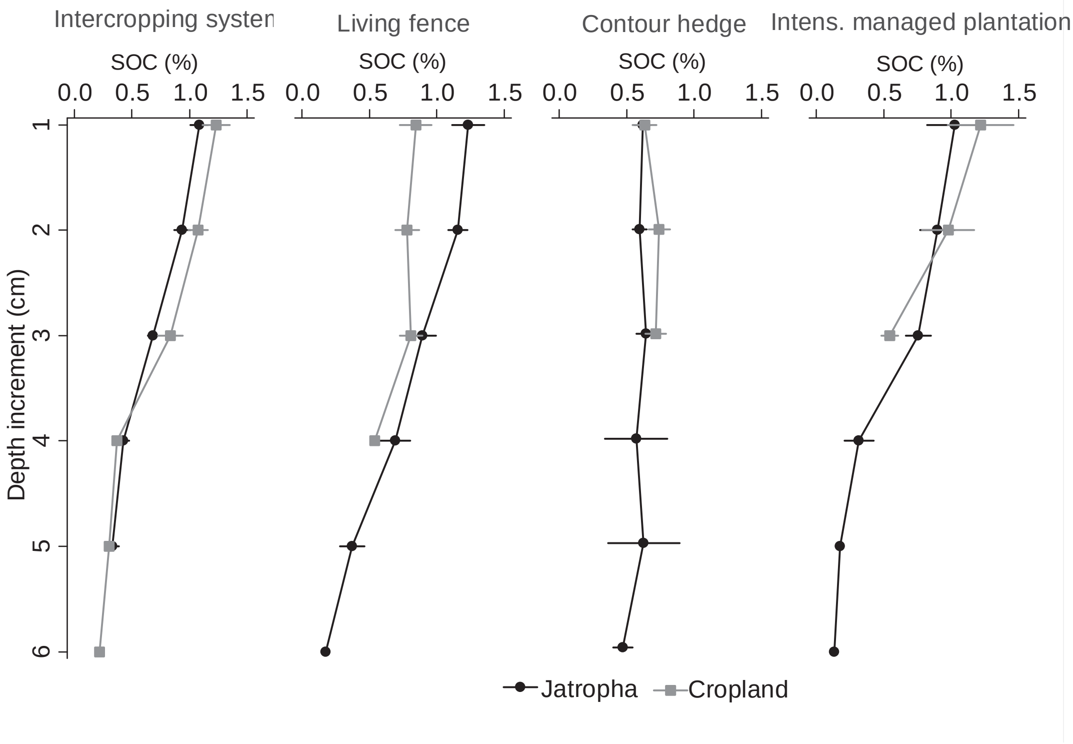


Figure 5.3 Mean values of total organic carbon (SOC) concentrations (%) as affected by soil depth for paired *J. curcas*-cropland sites. Intercropping system include 1-4-year-old plantings, living fence - 15 and 20 y.o., contour hedge - 2 and 3 y.o., intensively managed plantation - 3 and 4 y.o.. Deeper soil depths in cropland soil could not be auger-sampled due compacted or gravelly soil.

SOC stocks to a depth of 80 cm in soils under contour hedges were higher than those in the other plantation systems whereas the topsoil was the poorest among the studied systems (Figure 5.3). All recently established *J. curcas* sites showed somewhat lower SOC concentrations than the adjacent cropland (Figure 5.3). In contrast, SOC concentrations in mature living fences significantly exceeded those in the reference cropping sites, indicating C accrual following *J. curcas* planting. Significant differences were detected among the systems for SOC concentrations in the top 20 cm soil layer (Table 5.2; Figure 5.4). Contour hedges had significantly lower SOC values (0.61±0.08) than living fences (1.19±0.08) and afforestation sites (1.08±0.11). Given the differences in soil types among these systems, the observed variations have to be at least partly attributed to the location specific soil properties. Among the cropland sites (pooled for each corresponding *J. curcas* system) no significant differences were observed (1.01±0.10), although croplands associated with the intercropping and intensely managed plantations showed mean SOC concentrations at least 1.5 times as high as those adjacent to living fences and contour hedges. Below the 20 cm soil depth, variations among the systems were not significant.

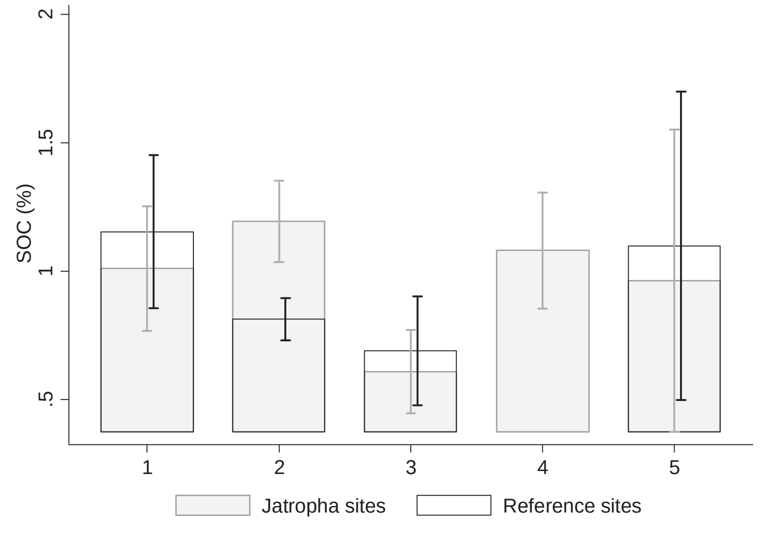


Figure 5.4 Mean values and their confidence intervals (95%) (robust cluster estimation and Bonferroni adjustment for multiple comparisons) of total organic carbon (SOC) concentrations (%) to 20 cm soil depth of paired *Jatropha curcas* and cropping sites (1: Intercropping system; 2: Living fence; 3: Contour hedge; 4: Afforestation system; 5: Intensely managed plantation).

SOC expressed in mass per unit area (kg m^{-2}) for the top 20 cm soil layer is shown in Figure 5.5. Living fences exhibited significantly higher SOC masses (3.9 kg C m^{-2}) than all other systems ($p<0.001$), except intensely managed plantations. Among the reference sites (pooled for each corresponding *J. curcas* system), significant differences were only observed between sites next to living fences and contour hedges ($p<0.05$). In agreement with results on SOC concentrations, also SOC mass of cropland soils was higher than that in *J. curcas* plantations in all paired sites, except for living feces.

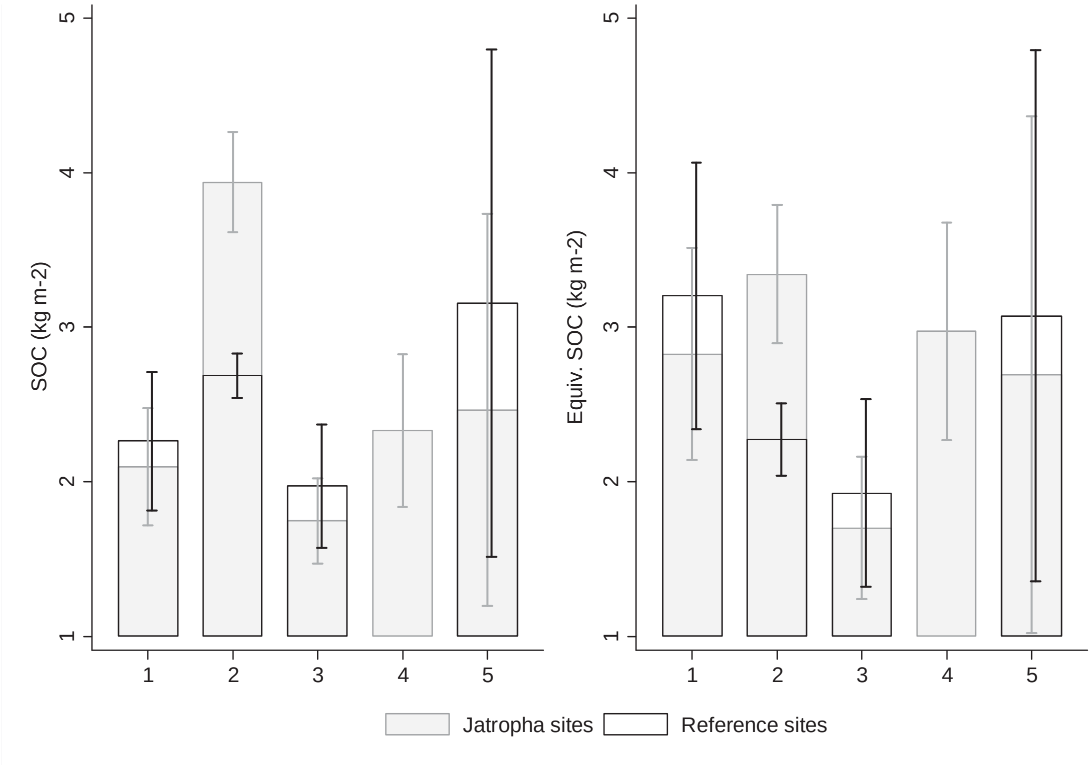


Figure 5.5 Mean values and their confidence intervals (95%) (Robust cluster estimation and Bonferroni adjustment for multiple comparison) of total soil organic carbon stocks (SOC) in mass per area and in equivalent soil mass (14 g cm^{-2} per 10 cm soil increment) to 20 cm soil depth of paired *Jatropha curcas* and cropping sites (1: Intercropping system; 2: Living fence; 3: Contour hedge; 4: Afforestation system; 5: Intensely managed plantation).

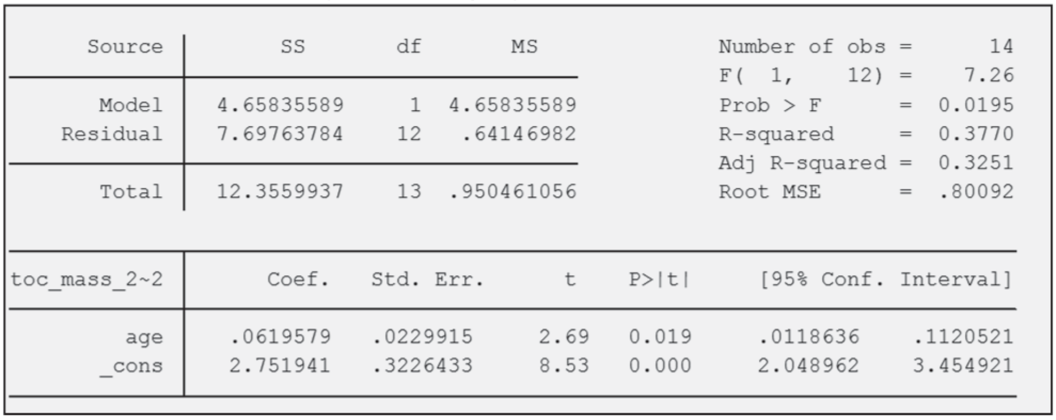
Calculating SOC according to the equivalent soil mass of 28 g cm^{-2} for the first 20 cm increment resulted in more homogeneous SOC among *J. curcas* systems. Only contour hedges still showed the lowest values ($p<0.05$). SOC masses in intercropping and afforestation systems increased following the calculation of the equivalent soil mass because of high gravel content, and consequently low density of these soils.

5.3.3 Soil organic carbon change over soil chronosequence

The construction of chronosequences for newly introduced *J. curcas* plantation systems did not reveal a clear SOC trend over four years. For some paired sites in the intercropping systems and intensely managed plantations, croplands showed higher SOC masses ($p<0.05$) in the first 40 cm layer (Figure 5.5). Over all systems and sites, no differences between SOC stocks measured in 2010 and in 2011 were observed.

In contrast, the chronosequence consisting of cropland soil (0 years) and living fences aged 15 and 20 years, showed significant though low linear correlation between SOC ($R^2=0.38$, $p<0.05$), N_t ($R^2=0.45$; $p<0.05$)) and living fence age in the top 20 cm. In deeper soil layers, no significant SOC stock increase over time was observed. SOC concentrations exhibited patterns similar to those of SOC stocks.

Table 5.3 Linear regression model relating plantation age and total soil organic carbon (SOC) stocks (kg m^{-2}) under living fences in the center region of Burkina Faso (STATA Output)



```
      Source |       SS       df       MS              Number of obs =      14
-------------+------------------------------           F(  1,    12) =    7.26
       Model |  4.65835589     1  4.65835589           Prob > F      =  0.0195
    Residual |  7.69763784    12   .64146982           R-squared     =  0.3770
-------------+------------------------------           Adj R-squared =  0.3251
       Total |  12.3559937    13  .950461056           Root MSE      =  .80092

------------------------------------------------------------------------------
toc_mass_2~2 |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         age |   .0619579   .0229915     2.69   0.019     .0118636    .1120521
       _cons |   2.751941   .3226433     8.53   0.000     2.048962    3.454921
------------------------------------------------------------------------------
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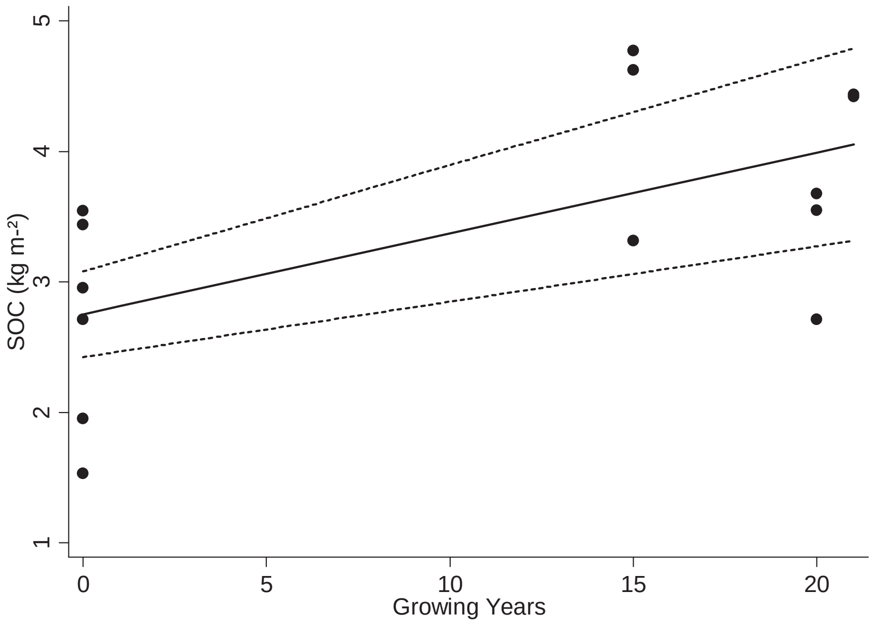

Figure 5.6 Linear regression and observed data points of total soil organic carbon (SOC) stocks (kg m^{-2}) in the topsoil (0-20 cm) in *Jatropha curcas* living fences in the central region of Burkina Faso. Dotted lines indicate confidence interval (95%).

SOC masses of the cropping sites averaged 2.7 kg m^{-2} and increased to approximately 4.0 kg m^{-2} under mature living fences. The linear relationship for 0-20 cm soil layer corresponds to a SOC accumulation rate of 62±23 g C m^{-2} yr^{-1} (N_t: 4±1.3 g N m^{-2} yr^{-1}). The increase was the highest for the top 10 cm soil layer. Expressed in SOC concentration, an annual 0.02% increase from the initial 0.84% resulted in a SOC of 1.2%. Assuming soil coverage of 1200 m² by living fences (400 m hedge fencing one hectare with a mean diameter of 3 m), a SOC sequestration of 77 kg per hectare and year can be expected. Over the period of 20 years, this accumulates to 1.5 t C ha^{-1}. With 6.3 t C ha^{-1} sequestered in the woody above- and below-ground biomass of *J. curcas* living fences over 20 years (section 4.3.6), the contribution of topsoil SOC sequestration to the total ecosystem C accrual was 19%.

5.3.4 Changes in $\delta^{13}C$ values

Consistent with the results on SOC content in paired *J. curcas* and cropping sites in recently introduced *J. curcas* plantations, the $\delta^{13}C$ signature of young *J. curcas* stands did not show evidence of new C_3-derived soil C (Table 5.4). The observed shift of the $\delta^{13}C$ signature to significantly lower negative values in the afforestation system can probably be traced back to a high thick weed (C_4) cover in the plantations.

In traditional living fences with mature *J. curcas* plants, the $\delta^{13}C$ values in 0-20 cm topsoil were more negative than in the adjacent sorghum fields, indicating a contribution of *J. curcas* to soil C. The new C_3-derived C amounted to 10% (f_{new}) of SOC and eventually contributed to the significant increase in SOC (Figure 5.6). The proportion of C_3-C was particularly high in the first 0-10 cm soil layer. In the sparse plantation of >15-year-old *J. curcas* trees where a young *J. curcas* intercropping system was integrated, parkland trees and ancient C_3 vegetation most likely contributed to the highly negative ^{13}C value observed (Table 5.4). However, despite the observable trends, overall analyses did not prove significant differences in $\delta^{13}C$ values between the mature *J. curcas* and neighboring sorghum sites.

Table 5.4 Comparison of $\delta^{13}C$ (‰) in soils (0-20 cm) under *Jatropha curcas* and sorghum

	Sample site (Table 5.1)	*J. curcas* **$\delta^{13}C$ (‰)**	**Sorghum $\delta^{13}C$ (‰)**	f_{new}	*p*	**n**
2-year-old afforestation system	17	-14.6±0.14	-15.6±0.44	/	0.02	15
4-year-old intercropping system[a]	6	-16.7±0.45	-17.3±0.37	/	0.29	18
20-year-old living fence	13	-16.3±0.55	-15.1±0.57	0.10	0.14	18
>15-year-old *J. curcas* **trees in sparse plantations**	11	-20.5±0.65	-19.9±0.42	0.07	0.50	14

[a] *Sorghum and groundnut intercropping stopped one year before sampling; Jatropha curcas leaves had a mean $\delta^{13}C$ value of (-27.9±0.2‰) (n=4); $\delta^{13}C$ value of sorghum, millet, grass averaged (-11.7±0.1‰) (Bayala et al. 2006). f_{new}: proportion of newly derived C from J. curcas plots.*

5.3.5 Leaf litterfall and decomposition rates

The bulk litterfall (85%) in the intercropping system occurred between October and January in the dry season, no litterfall was recorded from March to May, and low litterfall through the rainy season (15%) (Figure 5.7). However, leaf fall is closely linked to water availability, e.g., the plantation irrigated during the dry seasons showed green leaves for a longer period and later bulk litterfall (30% in February) than rainfed plots. The same could be observed in contour hedges where soil moisture remains longer along the stone walls.

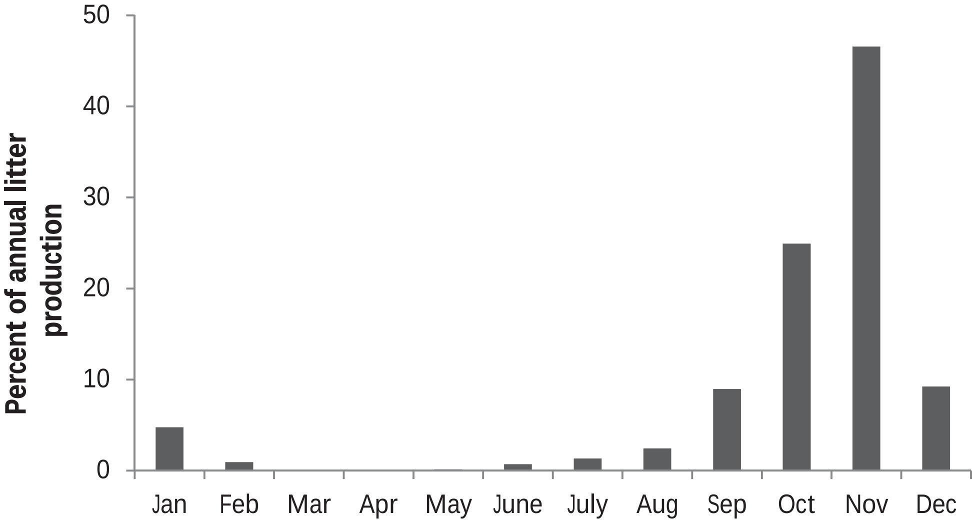

Figure 5.7 Litterfall over the year 2011 in percent of total annual litter production in a 2-year-old rainfed intercropping system in the south-western region of Burkina Faso

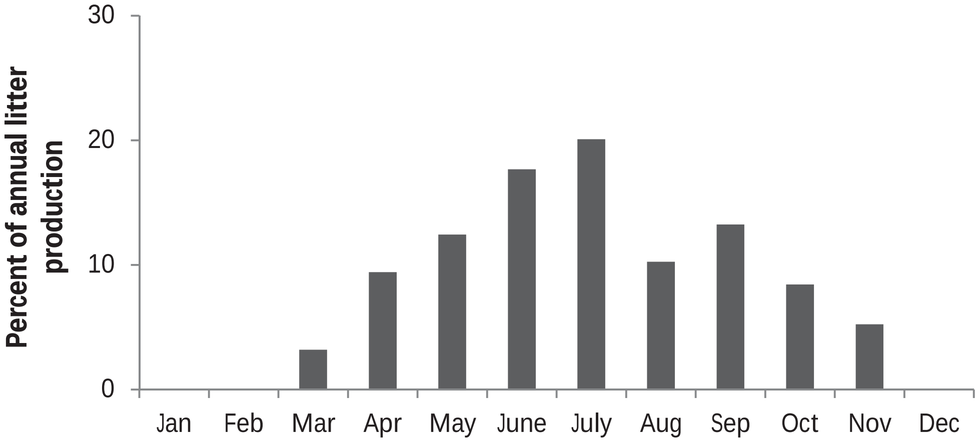

Figure 5.8 Litterfall over the year 2011 in percent of total annual litter production illustrated for two mature living fences in the center region of Burkina Faso

Living fences showed a different litterfall pattern with maximum rates in June and July. This trend can be explained by the high density of these stands. In mature living fences, foliage mass rapidly increased with the onset of the rainy season leading to early canopy closure. After canopy closure, increases in leaf mass are matched by litterfall (Landsberg and Sands 2011), therefore litterfall starts comparably early.

Annual leaf production accumulated to 451±177 kg ha^{-1} in the 2-year-old intercropping plantation and to 1217±429 kg ha^{-1} in the 4-year-old intensely managed plantation (625 trees ha^{-1}). In the living fences, a mean annual litterfall of 3.1 kg m^{-2} could be observed, which results in 3720 kg ha^{-1} assuming a closed hedge around a one-hectare field (400 m) with a mean diameter of 3 m. Leaf production was strongly correlated with stem diameter and tree height ($p<0.05$). Annual leaf production accounted for 20% of the woody above-ground biomass production of young plantation systems (averaged over 7 observed trees) with rising partitioning up to 38% for mature living fences. The decomposition of leaf and shell material over the course of one year is illustrated in Figure 5.9. Shells showed a faster mass loss than leaves even though their C:N ratio (47:1) was higher than that of leaves (20:1). Increasing masses after 180 days for leaves in Dano (intercropping system) and shells in Boni (intensely managed plantation) can be explained by two different observations: In Dano, contamination of the litter bags with organic debris could be observed during the rainy season, while in Boni all shell bags were highly infested by termites leading to high sand and organic matter accumulation in the bags. Weight correction through the estimation of ash concentration could only filter out the weight contributed by sand and not that of organic material.

The decay function could be fitted to the observed data *Leaf Boni* with $R^2=0.98$ and a daily decay rate (k) of 0.0026. After 360 days, 41% of the initial leaf mass remained, t_{50} was reached after 268 days, and t_{95} after 1159 days. For the *Shell Boni,* the decay function could be fitted to the data previous to day 270, and resulted in $k=0.005$. After 180 days, 30% of the initial mass had remained; half-time was reached after 140 and t_{95} after 606 days. In case of *Leaf Dano*, no function was fitted due to flawed data.

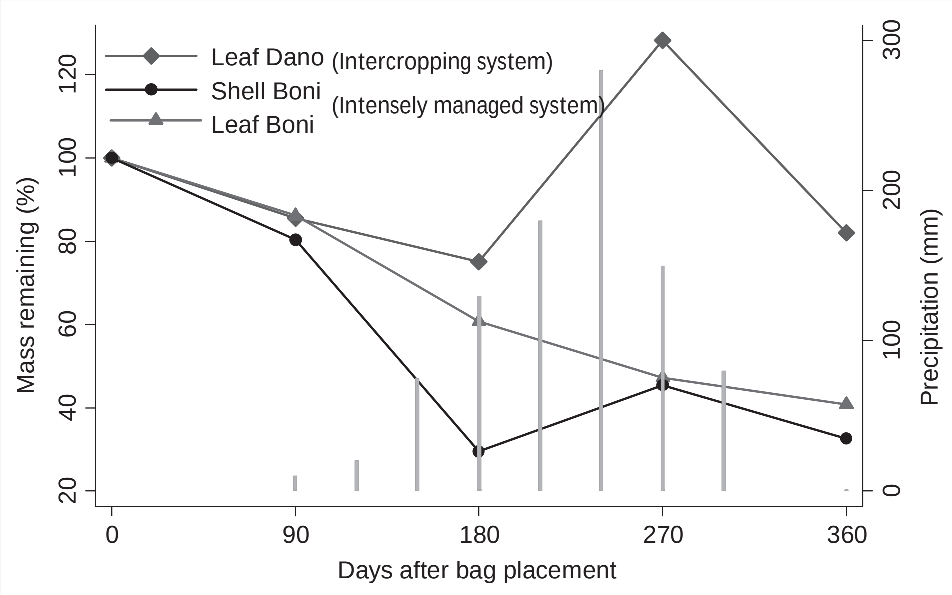

Figure 5.9 Remaining leaf- and shell mass and number of days after bag placement (DAP) in two different locations (intercropping and intensely managed system, Sudanian AEZ); average monthly rainfall over the course of one year starting in December 2010 (DAP=0).

5.3.6 Contribution of organic material to the soil carbon cycle

Inputs from leaf and fruit shells, their decay rates and the resulting annual accumulation of organic matter for the different *J. curcas* systems were determined (Table 5.5). In afforestation systems, *J. curcas* trees survived poorly due to lacking management and to soil constraints (section 4.4.4); therefore, the afforestation system is omitted in the following calculations.

The annually remaining 725 g OM m^{-2} under living fences eventually contributed to the SOC accumulation range of 12-112 g C m^{-2} yr^{-1} derived from the regression model (Table 5.3). Neglecting possible C inputs by root turnover, this would mean that from the initially introduced C of 1.09 t C ha^{-1} approx. 1-12% were transferred into more stable soil C pools under *J. curcas* living fences. Applying this turnover rate to the *J. curcas* plantation systems would result in soil C accumulation of 14-188 kg C ha^{-1} yr^{-1}, which is in line with Lal's (2006) statement that a soil C sequestration of 40 to 150 kg C ha^{-1} yr^{-1} for biofuel plantation systems under semi-arid conditions can be expected.

Table 5.5 Organic matter (OM) input and its decomposition in *Jatropha curcas* based systems averaged over a growing period of 20 years

	NPP[a]	**OM input by leaf fall**	**OM input from fruit shells**	**Total C input**[b]	**Annually remaining OM**[c]	**Annually remaining OM**[d]
System	t ha^{-1} yr^{-1}					g m^{-2} yr^{-1}
Intercropping	1.28	2.75	0.41	1.35	1.15	114
Living fence	0.77	1.97	0.59	1.09	0.87	725
Contour hedge	0.34	0.67	0.13	0.34	0.28	37
Intensly managed	1.28	3.24	0.41	1.57	1.34	134

[a] *NPP: Net primary production. Woody above-and below-ground biomass averaged over 20-year growing period. Biomass-prediction models from section 4.3.5;*

[b] *43% C in leaves, 42% C in fruit shells;*

[c] *Decay rate of k=0.0026 for leaves and k=0.005 for fruit shells;*

[d] *For living fences and contour hedges, a soil cover of 1200 m² is assumed (400 m closed hedge with a mean diameter of 3 m). Plant density (trees ha^{-1}): Intercropping 625, living fence 900, contour hedge 200, intensely managed plantation 625.*

5.4 Discussion

The low soil C concentrations (0.7-1.0% C) and stocks (3.3-6.6 kg C m^{-2}) in the first 60 cm of soil observed over all sites comply with the values typically found in West African soils (0.1-0.8% C; 4.2-4.5 kg C m^{-2} in the first 100 cm of soil (Bationo and Buerkert 2001; Batjes 2001)). The comparison of *J. curcas*-based systems showed significant differences in C concentration and stock. However, the systems are of different age and located in different agro-ecological zones with diverging soil properties; therefore, inter-system variation can be attributed to locational differences.

5.4.1 Soil carbon dynamics in contour hedges

In the northern region of Burkina Faso around the investigated sites, an area of 1500 km² has been equipped with stone lines for 20 years (Landolt 2010). All reference sites of the *J. curcas* contour hedges had undergone soil and water conservation (SWC) measures. However, in studies conducted in a nearby area without SWC, SOC concentrations of about 0.6% were reported (Zougmoré et al. 2002; Soulama 2008), which is not different from the values observed in contour hedges and their references (Table 5.1). The observed significantly lower SOC concentration in the topsoil under contour hedges, relative to the other *J. curcas* systems, can therefore not be attributed to *J. curcas* cultivation but has to be seen as regional specific, nor can a conclusion be drawn on the contribution of contour stone walls to soil amendment. Also, Zougmoré et al. (2002) could not prove that improved soil water balances in fields equipped with stone lines can lead to better soil fertility. Nevertheless, constant SOC concentrations over the entire soil depth under contour hedges and stone lines indicate steady C stocks, where C might be already transferred to deeper layers. Consequently, SOC stocks to a depth of 80 cm in soils under contour hedges are higher than those in plantation systems. Regarding the effects by the *J. curcas* contour hedge itself, stabilization of the stone walls, soil moisture improvement and additional C input through litterfall can be expected in the long run.

5.4.2 Soil carbon dynamics in living fences

Soils under *J. curcas* living fences showed significant higher total SOC masses per m² than those in the other *J. curcas* systems. The difference is leveled when considering SOC concentration or equivalent soil masses, since soils in the area of *J. curcas* living fences had a higher density. However, the chronosequence study (covering 20 years) showed an average annual SOC accumulation of 62 g m^{-2} in the top 20 cm (48% increase over 20 years) under *J. curcas* hedgerows. This value was corroborated by observable changes in $\delta^{13}C$ values, indicating a contribution of C_3-derived C to total soil C. The observed increase in SOC of living fence systems is in line with findings of Soulama (2008) showing a SOC mass increase in 20 cm topsoil from 2.3 kg m^{-2} in a cropping site to 3.7 kg m^{-2} under a mature *J. curcas* living fence in the northern region of Burkina Faso. The observed values are high compared to rates reported in literature, for example, 33.8 g C m^{-2} yr^{-1} global average accumulation in forests (Post and Kwon 2000) and 10-20 g C m^{-2} yr^{-1} in Senegal under best management practices (Batjes 2001). Also the findings of a meta-analysis by Guo and Gifford (2002) that land-use conversion from crop to plantation might cause a soil C-stock increase of 18% (corrected to 26% by Laganière et al. 2010) is substantially below the value of 48% calculated for the presented case. However, the high value can be explained given the localized planting with dense spacing in *J. curcas* living fences (<1 m distance between trees). The share of SOC accumulation in the total C sequestration potential of living fences measured 19% over a growing period of 20 years.

Despite an average rooting depth of 70 cm in mature living fences, SOC changes over time below 20 cm soil depth were not significant. This trend can also be observed in numerous other studies reporting only C changes for the topsoil (0-7 cm) or the first soil layer (0-30 cm), as they are more prone to change in C contents by cultivation practices and land-use management (Batjes 2001; Guo and Gifford 2002; Degryze et al. 2004; Epron et al. 2009). However, in the presented case, limited subsoil samples due to the technical difficulty in inserting the auger to a depth below 40 cm do not allow conclusions for all *J. curcas* systems.

Last but not least, living fences are said to be an effective erosion control method in the Sahel (Spaan et al. 2004), reducing runoff and sediment transport and improving rainwater infiltration (Zougmoré et al. 2002), thus leading to increasing crop production in the surrounding area. At the same time, their establishment is less labor intensive than the building of contour stone walls (Spaan et al. 2004).

5.4.3 Soil carbon dynamics in plantation systems

Intercropping systems and intensely managed plantations did not differ in SOC concentrations and stocks between each other. Furthermore, they both showed a fast decline in SOC over depth. Regarding the evolution from C stocks to C sequestration, i.e., the capturing of atmospheric C in pools with long turnover rates over the years (Batjes 2001; Lal 2004), the following trends could be observed. The established short chronosequences (0-4 years) did not show an increase in soil C stocks over the first years, but rather significant decreases after land-use change from annual cropping to *J. curcas* plantations. The isotopic tracer technique could not prove a contribution of *J. curcas* trees to the soil C content, either. The C decline following afforestation in the first years is commonly observed and explained by the soil disturbance during plantation establishment and fast mineralization of the fresh litter (Jug et al. 1999 in Cerli et al. 2006; Epron et al. 2009; Laganière et al. 2010). From a long-term perspective, though, following the C input calculations (Table 5.5) and the statement by Lal (2006), soil C sequestration can be expected to range from 13 to 188 kg C ha^{-1} yr^{-1}.

5.4.4 Soil carbon dynamics in afforestation systems

In the afforestation systems, most *J. curcas* trees died in the first years after planting due to soil constraints and lacking management. Hence, the relatively high SOC stocks observed in these sites (Figure 5.5) are rather due to a contribution by the fallow vegetation and the absence of soil tillage.

5.4.5 Carbon input and turnover

In comparison to annual cropping systems such as maize and cotton where usually only the root biomass of ~0.2-0.3 t C ha^{-1} (Tiessen et al. 1998) remains in the soil, *J. curcas* systems have substantial returns of organic material to the soil. Year-round observations of leaf fall showed that leaf litter accounted for 20% of the above-ground biomass production in young plantation systems with increasing partitioning of biomass into foliage for mature trees, which is a commonly observed trend over age (Ghezehei et al. 2009). Moreover, leaves are neither eaten by animals due to toxic compounds nor burned in the field as *J. curcas* trees are highly susceptible to fire damage. But, particularly in young plantations, they can be partly blown away by strong winds (Harmattan) during the dry season.

The observed relatively low decay rates were likely caused by dry conditions in the first months (Zhang et al. 2008) and the fact that the decomposer community is not fully developed in young succession systems with a low density of soil fauna and flora (Martius et al. 2004; Massucati 2006 in Lamers et al. 2010). A study undertaken in *J. curcas* stands in Ghana (1300 mm annual rainfall, age of trees is not mentioned) (Abugre et al. 2011) showed much higher decay rates ($k=0.02$) pointing to the accelerating impact of precipitation on decomposition. Taking the C:N ratio for the prediction of decay rates as often proposed in literature (Singh et al. 1999; Zhang et al. 2008) did not seem accurate for the present case, because shells decompose much faster than leaves despite the higher C:N ratio. This is in line with findings by Lamers et al. (2010), who showed that the C:N ratio is a less useful predictor when the whole decomposer community participates in the decomposition processes as is the case in coarse-mesh litter bags. In general, in perennial systems with less soil disturbance, organic matter decomposition is slowed down.

Eventually, high litterfall rates coupled with low decay rates lead to increasing litter stocks over time (Martius et al. 2004). For the presented 3-year-old intensely managed plantation, this would mean that after one year 41% (487 kg ha^{-1}) of the produced litter (1217 kg ha^{-1}) remains as litter stock. But how much of the added C is eventually sequestered in stable pools? Lal (2004) gives an estimate in the range of 2-20% being transformed by humification and the rest being released by soil respiration. This range would cover the suggested turnover rate of organic material of 1-12% (section 5.3.6). Still, many of the processes contributing to increasing soil C remain poorly understood (Batjes 2001; Laganière et al. 2010). Data on soil respiration could help to estimate C losses from soil (Raich and Schlesinger 1992), but very few CO_2 efflux measurements for arid and semi-arid regions exist. Also little is known about the dynamics of growth, decay and turnover of roots in agroforestry systems, although the contribution of roots to soil C is probably higher than that of litterfall (e.g., Jackson et al. 1997; Gill and Jackson 2000; Matamala et al. 2003; Nair et al. 2009; Lukac 2012).

5.4.6 Global targets and local needs

From the climate change mitigation viewpoint, a plantation period of 20 to 50 years would be optimal, allowing to reach the new C steady state in soil (Batjes 2001). However, this time frame is too long for economically used *J. curcas* stands, where sexual maturity is reached between year 3 and 5 after planting (Jongschaap et al. 2007; van Eijck et al. 2010) and productivity slows down with increasing age (Sharma et al. 1997 in Francis et al. 2005). Moreover, Smith (2008) calculated that soil C sequestration can only contribute to a maximum of 2-5% towards reducing the global C emission gap till 2100. Plants on drylands make an even smaller contribution due to comparatively small stores of biomass and soil carbon (Batjes 2001).

Apart from climate issues, SOC needs to be seen as an important indicator for sustainable land management (Woomer et al. 1994). It plays a vital role in soil fertility and crop production, since many soil functions are linked with SOC (e.g., fertilizer use efficiency, water retention, biological activity) (Bationo et al. 2006). The incentive for *J. curcas* management leading to increasing SOC should therefore be seen in raising site productivity. The idea to combine the monetary value of environmental services and C within the concept of CDM (Djanibekov et al. 2012) could provide incentives for proper establishment of *J. curcas,* also at sites low in productivity.

5.4.7 Remarks on the methodology

As SOC dynamics are principally difficult to estimate, and precision in methodology significantly contributes to the research outcome, some critical words should be said about the methodological approach used in the present study. Although the chronosequence method is widely used due to financial and time constraints, shortcomings nevertheless exist. A meta-analysis by Laganière et al. (2010) showed an overestimation of SOC changes by 6% relative to the permanent plot design. Difficulties can arise when the assumption of constant soil-forming factors is not met or “effects of change in the nature of the treatment over time” are misinterpreted as “change with time since treatment” (Yanai et al. 2000, p.273).

The ^{13}C natural abundance technique, which is seen as a very sensitive indicator of the influence of trees on soil previously vegetated by C_4 crops and grasses (Nyberg and Högberg 1995), could only be applied to four appropriate sites. Nonetheless, shifts in δ^{13}C values under mature *J. curcas* trees could be observed. Stable C isotopic studies based on extensive soil sampling aligned specifically to the ^{13}C natural abundance technique could therefore give valuable insights into the contribution of *J. curcas* trees to SOC, complementary to the chronosequence approach.

Correction to equivalent soil mass is needed in chronosequence studies when changes in soil density occur over time following land-use change and C accumulation. As differences in soil density are not induced by land-use change but are region dependent, the concept of equivalent soil mass did not prove applicability in the present case.

5.5 Conclusions and recommendations

Statistically significant SOC accumulation over time could be observed solely under living fences, as these are the only systems existing over a long enough time period in Burkina Faso. Even if no increase in SOC in the newly introduced *J. curcas* plantation systems could be discovered over the first years, long-term SOC accumulation can be expected based on the high organic matter inputs through annual foliage deposition, in contrast to annually harvested crop biomass. Keeping this in mind, it is recommended to practice long-rotation afforestation in order to reach maximum soil C sequestration. Longer-term measurements comprising standard soil analyses and ^{13}C natural isotope abundance should be undertaken in growing *J. curcas* plantations to investigate SOC changes over time. Furthermore, the contribution of *J. curcas* roots to the soil C cycle remains to be quantified.

In *J. curcas* living fences localized plantings with high tree densities, high litter production and low soil disturbance led to comparably high soil C sequestration rates, which made an important contribution to the total C budget of the living fences. Thus, ignoring SOC changes would lead to an underestimation of the C sequestration potential. From a global perspective, the contribution to climate change mitigation remains small; however, local effects of SOC increase on the site productivity might be essential. Therefore, environmental services should be implied in carbon credit mechanisms in order to provide incentives for proper establishment of *J. curcas* also at sites low in productivity.

6 GREENHOUSE GAS AND ENERGY SAVINGS IN *JATROPHA CURCAS* BIOFUEL PRODUCTION SYSTEMS

6.1 Introduction

According to published reports, *Jatropha curcas,* the most important energy crop grown in Burkina Faso, could supply energy for several application areas. (1) The cultivation of *J. curcas* on 2.4% of the arable lands in Burkina Faso would suffice for the production of biofuel to replace 100% of fossil fuels in the thermal power stations of the national electricity company (Nonyarma and Laude 2010), thus reducing the dependency on imported fossil oil. (2) The local use of *J. curcas* straight vegetable oil (SVO) in stationary diesel engines for the generation of motive power or off-grid electricity could help to overcome energy scarcities in rural areas (Blin et al. 2013). (3) The use of SVO in plant-oil stoves could replace large amounts of fuel wood and remedy the associated environmental and social burdens (FACT Foundation 2009). (4) In the long term, *J. curcas* biodiesel could be used in the transport sector (Tatsidjodoung et al. 2012). Based on the results presented in Chapter 3, SVO production and its local consumption will likely be supplied by extensive *J. curcas* systems as the intercropping and hedge systems supported by NGOs. The intensely managed plantations run by private enterprises will rather provide the centralized biofuel production units for the energy supply of national power stations and the transport sector.

It is generally agreed that sustainable bioenergy systems must provide net energy gains, have environmental and local socio-economic benefits, and be producible in large quantities without impacting food supplies (Fritsche et al. 2005; Hill et al. 2006; Mangoyana 2009). Also, the association of biofuels with carbon neutrality and climate change mitigation has to be case-specifically justified in view of agro-inputs in energy crop production and impacts bound to land-cover change from ecosystems high in carbon (C) stock to energy crops (Fargione et al. 2008). The life cycle assessment (LCA) is a common tool to evaluate the energy efficiency and carbon neutrality of biofuel production systems (Gnansounou et al. 2009) through the process steps of cultivation, seed processing, transportation, and final consumption. Moreover, LCAs became relevant with the emergence of carbon trading markets, which require documentation of the carbon saving potential of projects (UNFCCC 2012), and of the EU regulations for biofuel markets that demand greenhouse gas (GHG) emission reductions for all imported biofuels by 35% (EC 2009). In Burkina Faso and most African countries biofuel production is not pursued primarily as a climate change mitigation strategy or exportation good, but rather aims at national energy independency (Gasparatos et al. 2012). In Burkina Faso, the export of biofuels is explicitly excluded from the national bioenergy agenda as long as the domestic demand is not saturated (MMCE 2009). Overall, Africa has a share of merely 1% in worldwide carbon trading activities as opposed to, for example, 47% in Europe (Peters-Stanley and Hamilton 2012). If *J. curcas* biofuel projects and their linkage to global carbon markets can contribute to pro-poor mitigation (Bryan et al. 2008), still remains a topic to be investigated.

Most LCAs conducted for *J. curcas* show positive results with regard to GHG emission reduction and energy savings (Reinhardt et al 2007; Dehue and Hettinga 2008; Struijs 2008; Whitaker and Health 2009; Ndong et al. 2009; Achten et al. 2010d; Gmünder et al. 2010; Prueksakorn et al. 2010; Pandey et al. 2011; Paz and Vissers 2011). However, many studies are not based on empirical data but rely on default values from varying LCA methodologies (e.g., RTFO (Renewable Transport Fuels Obligation), RED (Renewable Energy Directive)) and different scenario calculations (e.g., Dehue and Hettinga 2008; Whitaker and Health 2009) leading to wide ranges of saving potentials. Moreover, most LCAs are difficult to compare due to differences in system boundaries, functional units, local contexts, reference systems and allocation rules (Benoist et al. 2008; Gnansounou et al. 2008). To date, no LCA has been conducted for *J. curcas* biofuel production in Burkina Faso, and *J. curcas* initiatives are currently proceeding without knowledge of case-specific environmental consequences. Ndong et al. (2009) presented a study for West Africa, but they did not include C-stock changes due to land conversion, and assumed more than 50% higher seed yields than is actually observed in Burkina Faso. Over-optimistic *J. curcas* yield estimations were also reported by Gasparatos et al. (2012) as a major error source in LCAs. Achten et al.

(2012) criticized the absence of C-stock changes in most LCA calculations, because bioenergy-induced land-use and land-cover changes are known to have large impacts on environmental sustainability (Fritsche et al. 2005). For *J. curcas* systems, this means that better estimation of soil and biomass C-stocks are needed as called for by Reinhardt et al. (2007). Energy needs for human labor are not included in most LCA methodologies (EC 2009); however, in manual labor-intensive small-scale systems this source of energy can be substantial, as shown by Ndong et al. (2009).

The analysis presented in this chapter aimed to evaluate the environmental performance of *J. curcas* SVO and biodiesel production in Burkina Faso using the LCA methodology with focus on GHG emissions and fossil energy use. In order to present a complete LCA, the calculations comprised (i) C-stock changes due to land conversion to *J. curcas* production, (ii) human labor energy requirements, and (iii) process steps based on empirical field data (Chapter 3, 4 and 5). Based on the results, the relevance of carbon trading was evaluated for Burkina Faso.

6.2 Methodology: Life cycle assessment

The fundamental principle of LCAs is to estimate the environmental impacts of a product during its whole lifecycle, “from cradle to grave”, i.e., from the extraction of raw materials to the end-product disposal (Benoist et al. 2008). The LCA methodology is internationally standardized by the ISO norm 14040&14044 (ISO 2006a, 2006b), and follows four phases of goal and scope definition, inventory analysis (collection of all input and output data within the system boundary), impact assessment and interpretation of the results.

6.2.1 Goal and scope definition

The overall goal of the LCA is in line with the study objective outlined above. The system boundary of *J. curcas* production systems encompassed the complete life cycle of *J. curcas* oil and biodiesel from cultivation through seed processing and transportation to final consumption of the products (Figure 6.1). The *J. curcas* production pathway is then compared to reference scenarios, which are constituted by alternative land-use systems and by the life cycle of wood and diesel fuel. The sustainability of *J. curcas* is finally expressed in GHG emissions reduction and fossil energy savings.

Box 6.1 *Jatropha curcas* production pathway (Figure 6.1)

The decision-making process at the farm level, i.e., where, how and what kind of *J. curcas* systems are established, is influenced by the legal environment. The farmer will choose an appropriate site and agronomic practices which, together with environmental parameters, determine the productivity of *J. curcas*. At this level, *J. curcas* systems provide biomass and fruit yields which can be processed and used, offer protection as living fences and, if a carbon financing mechanism is applied, present a monetary value for C sequestration in the biomass. Land conversion from savannah, cropland or marginal land to *J. curcas* systems is depicted in the reference system. Dependent on the intended use of *J. curcas*, the seeds are processed and transported to the consumer. The plant oil can be used purely for cooking stoves, lighting, motive power, or soap production. After transesterification of the vegetable oil, biodiesel is obtained that can be applied in the transportation sector. Eventually, *J. curcas* fuel substitutes other products, such as wood for cooking or fossil fuel for motive power, where the processing pathway has to be compared to the *J. curcas* system. If *J. curcas* oil is a substitute for fossil fuel, the resulting carbon offset can be again monetarily valued through carbon financing schemes.

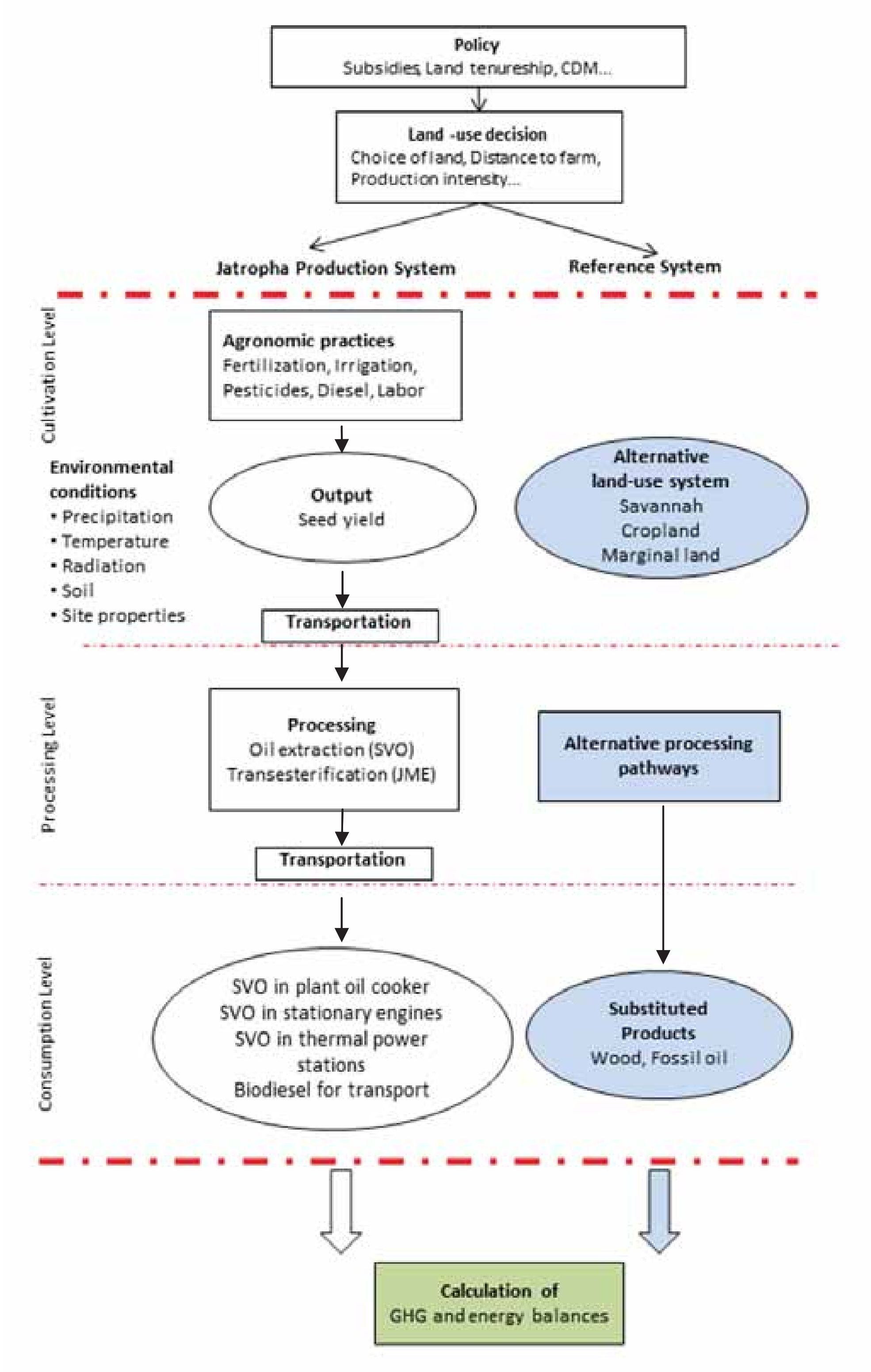

Figure 6.1 Boundaries of *Jatropha curcas* production pathways with process levels and reference scenarios

Functional unit of GHG and energy balance

The overall GHG budgets of the *J. curcas* systems annualized over a life span of 20 years were calculated by adding GHG emissions arising on- and off-farm (C_f, C_i), savings or emissions from changes in above- and below-ground C stocks and soil organic C after land use conversion (ΔC_{LUC}), and avoided emissions (C_a) through the substitution of energy carriers.

$$C_{budget} = \pm\Delta C_{LUC} + \left(C_f + C_i\right) - C_a \tag{6.1}$$

The functional unit is area based (CO_2e ha^{-1}yr^{-1}) and product based (CO_2e GJ$_{SVO}$$^{-1}$; CO_2e GJ$_{JME}$$^{-1}$) (carbon dioxide equivalent per giga-joule of *J. curcas* methyl ester). Multiplication with the efficiency of the end-use appliance η_{use} resulted in GHG emissions per GJ useful energy (CO_2e GJ$_{use}$$^{-1}$). GHG emissions comprised carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Carbon was expressed in CO_2 by multiplication with the factor 44/12. All emissions were converted into CO_2 equivalents (kg CO_2e) using the 100-year Global Warming Potentials (GWP) with CO_2: 1, CH_4: 23, and N_2O: 296 (BioGrace 2013). Other environmental impacts such as soil acidification and water use, which can be assessed by LCAs and could be relevant for Burkina Faso, were beyond the scope of this study.

The cumulated auxiliary energy demand was calculated by summing all energy requirements along the production pathway and is expressed in GJ$_{aux}$ ha^{-1}yr^{-1} and in GJ$_{aux}$ GJ$_{SVO}$$^{-1}$ or GJ$_{aux}$ GJ$_{JME}$$^{-1}$. The Net Energy Ratio (NER) between the quantity of renewable energy attained and the quantity of fossil fuel consumed provides information on the efficiency of the fossil energy use for the production of one unit of biofuel and is expressed in GJ$_{SVO}$ GJ$_{fossil}$$^{-1}$ or GJ$_{JME}$ GJ$_{fossil}$$^{-1}$ (Prueksakorn and Gheewala 2008). With NER>1, the fuel can be considered as renewable. The cumulative total energy demand (CED) as the sum of primary energy input E_{Pri} (renewable) and the auxiliary energy consumed E_{aux} (fossil) (Gmünder et al. 2010) divided by the efficiency of the end-use appliance η_{use} resulted in the total energy input per useful energy output (CED_{use}) expressed in GJ$_{input}$ GJ$_{use}$$^{-1}$:

$$CED_{use} = \frac{(E_{Pri+}E_{aux})}{\eta_{use}} \tag{6.2}$$

The secondary energy requirement for the manufacture of processing equipment and infrastructure was not accounted for.

6.2.2 Inventory analysis

The database on inputs and outputs along the *J. curcas* production pathway comprised empirical data gained through observations in *J. curcas* plantations in Burkina Faso, laboratory analysis of soil and plant samples, household surveys, stakeholder interviews and focus group discussions. LCA calculations were completed by relevant data from literature (primarily publications of data from Burkina Faso and West Africa; if not available also from other regions) and by consultation with experts in Burkina Faso. If appropriate, default values were taken from LCA databases, such as the standard values[7] for inputs (e.g., fertilizer) and process-related emissions coming from the BioGrace list of standard values version 4, list of additional standard values version 1, and the BioGrace GHG calculation tool version 4b (pathway sunflower). BioGrace follows the methodology from Annex V of the Renewable Energy Directive (RED) (EC 2009). Data were registered in an Excel database, and all calculations were done in an Excel spread sheet. The data collection process and the data itself are presented in the following sections divided into the LCA stages *J. curcas* cultivation, induced land-use change, oil pressing and processing, and end consumption.

Allocation of GHG and energy expenses to by-products

Allocation refers to the distribution of the GHG and energy expenses among the co-products, including fruit husks, press cake, and glycerin, accruing along the *J. curcas* biofuel production chain (Table 6.1). The choice of the allocation rule influences the results of a LCA and has therefore to be selected carefully (Benoist et al. 2008;

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[7] Standard values are emission factors, lower heating values and other background data that are required to convert input data in GHG emissions.

Gnansounou et al. 2009). Allocation according to the economic value of the by-products (García et al. 2011) could not be considered because *J. curcas* by-products did not yet have real market values in Burkina Faso (Tatsidjodoung et al. 2012). Allocation by system expansion, meaning that each *J. curcas* co-product substitutes another product thereby saving emissions and energy (Dehue and Hettinga 2008), was not applicable as the life cycles of possible substituted products were not known. Allocation by energy content of the co-products was chosen as the most reliable approach in the present study. Table 6.1 lists all by-products, their lower heating values (LHV) and the thereby resulting allocation factors. Overall, in the extensive *J. curcas* production systems (intercropping and hedges), 33.3% of the emissions are allocated to SVO, while in the intensely managed production systems 23.3% of the emissions are allocated to *J. curcas* methyl ester (JME).

Table 6.1 Lower heating values (LHV), mass flows and allocation factors of *Jatropha curcas* biodiesel by-products

	LHV (MJ kg^{-1})	Kg GJ$_{JME}$$^{-1}$	Allocation factor
Fruit husks	10[a]	56.4	0.16 Husk 0.84 Seed
Press cake	21[b]	105	0.67 Press cake 0.33 SVO
Glycerin	16[c]	3.95	0.06 Glycerin 0.94 JME

[a]Jatrop BioJet Fuel 2013 ; [b]Achten et al. 2008 ; [c]BioGrace 2013.

Fruit husks were only considered as a by-product in intensely managed plantations and in the centralized biodiesel production pathway where husks were collected and briquetted for use as solid biofuel. In the extensive systems, husks remained as agricultural residue in the field and therefore did not leave the system. Press cake is the by-product of oil expelling, where the extraction efficiency determines the energetic value of the press cake. So far, press cake is not marketable in Burkina Faso, but its use as bio-fertilizer to replace mineral fertilizer or as feedstock for biogas production is currently being investigated (Tatsidjodoung et al. 2012). Glycerin is the main co-product from transesterification and can be used after purification for soap production.

6.2.3 *Jatropha curcas* cultivation

The management regimes of the different *J. curcas* systems are described in Chapter 3. All input parameters used for the LCA stage *J. curcas* cultivation are based on these data, which were mainly gained through farmer inquiries and focus group discussions. The *J. curcas* cultivation phase included the following steps: volatilization of nitrogen fertilizer, emissions and energy consumption for fertilizer and pesticide production, fossil diesel fuel used for mechanized agricultural activities, and energy need for human labor. Underlying data are given in Table 6.2. In the case of intensely managed plantations, water for drip irrigation is pumped into a tower and then gradually used for irrigation, thus reducing the operating time of the pump. Fuel requirement estimates from irrigation experiments in Egypt (El Qousy et al. 2006) were therefore adjusted to the reduced pump running time.

All interventions were translated into kg CO_2e and MJ using standard conversion values from BioGrace (List of standard values version 4). N_2O field emissions from nitrogen fertilizer application were calculated according to the Tier 1 approach (IPCC 2006):

$$N_2O_{direct}=0.01 \cdot N_{fertilizer} \cdot 44/28 \tag{6.3}$$

with 0.01 as emission factor for N_20-N and 44/28 as conversion factor of N_2O-N emissions to N_2O.

In *J. curcas* intercropping and hedge systems, the amount of fertilizer applied annually to the adjacent crops was allocated to *J. curcas* trees according to their space occupation, which was estimated by the Eq. 3.2 (section 3.2.3). Annualized over 20 years, intercropped *J. curcas* trees occupied 71% of the field and hedge systems 13%, resulting in the land allocation factors of 0.71 and 0.13, respectively. Over the 20 year horizon, the resulting nutrient input (S1) to *J. curcas* trees would be below the nutrient removal through seed harvest in most of the *J. curcas* cultivation systems. In contrast, the intensive systems received more N and P input with fertilizer than the amount removed at seed harvest. Therefore, in a second scenario (S2), fertilizer was allocated according to the amount of nutrients withdrawn from the soil by *J. curcas* seed harvest (Table 6.2).

Table 6.2 Management interventions during the cultivation phase in *Jatropha curcas* cultivation systems

System / Intervention	**Intercropping**	**Intensely managed**	**Living fence**[e]	**Contour hedge**[e]
Nitrogen (kg ha^{-1} yr^{-1})				
Scenario 1 (S1)	7.6	37.0	4.3	4.3
Scenario 2 (S2)	19.3	34.0	17.1	6.2
Phosphate (P_2O_5 kg ha^{-1} yr^{-1})				
Scenario 1 (S1)	4.72	23.0	2.7	2.7
Scenario 2 (S2)	8.6	13.6	7.6	2.7
Potassium (K_2O kg ha^{-1} yr^{-1})				
Scenario 1 (S1)	2.9	14.0	1.6	1.6
Scenario 2 (S2)	6.1	33.4	5.4	1.9
Pesticides (kg ha^{-1} yr^{-1})	/	2	/	/
Diesel (kg ha^{-1} yr^{-1})[a]	/	7.7	/	/
Irrigation (kg diesel ha^{-1} yr^{-1})[b]	/	24	/	/
Yield (t dry seeds ha^{-1} yr^{-1})[c]	0.81	1.25	0.72	0.26
Labor (h ha^{-1} yr^{-1})[d]	1165	836	1002	396

S1: 100 kg NPK (14-23-14) and 50 kg urea (23% N) ha^{-1} to adjacent crop;

S2: Nutrient content of sun-dried ripe seeds under field conditions: 2.8% N, 1.24% P_2O_5, 0.88% K_2O (Reinhardt et al. 2008); seed harvest from year 3 onwards; seed husks returned to field, except in intensely managed system;

[a] *diesel consumption estimated according to Downs and Hansen (1998);*

[b] *~0.11 kg diesel m^{-3} irrigation water (field experiment in Egypt: surface drip, groundwater, diesel pump (El-Qousy et al. 2006), reduced operating time of pump (1/2) assumed for own case); drip irrigation took place during the dry season (Feb. till May), two times per week with 15 l per tree (A.K. Sanou 2011; personal communication);*

[c] *Yield data from own monitoring (section 4.3.2); yield increase assumed for contour hedges based on average per tree yield of intercropping system (1.3 kg $tree^{-1}$);*

[d] *Comprising plantation establishment, harvesting and dehusking, annual land preparation for intercropping, fertilization and weeding of intercrop (Appendix 9.10);*

[e] *For living fences and contour hedges, 1 ha means 400 m closed hedge.*

In Burkina Faso most work is accomplished manually; therefore, human energy can be a substantial factor. According to Pandey et al. (2011), 150 pits can be dug and 300 plants can be planted per man-day. The labor requirement for harvesting and dehusking was adopted from Grimsby et al. (2012) with 4.1±0.8 h for picking 5 kg of dry *J. curcas* seeds, and 3.4±1.0 h for dehusking of these seeds. Energy expenditure was assumed to be 183 kcal h^{-1} and 91 kcal ha^{-1} for harvesting and dehusking, respectively (Grimsby et al. 2012), and 300 kcal h^{-1} for plantation establishment. Labor spent on the cultivation of the adjacent crop (ox-plow for land preparation, 2 x weeding and fertilization), which indirectly benefits *J. curcas*, was allocated to *J. curcas* according to its space occupation. Working hours for these tasks were taken from Bishop-Sambrook (2003). Harvesting and fruit processing were accounted for from the third growing year onward, and initial pit preparation and plantation were annualized over the plantation life period of 20 years. In intensely managed plantations, only pit preparation and seed harvesting were done manually (see Appendix 9.10).

6.2.4 Biomass carbon stocks and land-use change

During *J. curcas* growth, atmospheric CO_2 is sequestered into standing woody biomass both above- and below-ground, and is temporarily bound in leaves and fruits. The leaves drop to the soil and decompose, contributing C to soil organic matter and releasing gaseous CO_2. The same applies to fruit shells when they are returned to the field after fruit dehusking. The annually produced seeds leave the cultivation system as energy feedstock (Figure 6.2), and the C bound in the seeds is released later during combustion.

To date, the amount of sequestered C in above- and below-ground biomass (AGB, BGB) and possible soil C accumulation in *J. curcas* systems have rarely been integrated in LCA studies due to lacking empirical data. In the present study, C biomass stocks were projected by empirical growth models (Chapter 4), C sequestration in soil was accounted for based on the estimations described in Chapter 5, and fruit and seed yields were taken from the yield monitoring presented in Chapter 4.

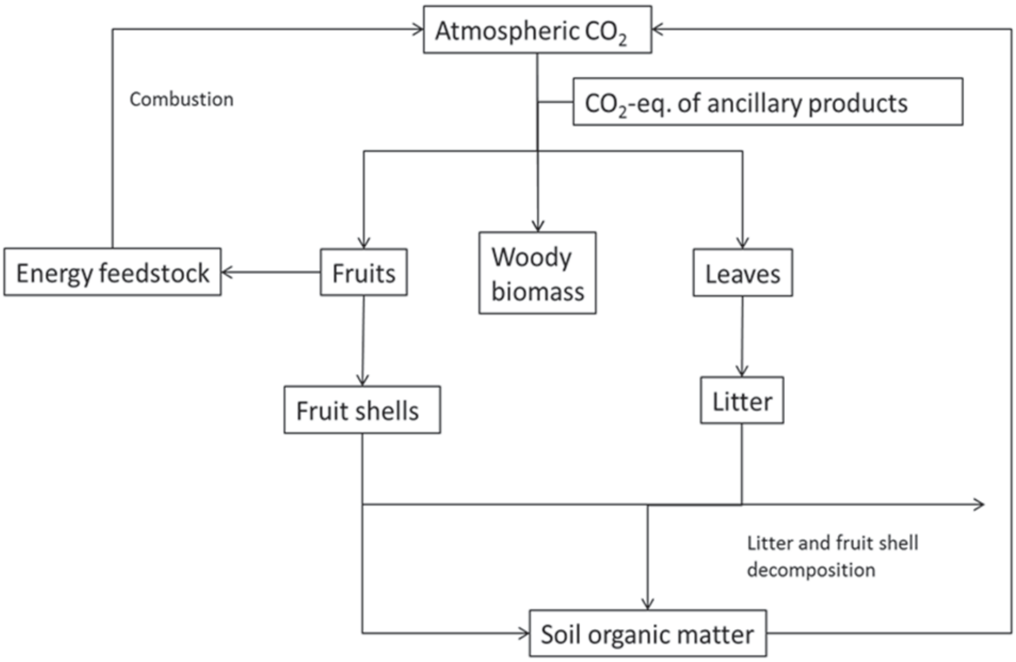

Figure 6.2 Carbon cycle of *Jatropha curcas* cultivation phase (adopted from Baral and Guha 2004)

Whether a system can be a sink or a source of C depends on the land-use system that has been replaced (Montagnini and Nair 2004). The "carbon debt" (Fargione et al. 2008), meaning loss in C stocks through land-use change (LUC), can be repaid over time if biofuels entail lower GHG emissions than the life-cycle of the displaced fossil fuels (Fargione et al. 2008). In the presented case, therefore, the effect of *J. curcas* integration in the landscape was locally examined (Chapter 3), and the C stocks of the systems that have been replaced were subtracted from the new C stocks in *J. curcas* systems. This resulted in the C-stock change (ΔC_{LUC}) depreciated over the life span of a *J. curcas* plantation. Any loss in C was assumed to be emitted as CO_2. According to field observations (Chapter 3), the expansion of *J. curcas* cultivation to annual cropland, to nutrient-poor soils with sparse vegetation, and to natural savannah was considered as most relevant. The AGB, BGB and SOC data of these ecosystems were derived from Achten et al. (2012), Brown et al. (2012) and own measurements (Table 6.3).

Table 6.3 Carbon stocks (t ha^{-1}) in 20-year-old *Jatropha curcas* systems and other land-use systems

Carbon	Inter-cropping	Int. managed	Living fence	Contour hedge	Crop-land	Marginal land	Shrub savannah
Biomass C[a]	11	11	6.5[b]	2.8[b]	5[c]	6[c]	46[c]
SOC (20 cm)[d]	23.3	32	5.4	5.4	30	30	35[c]

Own data if not indicated otherwise;

[a] *Biomass carbon of J. curcas systems according to growth models (section 4.3.5);*

[b] *Biomass carbon of 400 m closed hedge surrounding one-hectare field;*

[c] *Biomass carbon estimates for "cultivated and managed land", "sparse shrubs and bare areas" and "shrubland" (Global land cover land use typology (JRC 2003)) in sub-humid and semi-arid regions of Sub-Saharan Africa (Ruesch and Gibbs 2008 in Achten et al. 2012;*

[d] *30 t C ha^{-1} initial soil carbon stock. Allocated to intercropping (0.71) and hedge systems (0.13) according to the space occupation of J. curcas. + SOC increase of 2 t C ha^{-1} under J. curcas plantations over 20 years; 1.5 t C ha^{-1} under J. curcas hedges over 20 years (section 5.3).*

The gradual land-use change induced by the integration of *J. curcas* intercropping and hedge systems into annual cropland was taken into account by using the space allocation factor 0.71 and 0.13, respectively (section 6.2.3). For intensely managed plantations, complete land-use change was assumed. When it comes to total replacement of annual cropping systems with simultaneous stable demand for the crop, the cultivation will most likely be shifted to other land thus inducing indirect land-use change (iLUC) (Cornelissen and Dehue 2009). This spillover effect was not addressed by the present study.

6.2.5 Transformation phase of *Jatropha curcas* seeds

While data for the cultivation step were empirical in nature (Chapter 3, 4 and 5), most of the input and output data for the industrial phase were taken from secondary sources such as relevant literature and databases (BioGrace GHG calculation tool) and personal communication. Two *J. curcas* processing scenarios were considered: (1) decentralized *J. curcas* SVO production supplied by extensively managed *J. curcas* systems (intercropping, living fence and contour hedge), and (2) centralized SVO and JME production supplied by intensely managed plantations.

In the first scenario, fruits were sun dried and husks were removed manually. Husks were returned to the field directly or put into the compost. Dry seeds were transported by ox, bicycle or on foot to an oil expelling unit located in the center of the nearest village. After oil expelling, the raw oil is filtered through a filter press to remove impurities. In total, 5 kg seeds are needed for 1 kg oil. In the LCA, human energy consumption during seed transportation (dehusking is part of the cultivation phase) and emissions and energy requirements arising from the electrically driven screw and filter presses were considered. The generated seed cake is factored into the LCA calculations by energetic allocation.

Table 6.4 Data on *Jatropha curcas* seed processing

		Decentralized option	**Centralized option**	**Source**
Seed transport	Km	10	200	own observation
Oil extraction				
Extraction rate	Kg oil kg^{-1} seed	0.2	0.2	Laude 2011
Cold pressing	kWh kg $^{-1}$oil	0.5	0.5	A. Chapuis 2013 (pc)
Filter press	kWh kg^{-1} oil	0.5	0.5	A. Chapuis 2013 (pc)
Refining	MJ kg^{-1} oil		0.03	BioGrace 2013^{a}
Steam (natural gas)	MJ kg^{-1} oil		0.46	BioGrace 2013^{a}
Fuller's Earth	Kg kg^{-1} oil		0.008	BioGrace 2013^{a}
Briquetting	kWh t^{-1} husks		0.11	Reinhardt et al. 2008
Transesterification				
Biodiesel yield	%		95	Reinhardt et al. 2008
Methanol input	%		11	Ndong et al. 2009
Glycerin output	%		15	
Electricity use	kWh kg^{-1} JME		0.02	
H_3PO_4 addition	g kg^{-1} JME		0.8	
H_2SO_4 addition	g kg^{-1} JME		0.5	
NaOH addition	g kg^{-1} JME		18	
Steam (natural gas)	MJ kg^{-1} JME		0.97	
Glycerin processing (natural gas)	MJ kg^{-1} glycerin		1.3	BioGrace 2013^{a}
Electricity mix (Benin)^{b}	g CO_2 MJ^{-1}		322	BioGrace 2013^{c}

[a] *BioGrace GHG calculation tool version 4b: data from sunflower oil refining and esterification;*
[b] *100% fossil (IEA 2013);*
[c] *BioGrace additional standard values version 1;*
pc: personal communication.

In the second scenario, complete fruits were transported by trucks to the nearest biodiesel factory located near Boni and Ouagadougou. There, fruits were mechanically dehusked and husks were briquetted for use as solid biofuel. Oil from seeds was expelled using electrically driven screw presses, and SVO was then transformed into methyl ester (biodiesel) by adding methanol. Glycerin generated through this process is purified for soap production. Accordingly, GHG emissions and energy expenditures of centralized processing comprised fruit transportation by truck, grid-imported electricity for pressing, briquetting, transesterification and glycerin purification as well as the energy needed for the production of methanol (Table 6.4).

6.2.6 *Jatropha curcas* oil consumption and energy substitution

Most LCAs conducted for *J. curcas* biofuel pathways have so far focused on the processing phase and have not included the end use of the energy carrier even though this step can have the highest energy losses (Gaul 2012, 2013). Therefore, in the present study, three scenarios of *J. curcas* fuel consumption were considered: (1) Use of *J. curcas* SVO for cooking in rural areas replacing fuel wood, (2) local SVO use in stationary diesel engines (e.g., in multifunctional platforms) replacing fossil diesel, and (3) consumption of centralized produced SVO for the generation of electricity in a national power plant compared to the baseline of petroleum-based electricity[8]. Losses occurring during transmission and distribution of electricity were not accounted for. The use of biodiesel in the transport sector might be a long-term option, but was not considered in the present study. All underlying data are displayed in Table 6.5.

The amount of GHG emissions avoided and energy saved by substituting fossil diesel was taken from BioGrace with 87.64 g CO_2e MJ^{-1} and 1.16 MJ MJ^{-1}, and comprises crude oil extraction, pre-treatment, transportation, processing and combustion. Collection, transportation and drying of wood were done manually, thus there were no additional fossil energy demands or emissions. The combustion of wood emits approx. 109.6 g CO_2e MJ^{-1} (Quaschning 2013), but is usually seen as carbon neutral as all CO_2 emitted was previously sequestered from the atmosphere. However, as long as wood harvest and re-growth are not balanced, as is the case in Burkina Faso (Tatsidjodoung et al. 2012), wood consumption cannot be regarded as sustainable and

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[8] Electricity mix Burkina Faso: 8% hydropower, 44% fossil, and 48% import from Ivory Coast, Ghana and Togo (SONABEL 2011).

is therefore in the present case not considered as carbon neutral (Agostini et al. 2013). In contrast, combustion of *J. curcas* biodiesel emitting 71.5 g CO_2e MJ^{-1} (Pandey et al. 2011) was assumed to be carbon neutral, which is in line with the Renewable Energy Directive (EC 2009).

Table 6.5 Input parameters for baseline and *Jatropha curcas* fuel end-use scenarios

Efficiency of appliances			**Source**
3-stone wood stove	15	%	Yaméogo 2005
Improved wood stove	35	%	Yaméogo 2005
Pressurized plant oil stove (Protos)	50	%	BSH 2013
Small engine (7.25 kW)	~16.5	%	Gmünder et al. 2010
Thermal power plant	~31	%	eia 2013
LHV wood	13	$MJ\ kg^{-1}$	Sylla 2009
LHV SVO and JME	40	$MJ\ kg^{-1}$	Achten et al. 2008

Energy content of wood depends on wood type and humidity. In Burkina Faso, wood humidity ranges from 10 to 65% throughout the year, with a mean humidity of 30% (Sylla 2009).

The estimation of wood fuel consumption on the household level was based on local research. In the villages where the household survey was conducted (Table 3.2), women (n=100) were asked to bring the amount of wood they burn for cooking every day. The weight of the wood divided by the number of household members resulted in the fuel wood and energy consumption per person and day. Moreover, women were asked about their carrying capacity and the walking distance for wood collection. These factors were used for the estimation of working hours required for the collection of wood. Indirect effects of traditional bioenergy use as land degradation and indoor air pollution could not be included into the assessment.

6.3 Results

6.3.1 Cultivation phase

Depending on the management regime, the amounts of GHG emissions and energy consumption resulting from fertilization, pesticide application, machinery use, and irrigation differed (Figure 6.3).

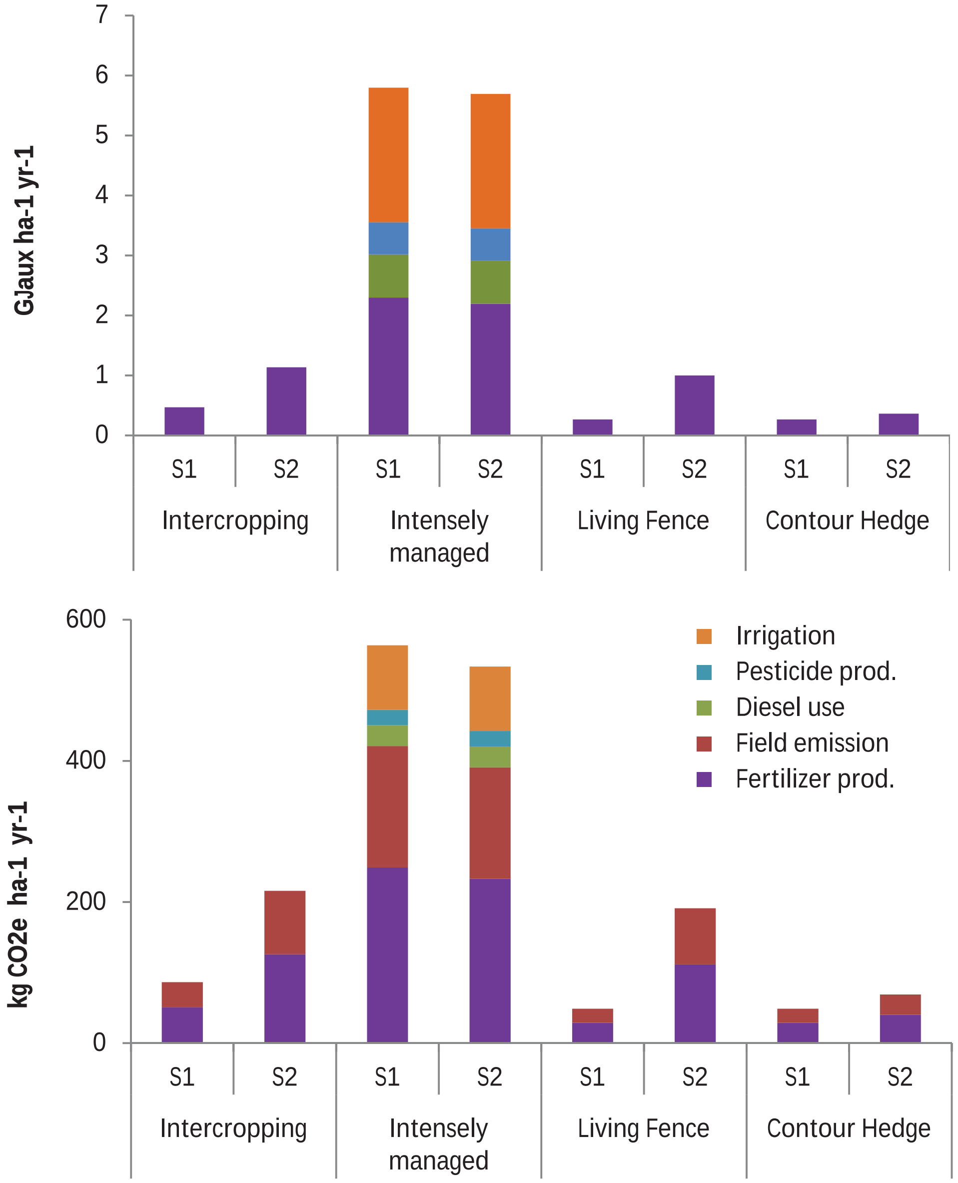

Figure 6.3 Energy requirements and CO_2 emissions on a hectare basis per management intervention for the different *Jatropha curcas* systems (not allocated to by-products); S1: actual applied fertilizer, S2: fertilizer according to nutrient removal by seed harvest.

Intensely managed plantations clearly had the highest CO_2 emissions (564 kg CO_2e ha^{-1} yr^{-1}) and energy requirements (5.8 GJ_{aux} ha^{-1} yr^{-1}) during the cultivation phase. This was due to diesel-driven operations such as soil preparation and irrigation and high amounts of applied fertilizer. Water for irrigation was pumped by a diesel-driven engine consuming substantial amounts of energy and contributing to a high share of

GHG emissions. The use of solar pumps could lead to a 17% and 40% decrease in emissions and energy use per hectare, respectively (manufacturing of solar cells excluded). However, the energy requirement of the diesel pump is an approximation based on estimates from literature, and can thus only give a rough impression of the irrigation effect in Burkina Faso.

For all systems, fertilizer application had the largest share in GHG emissions and energy consumption through fertilizer production and N_20 field emissions. Due to the very high global warming potential of N_2O, the contribution of field emissions to the overall balance was substantial. For intensely managed plantations, the actual applied fertilizer covered the nutrient amount needed for *J. curcas* seed production. For the other *J. curcas* systems such as intercropping, living fence and contour hedge, the shift from S1 to S2 brought an increase in energy and GHG emissions of about 60%, 70% and 30%, respectively. However, *J. curcas* cultivation under S1 might lead to soil nutrient mining and yield reduction in the long term. For the following calculations, therefore, only the second fertilization scenario (S2) was considered in order to display the life cycle of sustainable *J. curcas* production pathways.

When looking at the emissions and energy expenditures of the cultivation phase per $GJ_{biofuel}$, the great differences among the systems were partly leveled, as differences in seed yields per hectare were taken into account. Allocating the arising GHG and energy amounts to all by-products along the production chain led to a sharp decrease in GHG emissions and energy consumption per $GJ_{biofuel}$ (Table 6.6).

Table 6.6 GHG and energy budget of *Jatropha curcas* cultivation phase with and without allocation to by-products (human energy not included)

	Intercropping	**Intensely managed plantation**	**Living fence**	**Contour hedge**
		kg CO_2e GJ^{-1}		
not allocated	33.2	56.2	33.2	33.2
allocated	11.1	13.1	11.1	11.1
		GJ_{aux} GJ^{-1}		
not allocated	0.17	0.60	0.17	0.17
allocated	0.06	0.14	0.06	0.06

With the inclusion of human labor in the cultivation phase, the energy requirement for the production of 1 GJ biofuel increased by 58-66% in the extensive small-scale systems and by 11% in intensely managed plantations. The most labor-intensive tasks were harvesting and dehusking, followed by weeding.

6.3.2 Land-use change and carbon balance

The replacement of cropland, partly by *J. curcas* intercropping and hedge systems or fully by intensely managed plantations, led to a net C gain amounting to 3.7-9.3 t C ha^{-1} (Figure 6.4).

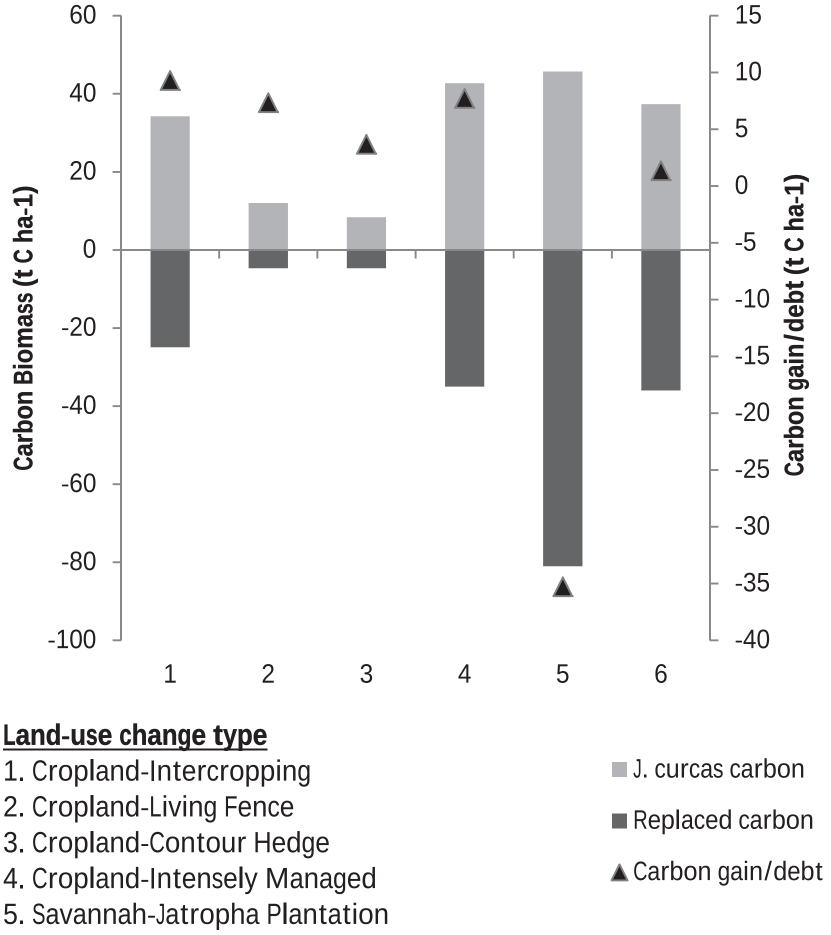

Figure 6.4 Land-use change from cropland, marginal land and savannah to *Jatropha curcas* systems (with space allocation factor 0.71 and 0.13 in intercropping and hedge systems, respectively) and induced carbon gain/debt

In contrast, the conversion of natural savannah to a *J. curcas* plantation would evoke a total carbon debt of 35.3 t C ha^{-1}. Partitioning this carbon debt between biofuel (0.23 allocation factor) and co-products (0.77), a seed production period of 53 years (with 58 kg CO_2e GJ_{JME}^{-1} currently saved by displacing fossil diesel) would be needed to repay the released carbon. With an increased yield prognosis, the repayment period would shorten. The cultivation of *J. curcas* on marginal land could increase the carbon stock by 1.4 t C ha^{-1} under the assumption that *J. curcas* stands on these lands sequester only 50% of the amount of carbon compared to *J. curcas* stands on core cropland due to soil constraints.

With 6.5 GJ ha^{-1} (intercropping system) and 9.5 GJ ha^{-1} (intensely managed systems), *J. curcas* plantation systems have relatively low land-use efficiency in terms of biofuel production. They thus have a high land-use replacement potential. With rising productivity per hectare, the LUC effect per GJ would decrease. For hedge systems, when applying the space allocation factor of 0.13, 44 GJ ha^{-1} can be attained in living fences and 16 GJ ha^{-1} in contour hedges, indicating high land-use efficiency due to localized planting and dense spacing.

6.3.3 From well to tank

Figure 6.5 illustrates all GHG emissions and energy requirements arising along the *J. curcas* biofuel production pathway separated into centralized biodiesel and decentralized SVO production.

With 70% in decentralized (intercropping, living fence and contour hedge) and 49% in centralized (intensively managed plantation) production systems, the agricultural phase was responsible for the highest share in overall GHG emissions. Intensively managed plantations had also very high fossil energy requirements (36%) due to diesel-driven applications for soil tillage and irrigation. For extensive systems, this part was replaced by human labor, amounting to 24% of the overall energy balance.

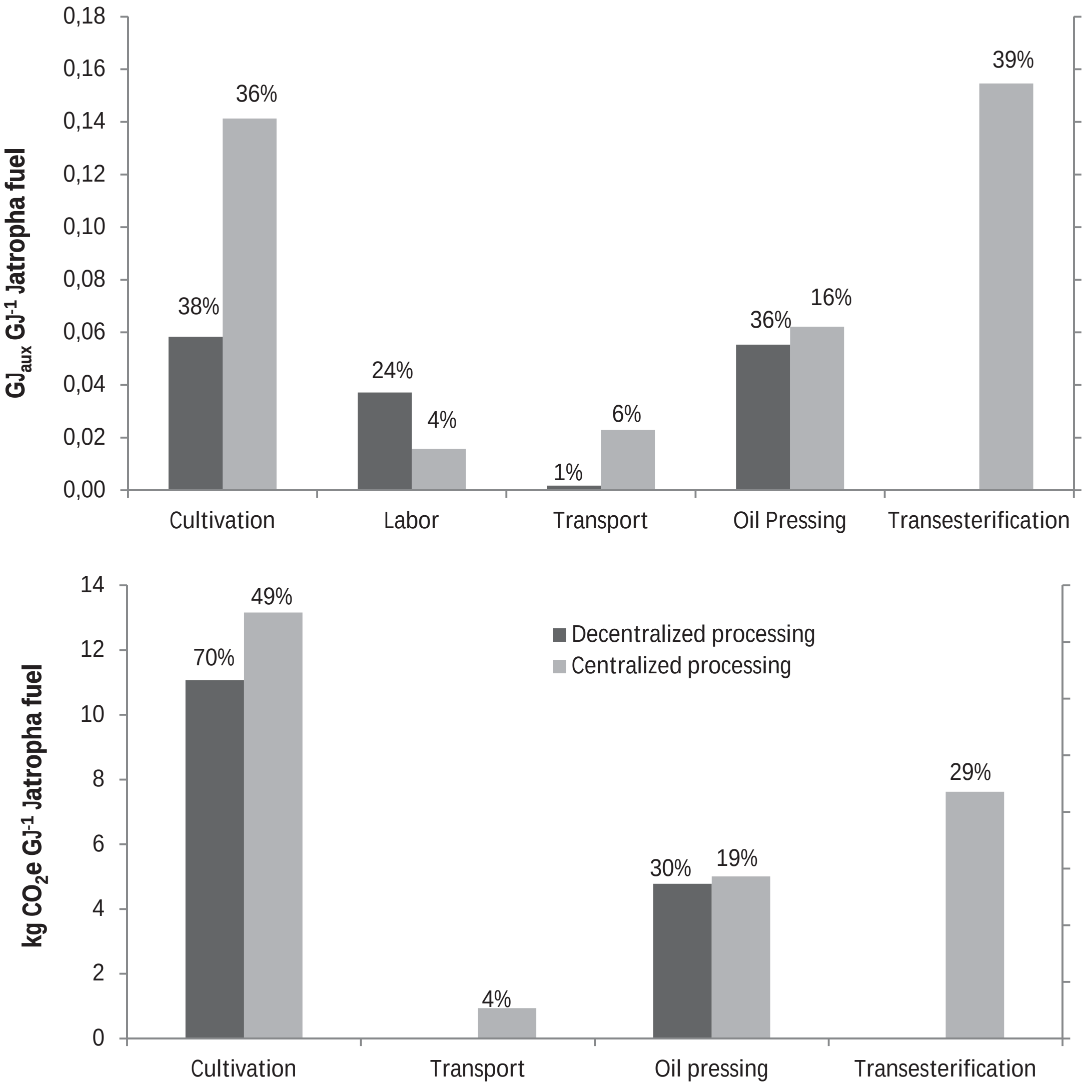

Figure 6.5 Carbon dioxide emissions and energy requirement per GJ locally produced SVO and centralized produced JME (by-product allocation applied)

During the decentralized processing phase, energy was only used (0.06 GJ GJ_{SVO}^{-1}) and GHG emitted (4.8 kg CO_2e GJ_{SVO}^{-1}) during oil pressing and filtering. The human energy requirement for manual seed transportation was negligible (Figure 6.5). In centralized biodiesel production pathways, feedstock transportation by trucks, oil pressing (comprising dehusking, oil refining and briquetting of husks), and oil esterification (including Glycerin purification) were contributors to the life cycle balances with 12.6 kg CO_2e and 0.21 GJ per produced GJ biodiesel. The transesterification process was the most energy demanding and GHG emitting stage due to high additives of methanol.

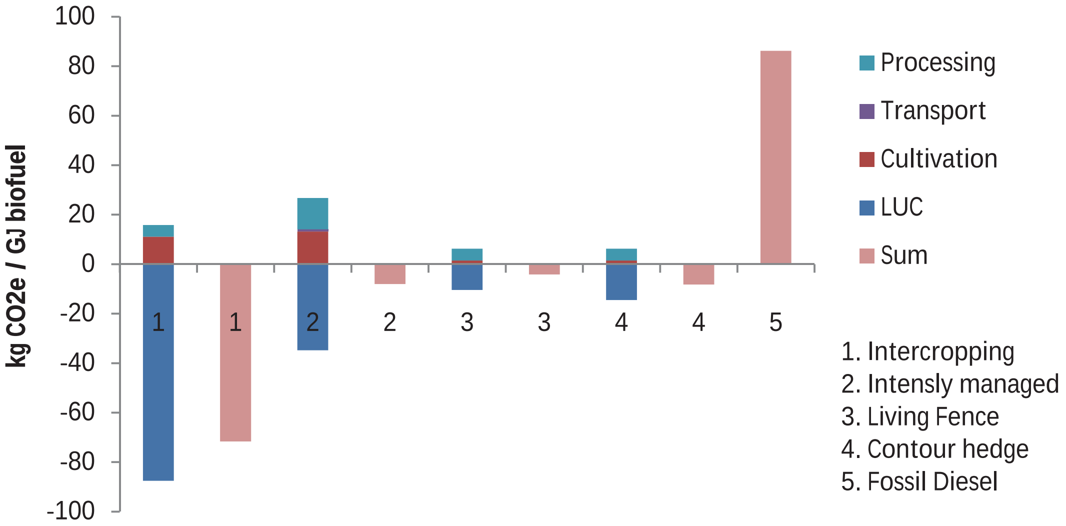

Figure 6.6 Total GHG balance of *Jatropha curcas* cultivation systems and biofuel production pathways including land-use change (LUC) effects (from cropland to *Jatropha curcas*) compared to the life cycle of fossil diesel fuel (by-product allocation applied)

Looking at the overall GHG balances (Figure 6.6) - without the inclusion of LUC- the extensive cultivation systems i.e. intercropping, living fence or contour hedge, and decentralized production of *J. curcas* SVO contributed to the reduction of 82% of GHG emissions as opposed to fossil diesel fuel. Intensively managed plantations and the centralized production of *J. curcas* biodiesel led to GHG emissions that were 69% lower than those of fossil fuel. The inclusion of LUC effects (cropland to *J. curcas* systems) in the GHG balance drastically increases the GHG saving by up to 110-200%.

The production of 1 GJ SVO in extensive systems required 0.15 GJ auxiliary energy, while intensive centralized *J. curcas* biodiesel production demanded 0.4 GJ GJ_{JME}^{-1} (Figure 6.7). This resulted in energy savings of 85% and 60%, respectively. All net energy ratios (NER) were greater than 1 (Table 6.7) meaning that *J. curcas* biofuel production in Burkina Faso can be considered as renewable. Not allocating emissions and energy inputs to all by-products would drastically decrease the GHG reduction and energy saving potentials to 45% and 66%, respectively, in extensive SVO production systems and would result in negative balances, i.e., -4% and -12%, in intensive centralized JME production systems.

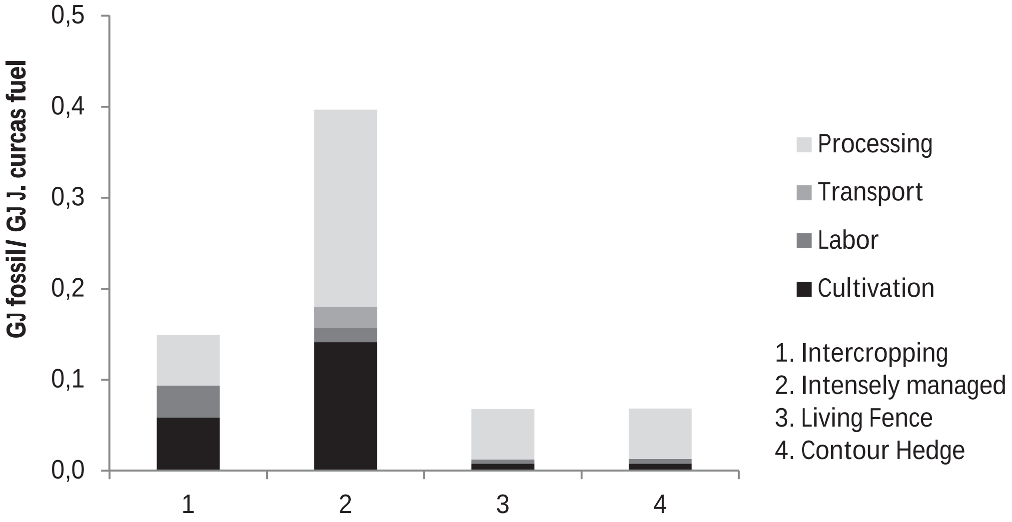

Figure 6.7 Total energy balance of *J. curcas* biofuel production pathways including human labor (by-product allocation applied)

6.3.4 Energy consumption

The three *J. curcas* fuel end-use scenarios S1-3, (see section 6.2.6), had respectively 96%, 82% and 77% lower GHG emissions than the reference scenarios (Figure 6.8).

The baseline scenarios had a total CED_{use} of 6.7 GJ (wood stove), 7.0 GJ (diesel engine) and 4.3 GJ (thermal power plant) per supplied GJ useful energy, with the CED of the wood stove being renewable[9] and that of diesel pathways being 100% fossil. The plant oil stove had a 63% lower CED_{use} than the reference 3-stone fire due to a higher energy efficiency of the plant oil cooker. The CED_{use} of the stationary SVO engine and the power plant options was comparable to the reference scenarios. However, when considering only the fossil energy source, biofuel pathways had 90% and 83% lower energy inputs, respectively (Figure 6.9). The use of biodiesel in stationary engines (30% energy use efficiency) would also lower GHG emissions and fossil energy needs in comparison to fossil diesel; however, this pathway showed a NER lower than 1,

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[9] It was mentioned before that wood consumption in the presented case was not considered as sustainable. Consequently, the energy source cannot be regarded as renewable. However, the CED_{use} of wood is named as renewable in order to distinguish it from fossil energy.

meaning that more fossil energy was consumed than useful energy could be supplied (Table 6.7).

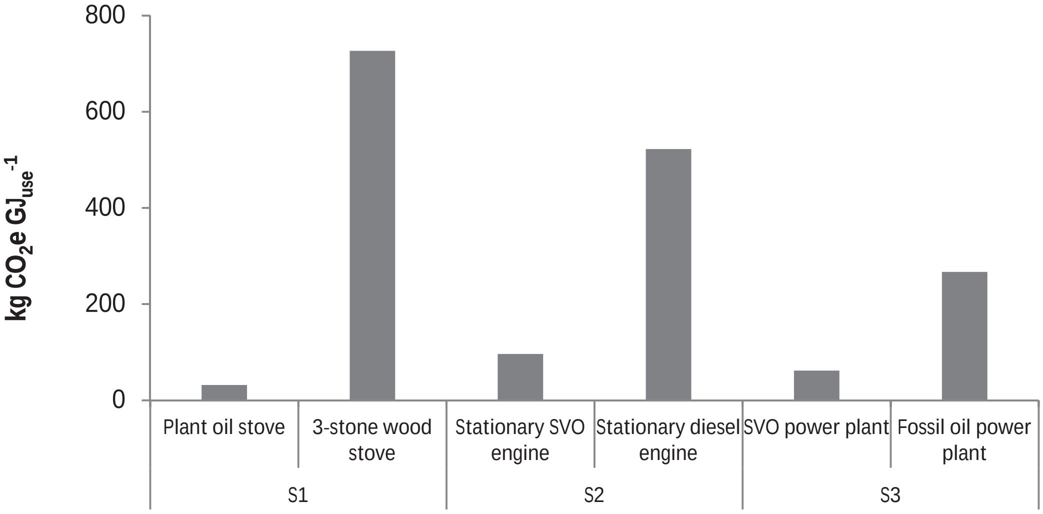

Figure 6.8 GHG emissions of three end-use scenarios (S1-3) of *Jatropha curcas* fuel compared to baseline scenarios

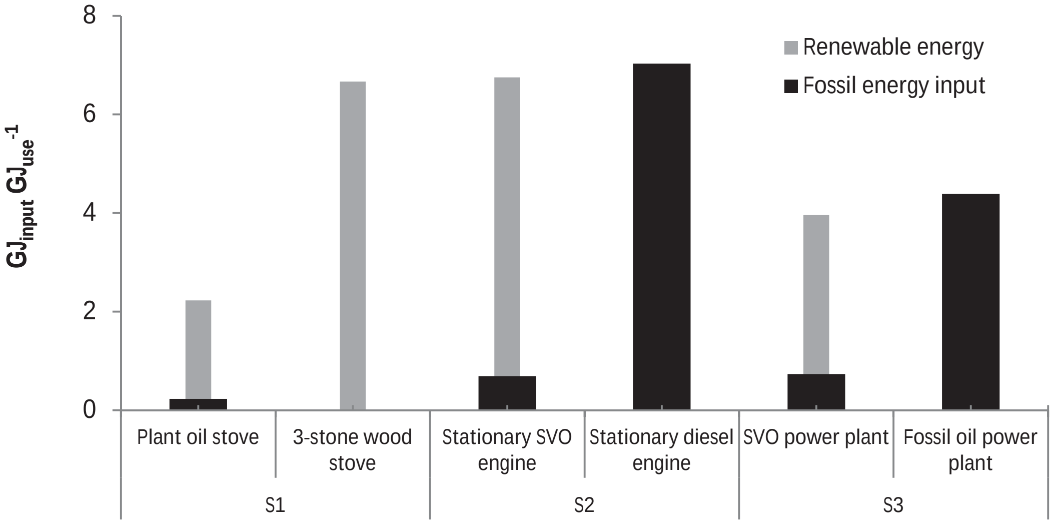

Figure 6.9 Cumulative energy demand (CED_{use}) of three end-use scenarios (S1-3) of *Jatropha curcas* fuel compared to baseline scenarios for the generation of 1 GJ useful *Jatropha curcas*-based energy

Table 6.7 NER of *Jatropha curcas* SVO and JME production pathways (without human energy)

	Extensive *J. curcas* **cultivation and decentralized SVO production**	**Intensive** *J. curcas* **cultivation and centralized SVO/JME production**
Biofuel production ($GJ_{biofuel}\ GJ_{fossil}^{-1}$)	8.75	2.62
Plant oil stove ($GJ_{use}\ GJ_{fossil}^{-1}$)	4.38	
SVO engine ($GJ_{use}\ GJ_{fossil}^{-1}$)	1.45	
SVO power plant ($GJ_{use}\ GJ_{fossil}^{-1}$)		1.35
Biodiesel engine ($GJ_{use}\ GJ_{fossil}^{-1}$)		0.78

Wood fuel consumption and its substitution through *Jatropha curcas* **oil**

Of the interviewed women, 88% (n=110) were using the traditional 3-stone oven, while only 12% had an improved stove. On average, women collected wood 3-4 times per week with a walking time of 3.7±1.4 h each time. In case not enough dry wood could be found, 33% of the women (n=110) said they also collected fresh wood. The weight of the carried wood depended on the distance that had to be walked and the physiology of the woman, resulting in a mean head load (*fagot*) of 33±12 kg (n=70).

Table 6.8 Wood collection and consumption (mean±SD)

Walking time	3.7±1.4 h	
Carrying capacity	33±12 kg $pers^{-1}$	
Daily wood consumption	2.04±1.05 kg $pers^{-1}$	26.5±13.6 MJ $pers^{-1}$
Daily energy need for cooking	3.97±2.04 MJ_{use} $pers^{-1}$	
Daily *J. curcas* oil need for wood substitution	0.20±0.1 kg SVO $pers^{-1}$	

Average dry wood consumption per person (children counted as half) and day (two hot meals per day) resulted in 2.04±1.05 kg, equaling 3.97 MJ_{use} $pers^{-1}$ day^{-1} when assuming an energy use efficiency of 15% and 13 MJ kg^{-1} wood (Table 6.5). With a plant oil cooker (50% energy use efficiency), 0.2 kg SVO would be needed to cover the daily personal energy demand for cooking resulting in 2.9 GJ SVO per year. This equals 72 kg *J. curcas* oil or 363 kg dry seeds. With the current *J. curcas* seed yields, a household consisting of 6 persons would need 2.6 ha *J. curcas* intercropped or 1200 m *J. curcas* living fence to cover their daily energy need. The time saved if no wood had to be collected (501 h yr^{-1} for a 6-person household) could be spent on *J. curcas* cultivation, but it would by far not cover the labor requirement of 1165 h ha^{-1} yr^{-1} for a *J. curcas* intercropping system (Table 6.2).

6.3.5 Carbon offsets

Under current seed yields (Table 6.2) and estimated GHG emission reduction potentials (section 6.3.3), replacement of fossil diesel by *J. curcas* biodiesel would result in 556 kg CO_2 savings per year and hectare in intensely managed plantations. Fossil diesel replacement by *J. curcas* oil would lead to GHG emission savings of 447 kg CO_2 ha^{-1} yr^{-1} in intercropping systems, 397 kg CO_2 ha^{-1} yr^{-1} in living fences, and 143 kg CO_2 ha^{-1} yr^{-1} in contour hedges. Assuming 17 years with stable harvests, 2.4 to 9.5 t CO_2 ha^{-1} could be saved by substituting for fossil fuel.

Considering C sequestration in soil and biomass through *J. curcas* afforestation (Chapter 4 and 5), 34.7 t CO_2 ha^{-1} in intercropping, 27.0 t CO_2 ha^{-1} in living fences, 13.5 t CO_2 ha^{-1} in contour hedges, and 29.4 t CO_2 ha^{-1} in intensely managed plantations could be traded over a plantation life span of 20 years. This amount of sequestered C is based on the integration of *J. curcas* into existing cropland and the land-use-induced change in C stocks (Table 6.3). The crop displacement potential of *J. curcas* in intercropping systems in the long run (Figure 3.1) and its effects on indirect land-use change was not accounted for in the presented figures.

With an average price of US$ 8 t^{-1} CO_2 (Peters-Stanley and Hamilton 2012) on global carbon markets, payments of US$ 19-76 could be gained by diesel substitution and US$ 108-278 for reforestation, on a hectare basis over a period of 20 years.

6.4 Discussion

6.4.1 Management as carbon emitting factor

GHG emissions and energy consumption during the cultivation of *J. curcas* in Burkina Faso had the highest share in the overall life-cycle balance (Figure 6.5), which is in line with other *J. curcas* LCAs documenting the highest emission and energy demands for the agricultural phase (e.g., Dehue and Hettinga 2008; Ndong et al. 2009; Prueksakorn et al. 2010; Pandey et al. 2011; Kumar et al. 2012). The emissions evolved particularly from fertilizer manufacturing and N_2O field emissions from nitrogen fertilization. Diesel-driven applications contributed to increasing emissions and energy needs in the intensified production system. Increasing the N_2O field emission factor from default 1% (IPCC 2006) to 5% as proposed by Crutzen et al. (2008), would increase the GHG emissions of the agricultural phase by 85%. The uncertainty in estimating GHG emissions from soils and their strong influence on the overall balance illustrates the sensitivity of LCAs to input parameter variation. Only through maximum transparency of assumptions and input data can traceability of the calculation be guaranteed (GBEP 2009).

In the studied extensive *J. curcas* systems, trees were only indirectly fertilized through the fertilization of adjacent crops. With 7.5 kg N ha^{-1} allocated to *J. curcas* trees in intercropping systems, the nutrient application was by far under the nutrient removal by seed harvest, which might lead to soil nutrient mining in the long term. Soil nutrient mining is characteristic for Burkina Faso where the national average fertilizer use rate is only 0.3 kg N ha^{-1} (Brown et al. 2012). Consequently, Burkina Faso has very low CO_2e emissions from agricultural operations (Brown et al. 2012), constituting only 0.9% of the overall CO_2 emissions in Sub-Saharan Africa, where the largest part of the CO_2 emissions are through land-use change (Vlek et al. 2004). In contrast to the concern that higher fertilizer and pesticide doses will probably lead to higher GHG emissions (Fritsche 2010; van Eijck et al. 2010), Vlek et al. (2004) demonstrated for Sub-Saharan Africa that higher fertilization rates would lead to higher productivity of the cropping systems and to freeing of land for re-vegetation or energy crop cultivation, which would result in net GHG emission reduction. This supports the reasoning that the low-productive *J. curcas* systems in Burkina Faso with very low land-use efficiency have to be intensified. Pandey et al. (2011) showed favorable energy balances for high-input small-scale *J. curcas* systems, demonstrating the high potential for increased productivity of *J. curcas* systems. The authors named appropriate crop fertilization practices leading to higher N-use efficiency as the key for high productivity with simultaneously positive GHG performance. However, sustainable intensification of *J. curcas* cultivation is only possible with profound knowledge of the input responsiveness of domesticated *J. curcas* breeds.

The high labor and thus high human energy requirement constituting 24% of the overall energy balance for the decentralized production of *J. curcas* oil agrees with the results of Ndong et al. (2009) demonstrating a significant increase in energy consumption through the inclusion of labor force. Despite the substantial increase, the overall energy balance remained positive as in studies by Ndong et al. (2009) and Grimsby et al. (2012). However, the return on labor is very low, and the viability of the extensive *J. curcas* production systems largely depends on the availability of labor willing to work for low incomes (Grimsby et al. 2012). Gaul (2013) emphasized the huge need of physical labor for the provision of one unit *J. curcas*-based energy, too.

6.4.2 Land-use effects

It could be shown that the integration of *J. curcas* production systems into existing cropland resulted in net C-stock gains of 3.7 to 9.3 t C ha^{-1}. The inclusion of this C-stock change into the carbon life cycle (as proposed by RED (EC 2009)) increased the GHG emission reduction potential to over 100% compared to fossil diesel. However, the positive picture in terms of C gain through land-use change might be misleading for intercropping systems. The gradual displacement of the interplanted crops by growing *J. curcas* trees (section 3.3.3) can adversely affect food supply. Unless the agricultural production is not intensified, relocation of the agricultural activities to other areas such as savannahs would induce land-use change and carbon stock losses there (Vlek et al., 2004). Hennecke et al. (2013) warned that by accounting for positive C-stock changes, incentives for land-use change can be set that do not consider such negative side effects. Taking indirect land-use change into account could even show that biofuels emit more GHG than fossil fuels (Hennecke et al. 2013).

Recently, semi-arid areas were increasingly assessed as potential cultivation areas for bioenergy crops (Cai et al. 2011; Wicke et al. 2011), assuming limited contribution of those areas to food production and to environmental services (Achten et al. 2012). However, Achten et al. (2012) stated that the carbon debts caused by conversion of those lands to *J. curcas* plantations greatly depend on the land-use types in these regions. Based on their estimated biomass C stocks of marginal and shrubland and own *J. curcas* C-stock calculations (Table 6.3), the cultivation of *J. curcas* on semi-arid marginal land resulted in a marginal C-stock gain, while the conversion of semi-arid shrubland into *J. curcas* plantations involved a carbon debt, which would require a repayment period exceeding the life span of any *J. curcas* plantation. In general, the carbon debt can provide information about useful lengths of plantation periods in regard to C sequestration potential. The lower the carbon debt, the shorter the plantation cycle should be (Liski et al. 2001). This means that the rotational period of *J. curcas* plantations on former cropland should be adjusted to the stage of fruit productivity decline.

The land-use replacement potential of *J. curcas* plantation systems per produced GJ biofuel is particularly high due to the low land-use efficiency (6.5 GJ ha^{-1}-9.5 GJ ha^{-1}) compared to other bio-energy cropping systems such as sunflower (36 GJ ha^{-1}) and sugarcane (110-140 GJ ha^{-1}) (estimates for developing countries from Girard and Fallot 2006). Low land-use efficiency also applies to the plantation systems that are classified as 'intensely managed' in Burkina Faso where superior planting material has yet to be developed and management interventions are not well adjusted to the tree's needs. As land resources should be used as efficiently as possible (Cherubini et al. 2009), the productivity increase of *J. curcas* systems is key to minimizing competition for land and C losses through direct and indirect land-use change. Consequently, as long as agricultural intensity is neither rising for *J. curcas* nor for annual crops, *J. curcas* should only be grown as field borders. Here, high land-use efficiency can be reached due to localized planting and dense spacing (living fence 44 GJ ha^{-1}, contour hedge 16 GJ ha^{-1}).

6.4.3 Performance of *Jatropha curcas* biofuel production pathways

The overall GHG emission reduction potential of 82% for extensive decentralized produced *J. curcas* SVO and of 69% for intensive centralized produced biodiesel compared to fossil diesel was in the range of documented emission reduction for *J. curcas* production pathways (Dehue and Hettinga 2008; Ndong et al. 2009; Achten et al. 2010d; Kumar et al. 2012). The NER of 8.75 for SVO and 2.62 for biodiesel production is supported by several authors (Ndong et al. 2009; Achten et al. 2010d; Prucksakorn et al. 2010; Pandey et al. 2011; Grimsby et al. 2012; Kumar et al. 2012). However, the direct comparison of LCA results is dependent on different modalities implied in the analysis (e.g., allocation rules, system boundaries, functional units).

For the decentralized SVO production pathway, the processing phase represented 30% of the energy used and 36% of the GHG emissions over the entire life cycle, while the centralized processing of *J. curcas* oil to biodiesel had energy and emission shares of 55% and 48%, respectively, with transesterification as the main contributor. In Burkina Faso, where methanol is not available locally and has to be imported, transesterification becomes particularly expensive (Tatsidjodoung et al. 2012). The production of biodiesel with locally produced ethanol instead of methanol is still under investigation (Tatsidjodoung et al. 2012).

For both *J. curcas* production pathways, transformation performance can be greatly improved by the optimization of oil recovery, which is currently at 0.2 kg oil per kg seed. For areas without grid connection, one could also visualize SVO-driven screw and filter presses consuming part of the produced *J. curcas* oil instead of fossil diesel, thus leading to an improved GHG and energy performance.

Overall, the decentralized SVO option showed better results in terms of GHG emission reductions and energy savings than biodiesel production, irrespective of the type of extensive *J. curcas* cultivation system analyzed (intercropping, living fence or contour hedge).

6.4.4 End use of *Jatropha curcas* fuels

The overall efficiency and competitiveness of an energy pathway is dependent on the fuel supply chain and the end-use appliance (Gaul 2013). All three scenarios analyzed showed lower GHG emissions and fossil energy consumption than their reference systems. The plant oil cooker had the highest energy use efficiency, and *J. curcas* SVO production had the shortest conversion pathway, resulting in the lowest cumulative total energy demand (CED_{use}) for the cooking option compared to all other cases (Figure 6.9). In the presented case, where wood fuel was not considered as renewable but as a net GHG emitting energy carrier, the use of *J. curcas* oil in an oil stove for cooking showed much better GHG performance and higher energy savings than the use of a traditional 3-stone fire. These results are in contrast to the sobering picture painted by Gaul (2012, 2013) showing very inefficient fuel supply chains of *J. curcas*-based energy carriers as indicated by very high total cumulated energy demands. A simple explanation for the discrepancy of the results can be found in the energy allocation along the conversion pathway. In contrast to the presented case where energetic use of all by-products was assumed, Gaul (2013) did not apply any allocation, thus high energy losses in form of fruit husks and press cake accrued. This example shows that in order to optimize energy use pathways, all arising by-products should be best used (section 6.2.2). Here, more research has to be done on possible application forms of seed husks and press cake, particularly at the village level.

Despite the GHG and energy saving potential of *J. curcas*-based cooking, this option does not present a viable alternative to wood-fuel-based cooking. Firstly, affordable plant-oil cooking stoves that are easy to handle are currently not available on the market (BSH 2013). Moreover, under the current yield levels of *J. curcas* in the extensive cultivation systems, the land and labor requirements for supplying households with the SVO necessary for cooking alone might be prohibitive for most small-scale farmers. The introduction of improved stoves that would increase energy use efficiency up to 35% (Yaméogo 2005) together with the plantation of fast-growing trees seems to be a better option. In this way, harmful emissions arising from open fires and the walking time for wood collection could be reduced. Moreover, the negative effects of excessive fuel wood collection such as deforestation and soil erosion could be tackled (Hanff et al. 2011).

The consumption of *J. curcas* SVO in diesel engines and for national electricity generation showed high total cumulated energy demands due to low energy use efficiency of the end-use device, even resulting in a NER lower than 1 when biodiesel is used. However, compared to their fossil fuel counterparts, all *J. curcas*-based options showed fossil energy and GHG emission savings.

Given the fact that 95% of the population in Burkina Faso does not have access to electricity and that it is widely accepted that energy access in rural areas is key for economic development (Hanff et al. 2011), the local use of *J. curcas* SVO in stationary engines (pumps, mills, power generation) should be prioritized (Blin et al. 2013). When the purity of the *J. curcas* plant oil is ensured, it can be used in most diesel engines without major adaption (Blin et al. 2013). The success of a local *J. curcas* SVO supply chain depends greatly on the establishment and management of village-based technology for SVO production and use (Tatsidjodoung et al. 2012).

6.4.5 Potential of global carbon trading for pro-poor mitigation

Carbon prices are highly volatile, ranging from US$ 1 to more than US$ 100 t^{-1} CO_2 (Peters-Stanley and Hamilton 2012). For *J. curcas* systems in Burkina Faso, with an average price of US$ 8 t^{-1} CO_2 (Peters-Stanley and Hamilton 2012), payments of US$ 19-76 could be gained by diesel substitution and US$ 108-278 for reforestation, on a hectare basis over a period of 20 years. Without entering the debate about transaction costs and accessibility of payments schemed for African small-scale farmers (Bryan et al. 2008), it can be stated that efforts to achieve payments are hardly worthwhile. Djanibekov et al. (2012) and Luedeling et al. (2011) also concluded that payments for C sequestration by agroforestry are most likely not generating substantial income for smallholder farmers if C payments are not combined with payments for other environmental services arising from agroforestry. For large-scale biofuel plantations the revenues from carbon trading can be considerable, but in this case the pro-poor C sequestration reward schemes most likely become irrelevant.

6.5 Conclusions and recommendations

All *J. curcas* biofuel production and end-use scenarios in Burkina Faso showed positive GHG and energy balances compared to diesel fuel and fuel wood. Hence it can be concluded that the production and use of *J. curcas* fuel can contribute to climate change mitigation and increasing energy independency in Burkina Faso. The positive balances are based on the assumption that all co-products are energetically used. However, particularly on a village scale, this might not be guaranteed. Here more research has to be done on possible application forms of seed husks and press cake, which then have to be introduced at the village level.

The overall low productivity of *J. curcas* systems resulted in low land-use efficiency and increasing land-use replacement potential of *J. curcas*. Even though the C-stock increased after the conversion of cropland to *J. curcas* plantations, the competition with interplanted crops increases over time thus threatening food security. As a consequence, *J. curcas* systems need to be intensified based on scientific knowledge on input responsiveness of domesticated *J. curcas* breeds. As long as there is no increase in agricultural productivity, *J. curcas* should only be grown as field borders.

Human energy had a particularly high share in the overall energy balance of extensive systems due to manual labor for harvesting and dehusking. It remains to be seen how long smallholder farmers are willing to further allocate high amounts of labor and land to *J. curcas* cultivation without gaining reasonable income. For the same reasons, the substitution of wood fuel used for cooking by *J. curcas* oil is not seen to be a viable option, though GHG and energy balances were significantly better for stoves using *J. curcas* oil than those using fuel wood. Local production and use of SVO in diesel engines for power and electricity generation substituting expensive fossil diesel or grid connection seems to be more promising in terms of energy access and rural development. Here, the local establishment and maintenance of the necessary technology is key for project success. National supply chains of *J. curcas* oil and biodiesel for power plants and the transport sector demand larger-scale production and transformation units, which is only possible if *J. curcas* cultivation is reasonably intensified. As long as the local demand in *J. curcas* fuel is not saturated, the decentralized production option should be favored.

Carbon trading under current prices is not seen to be an attractive option for small-scale *J. curcas* systems, neither for reforestation nor for biofuel projects. The combination of carbon trading with payments for other environmental services which can emerge from agroforestry might raise the prices adequately.

7 GENERAL OVERVIEW AND OUTLOOK

Modern bioenergy offers several advantages to Burkina Faso, a country that is heavily dependent on imported fossil fuel and greatly relying on traditional biomass use. In this context, *Jatropha curcas* has become popular as a low-maintenance energy crop with the potential for land restoration while simultaneously contributing to energy security and climate change mitigation. This thesis evaluated the ongoing *J. curcas* activities in Burkina Faso using the life cycle methodology and carbon and energy balances as sustainability indicators. The development of empirical models for *J. curcas* biomass prediction and a soil survey enabled precise carbon sequestration estimates in the overall balances. In the following, the main findings of the study are summarized, and recommendations for exploitation of the potential of *J. curcas* and suggestions for further research are formulated.

7.1 *Jatropha curcas* in Burkina Faso

The five studied *J. curcas* systems included intensely managed monoculture plantations, interplanting with annual crops, afforestation of abandoned cropland, plantings along contour stone walls, and traditional living fences (Chapter 3).

Private enterprises managing large-scale *J. curcas* plantations in Burkina Faso are currently operating on a limited scale (<500 ha country wide), as the government has yet to decide about the allocation of land for large-scale production of energy crops. Therefore, most stakeholders promote the integration of *J. curcas* as an intercrop in small-scale agricultural systems, which is claimed to be a solution for the production of biofuel that would not affect food security.

According to the model results, intercropping and intensely managed systems showed the highest potential above-ground biomass stock (21 t ha^{-1}) of all systems (section 4.3.5). However, the derived sequestration rate of 0.2-1.9 t C ha^{-1} yr^{-1} (section 4.3.6) falls in the lower range of rates reported in other semi-arid regions (Reinhardt et al. 2008; Struijs 2008; Hellings et al. 2012), and is much lower than those observed in humid regions (Firdaus et al. 2010). Besides low precipitation (<1000 mm), possible explanations include poor natural fertility of West African soils and sub-optimal management of the *J. curcas* systems in terms of irrigation, fertilization, hand tillage and weeding relative to management recommendations given in literature (e.g., Jongschaap et al. 2007; van Eijck et al. 2010; Contran et al. 2013). Even though the monoculture plantations can be described as maintenance intensive relative to the other systems, management practices are still in an experimental stage due to an overall lack of knowledge about optimized *J. curcas* management. The tree is still largely undomesticated, and input response and productivity are highly variable (e.g., Achten et al. 2010a; van Eijck et al. 2010; Singh et al. 2013).

The resulting low productivity and low land-use efficiency in terms of energy production (6.5-9.5 GJ ha^{-1}) leads to an increasing land-use replacement potential. Even though C-stock gains can be achieved after the conversion of cropland to *J. curcas* plantations (section 6.3.2), displaced agricultural activities are likely to induce land-use change and C-stock losses in other areas. Furthermore, dense spacing of *J. curcas* trees in the intercropping system leads to gradual displacement of food crops from comparable fertile soils (section 3.3.3). Land-use competition and low seed productivity (< 1 t ha^{-1}) (section 4.3.2) coupled with high labor requirement particularly observed in small-scale systems (section 6.3.1) made *J. curcas* intercropping a disappointing endeavor for smallholder farmers. For the cultivation of *J. curcas* in productive plantations, the whole system needs to be intensified following the recently presented paradigm of Sustainable Intensification (Montpellier Panel 2013). With increasing productivity per hectare, the land-use change effect per produced GJ would decrease, thus minimizing competition for land. Increasing GHG emissions bound to intensified *J. curcas* cultivation will probably be more than compensated by reduced emissions bound to land-use change (Vlek et al. 2004). Agroforestry domestication and breeding programs have to be undertaken that are tailored both to intensive monoculture cultivation and to smallholder farmers' needs (Achten et al. 2010c). Optimized cultivation techniques then have to be scientifically explored and adequately communicated to small-scale farmers through extension services.

Regarding the effect of *J. curcas* plantings on soil carbon, no significant increase in SOC could be detected in the young *J. curcas* plantation systems relative to reference cropland, neither through the isotopic tracer methodology nor by the soil chronosequence covering 4 years (section 5.3.2). In contrast, a significant decrease could be observed in some plantations, commonly explained by fast mineralization of the fresh litter and soil disturbance during plantation establishment (Jug et al. 1999 in Cerli et al. 2006; Epron et al. 2009; Laganière et al. 2010). From a long-term perspective, however, following the C-input calculations (section 5.3.6) soil C sequestration can be expected to range from 13 to 188 kg C ha^{-1} yr^{-1}.

Despite the persistent claim that *J. curcas* is suitable for dry areas and marginal soils (e.g., Heller 1996; Jongschaap et al. 2007; Achten et al. 2008) and the vision of the Burkinabe government to reclaim degraded areas through plantings of *J. curcas* (MMCE 2009), afforestation systems on low-productive soils play a negligible role in Burkina Faso (section 3.3.2). Afforestation systems were the least productive (<0.1 t biomass ha^{-1}) of all identified systems, and biomass growth could not be modeled due to poor survival at an early age. The bad plant performance and absence of fruit production (section 4.3.5) underline the necessity of adequate maintenance of *J. curcas* plantings on marginal land (Elbehri et al .2013). Regarding the potential for soil reclamation (section 5.3.2), no coherent soil data could be generated; however, the contribution of poorly performing afforestation systems to soil amendment is likely negligible. Should the seed production and soil amelioration goals be realized, the trade-off between the costs of intensified management and increased seed yields have to be considered. For the Burkinabe government, land allocation to *J. curcas* biofuel production remains a key challenge where a balance between marginal land reclamation and profitable biofuel production without affecting food security has to be found.

Jatropha curcas living fences have a long tradition and are widely distributed in the central region of Burkina Faso. They offer a variety of benefits to the farmers such as erosion control and protection against damage by animals, and can be established and maintained with relatively little effort (section 3.3.2). The planting of *J. curcas* trees as contour hedges along erosion control walls in northern Burkina Faso is still in the pilot phase, but it promises the same benefits as living fences. Biomass production for living fences and contour hedges reached its maximum at 12 and 6 t ha^{-1}, respectively (section 4.3.5). This is lower than in plantation systems. However, due to localized planting and dense spacing, the productivity per occupied area is highest, leading to a high land-use efficiency rate of 44 GJ ha^{-1} in living fences and 16 GJ ha^{-1} in contour hedges (section 6.3.2). In line with other studies (Liyama et al. 2012; Singh et al. 2013), it can be concluded that under the current knowledge status the *J. curcas* plantings as traditional living fences or along contour stone walls should be expanded. With a functioning collection system in place, hedge systems could contribute substantially to the national seed supply and to rural energy access (Bako 2011).

Under *J. curcas* hedgerows, the chronosequence study (covering 20 years) showed a significant SOC accumulation of 62 g m^{-2} yr^{-1} in the top 20 cm (section 5.3.3). This value was corroborated by observable but non-significant changes in $\delta^{13}C$ values, indicating a contribution of C_3 (*J. curcas*)-derived C to total soil (section 5.3.4). The observed C accumulation rate is high in comparison to reported values of 10-33.8 g C m^{-2} yr^{-1} (Post and Kwon 2000; Batjes 2001; Guo and Gifford 2002), but explainable given the dense spacing, high litter production, and low soil disturbance in *J. curcas* living fences.

7.1.1 Carbon and energy balances

For the production of straight vegetable oil (SVO) in extensive cultivation (intercropping, living fence and contour hedge) and decentralized processing systems, an overall GHG emission reduction of 82% could be reached compared to fossil fuel. Jatropha methyl ester (JME) from intensive cultivation systems and centralized processing schemes could reduce GHGs by 69%. The net energy ratio amounted to 8.75 for SVO and to 2.62 for JME (section 6.3.3). The JME production had lower energy saving and GHG reduction potentials due to the highly energy demanding and GHG emitting transesterification process. For both production systems (SVO and JME), the overall performance could be greatly improved by optimizing oil recovery (currently at only 20%) during the pressing process. The positive balances were attained under the assumption that all co-products are energetically used. However, particularly on the village level, more research has to be undertaken on possible application forms of seed husks and press cake. Furthermore, side effects such as indirect land-use change and its implications should be analyzed in LCAs at the landscape scale.

Prohibitive high land and labor requirements for the *J. curcas* production covering household energy needs (section 6.3.4) made the substitution of wood fuel through *J. curcas* oil an unviable option, although GHG and energy balances were significantly better for stoves fueled with *J. curcas* oil than for open wood fire. Moreover, affordable plant-oil cooking stoves, which are easy to handle, are currently not available on the market. The use of *J. curcas* oil at the village level for partly substituting expensive fossil diesel in engines for power generation seems to be more promising in terms of rural energy access, and should be prioritized (Blin et al. 2013). Here, the local establishment and maintenance of the necessary technology is the key for project success, e.g., introduction of a dehulling machine at the village level would significantly reduce the labor input. National supply chains of *J. curcas* oil and biodiesel for power plants and the transport sector demand larger scale production and transformation (Tatsidjodoung et al. 2012), which can only be reached if *J. curcas* cultivation is reasonably intensified.

7.1.2 Potential of carbon trading

Carbon sequestration both in biomass and in soil in *J. curcas* systems will not substantially contribute to the overall climate change mitigation target. Carbon offsets of 13-34 t CO_2 ha^{-1} could be traded on international markets, resulting in approximately US$ 106-268 over a period of 20 years. Regarding the potential of *J. curcas* biofuel projects for global carbon trading, over 20 years of *J. curcas* oil production 2-10 t CO_2 ha^{-1} could be saved through the substitution of fossil fuel, amounting to a monetary benefit of merely US$ 18-77 (section 6.3.5).

Without entering the debate about transaction costs and accessibility of payment schemes for African small-scale farmers, it can be stated that under current prices carbon trading does not present an attractive option, neither for small-scale *J.*

curcas afforestation projects nor for small-scale *J. curcas* biofuel projects. For large-scale biofuel plantations, the revenues can be considerable, but are unlikely to be achieved by the smallholder farmers. Apart from climate change issues, increasing C stocks must be realized as an important indicator for sustainable land management and for increasing site productivity. The inclusion of environmental values in carbon credit mechanisms as proposed by Djanibekov et al. (2012) could provide incentives for proper establishment of *J. curcas,* also at sites low in productivity.

7.2 Methodological issues

7.2.1 Estimation of biomass carbon

In accordance with many previous studies (Niklas 1994, 1995; Ketterings et al. 2001; Pilli et al. 2006; Zianis 2008), the developed allometric equations using basal stem diameter as a predictor for AGB and BGB of *J. curcas* provided acceptable outcomes (R^2>0.9), thus facilitating the non-destructive biomass estimation of *J. curcas*. This is particularly important with regard to large trees (section 4.3.4). Regression diagnostics with the relative difference between the directly measured and predicted values as an indicator showed that the power model, commonly seen as the ideal of tree allometry (Niklas 1995), was not automatically appropriate across the entire range of stem diameters sampled, thus confirming that different scaling relationships apply for trees differing in size and/or age (Niklas 1995; Pilli et al. 2006). By analyzing the height-diameter relation of *J. curcas* trees, three growth stages could be distinguished (section 4.3.3). The respective diameter thresholds, i.e., 5.5 cm and 12.3 cm marking the transition from the juvenile to adult and mature growth stage, enabled developing robust allometric equations for the biomass prediction for each ontogenetic phase, thus improving the accuracy of the biomass estimates. Regression diagnostics also highlighted that beside relative difference, absolute values must be considered when assessing the model fitness, particularly for the large-diameter classes where models with small percent errors can substantially over- or underestimate biomass values (section 4.3.4). Allometric equations should be applied with care for stem diameter data outside the range they have been developed for (Rothman 2002), as indicated by the diverging confidence intervals of the biomass estimates (section 4.3.4). Here, the validity range of the equations would be further improved by sampling trees with larger diameter stems.

By comparing the developed equations with allometric relationships from literature (Ghezehei et al. 2009, Achten et al. 2010a, and Hellings et al. 2012), it can be concluded that the influence of environmental factors on the model parameters is likely minimized when the analysis is performed according to growth stage as defined by the stem diameter classes (section 4.4.2). The allometric models could be validated for *J. curcas* trees from plantation systems, whereas the variability apparent in living fences was shown to also result in changing diameter-biomass relationships (section 4.3.7).

The widely accepted sigmoid function for tree growth (Winsor 1932; Niklas 1994; Landsberg and Sands 2011) adequately described the above- and below-ground biomass growth of *J. curcas* as a function of time (section 4.3.5). Overall, the validity of the growth models was confirmed through comparison of the predicted values with observations independent of those used for the model fitting, despite the management-induced deviations in biomass growth observed in the early growing phase (section 4.3.7).

Owing to the recent introduction of *J. curcas* in the crop production systems in Burkina Faso, the model development largely relied on a dataset from younger trees. The applied chronosequence approach, i.e., fitting one curve to trees originating from different sites, represents the only available option for the estimation of *J. curcas* biomass over a longer growing period; however, this required the assumption of similar management regimes and environmental conditions within each cultivation system. Accordingly, the projections for the mature growth stage can be further improved by including data from adult and mature trees when available. As no known growth model studies exist for *J. curcas*, the results provide a starting point to develop more precise models that could include functional relationships in plant growth processes once domesticated *J. curcas* varieties and long-term experimental data are available.

7.2.2 Changes in soil carbon

Different methodologies were applied for the investigation of soil-C dynamics after afforestation with *J. curcas* within a short period of time (Chapter 5): total C analyses of samples taken from soil chronosequences, ^{13}C natural abundance technique, and C input and output estimations. Increasing SOC stocks could only be detected in *J. curcas* living fences, but can be anticipated also for long-rotation plantations. Analysis of annual leaf fall in *J. curcas* systems (section 5.3.6) showed substantial returns in organic material to the soil amounting to approximately 20% of the AGB production. The decay rates of the leaf material were low, thus, it can be reasoned that litter stocks will likely increase over time (Martius et al. 2004). However, it remains unknown how much of the added C is eventually sequestered in stable pools. More investigations of C fluxes, e.g., soil respiration in arid and semi-arid regions and dynamics of growth, decay and turnover of roots in agroforestry systems, would help to identify the processes contributing to increasing soil C. Continuing measurements in maturing *J. curcas* plantations – preferably in a permanent plot design – should also be undertaken analyzing both total C and ^{13}C natural isotope abundance.

7.3 Overall conclusions

The results of the study show that all *J. curcas* cultivation and processing systems in Burkina Faso have high GHG emission reduction and energy-saving potentials, thus contributing to climate change mitigation and increasing independency from fossil energy in Burkina Faso. Despite the positive carbon and energy balances, the following challenges in the *J. curcas* production systems have to be considered:

- All *J. curcas* systems are sub-optimally managed leading to low and unpredictable productivity and low land-use efficiency. Due to lack of management, *J. curcas* fails on low-fertility land.
- Conversion of cropland to *J. curcas* plantations results in net carbon stock gains; however, the displacement of agricultural activities to other areas and associated changes in C stocks has to be analyzed from the landscape perspective.

- Due to low productivity and high labor demands, *J. curcas* plantation systems are not a viable option for small-scale farmers. This also applies to the substitution of fuel wood through *J. curcas* oil.
- Biodiesel production demands larger scale seed supplies that currently cannot be covered by the low-productive systems.
- International trading of carbon credits gained through carbon sequestration in biomass and soil and through carbon substitution of fossil fuel did not prove to be an attractive option for the Burkinabe smallholder farmers.

The following measures could help to overcome the above-mentioned shortcomings of *J. curcas* systems in Burkina Faso:

- All *J. curcas* systems need to be sustainably intensified based on scientific knowledge on input responsiveness of domesticated *J. curcas* breeds. To this end, domestication programs and experimental research have to be conducted and results have to be communicated to the farmers.
- For the cultivation of *J. curcas* on land low in fertility, besides improved management, incentives have to set by the Burkinabe government in order to make its cultivation economically interesting.
- The inclusion of environmental values in carbon credit mechanisms could provide incentives for proper establishment of *J. curcas* and raise the pro-poor mitigation potential of carbon trading.
- At present, *J. curcas* hedge systems remain the only compatible option for rural Burkina Faso. In order to tap the full biofuel production potential of this system, seed collection systems need to be developed and seed transformation techniques have to be put in place.

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9 APPENDICES

Appendix 9.1 Jatropha curcas intercropped with cotton in Boni

Appendix 9.2 *Jatropha curcas* on land abandoned from agricultural activities

Appendix 9.3 Intensely managed Jatropa curcas plantation

Appendix 9.4 Jatropha curcas living fence

Appendix 9.5 Jatropha curcas planted along erosion contour stone walls

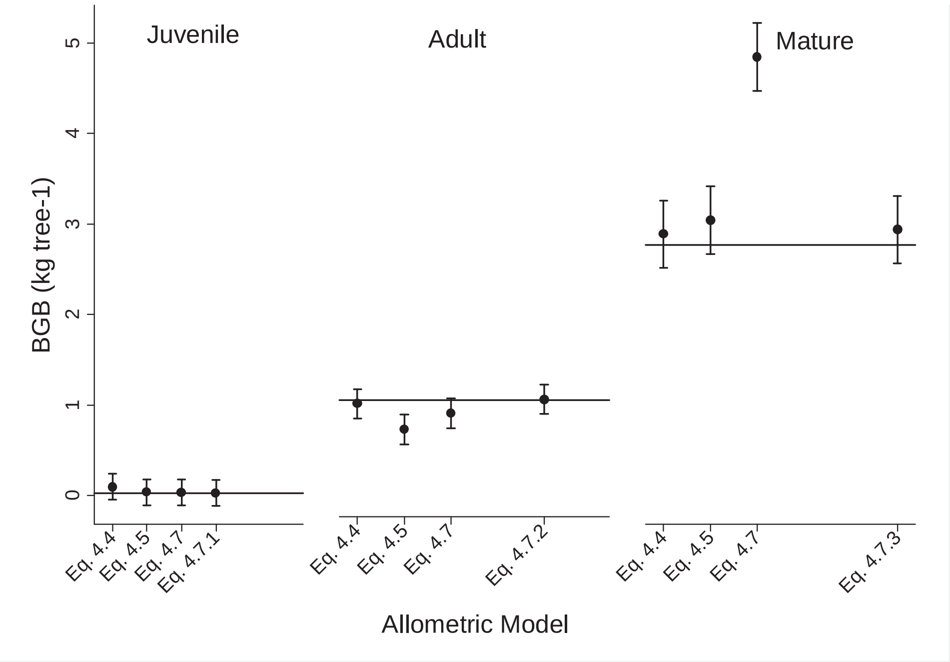
Appendix 9.6 Mature Jatropha curcas trees grown scattered on cropland

Appendix 9.7 Models predicting canopy expansion ($m^2\ ha^{-1}$) over time (years) of different *Jatropha curcas* spacing systems

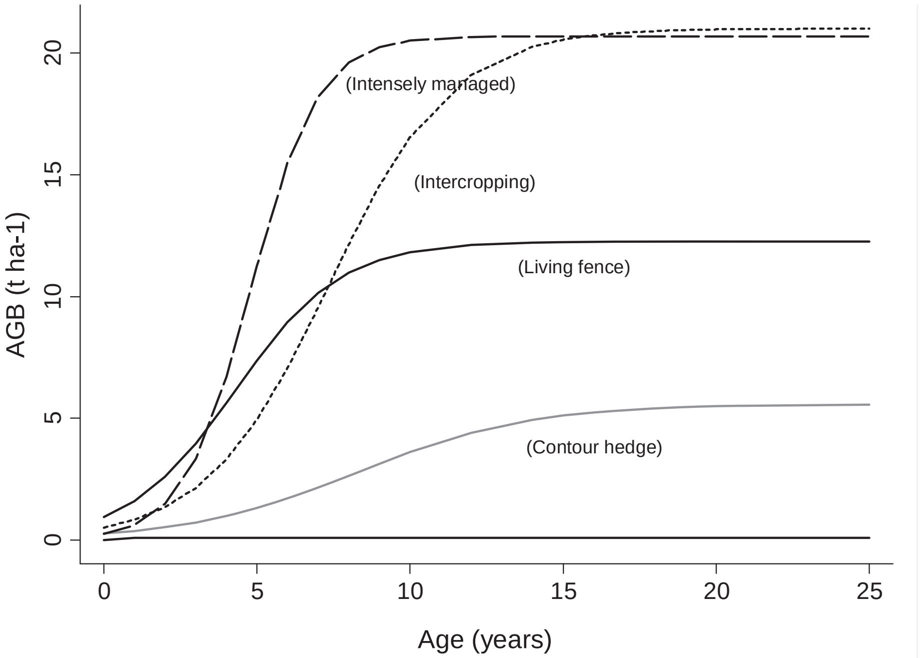
Spacing system	**Model for canopy expansion**	**R²**	**p**
4 m x 4 m	β_1 : 12192±702 β_2 :-13456±586 β_3 : 0.89±0.01	0.71	0.00
2 m x 4 m	β_1 : 24385±1404 β_2 :-26912±1172 β_3 : 0.89±0.01	0.71	0.00
1 m x 4 m	β_1 : 48770±2808 β_2 :-53825±2343 β_3 : 0.89±0.01	0.71	0.00
6 m x 4 m	β_1 : 8135±468 β_2 :-8978±390 β_3 : 0.89±0.01	0.71	0.00
Closed hedge	β_1 : 1651±46 β_2 :-1648±57 β_3 : 0.79±0.01	0.68	0.00

n:399

Appendix 9.8 Average values and CI (95%) of below-ground biomass (BGB; t ha^{-1}) estimated by allometric relationships for the three growth stages of Jatropha curcas. Horizontal line indicates average value of observed biomass over respective growth stage. Panel regression with repeated measurements and multiple, Bonferroni-adjusted comparisons.



Appendix 9.9 Empirical growth models predicting above-ground biomass (AGB t ha^{-1}) for Jatropha curcas cultivation systems in Burkina Faso



Appendix 9.10 Labor requirement for different agricultural activities

Task	Labor time	Source
Land preparation	8 man-day (ox-plow)	Bishop-Sambrook 2003
Planting hole preparation	150 pits / man-day	Pandey et al. 2011
Transplanting	300 pits / man-day	Pandey et al. 2011
Fertilization	5 man-days	Bishop-Sambrook 2003
Weeding	45 man-days	Bishop-Sambrook 2003
Harvesting	1.57 kg seeds /h	Grimsby et al. 2012
Dehusking	1.47 kg seeds /h	Grimsby et al. 2012

One man-day equals 8 working hours.

Appendix 9.11 Labor requirement (h ha^{-1} yr^{-1}) for cultivation of *Jatropha curcas*

Task	Intercropping	Intensely managed	Living fence	Contour hedge
Land preparation[a]	13.1	mechanical	7.4	7.4
Planting hole preparation[b]	1.7	1.6	cuttings	0.5
Transplanting[b]	0.8	0.8	1.2	0.3
Fertilization[a]	8.2	40	4.6	4.6
Weeding (2x)[a]	73.8	mechanical	41.8	41.8
Harvesting[c]	515	793	457	165
Dehusking[c]	552	mechanical	489	176
Sum	**1165**	**836**	**1002**	**396**

[a] *Labor time allocated to J. curcas according to space occupation (intercropping 0.71; living fences 0.13);*
[b] *Labor time annualized over 20 years;*
[c] *Labor time accounted for from the third growing year onward.*

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