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Yield, productivity and technical gaps that limit the cotton agricultural production system in the Colombian Caribbean

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Abstract

This thesis contributes to understanding factors related to production situations in agricultural systems of the Colombian Caribbean using decision analysis. Decision analysis has numerous advantages when it is used for this purpose. It is a multidisciplinary framework which helps decision-makers or stakeholders evaluate competing alternative actions or interventions in order to choose the preferable option. Decision analysis is a bottom-up approach that collects knowledge developed by stakeholders (including farmers) and combines it with available field data and disciplinary expertise. This approach allows the inclusion of all variables that are essential for the contextual description of the problem, even if these variables are difficult to measure. Risks and uncertainties are also included in decision analysis reflecting better the reality of agricultural production situations. As a final remark, decision analysis is focused on active assessment of alternatives for improving system performance with the explicit intention to take action and assess consequences and not just studying how a system works.

The first part of this study describes the application of conceptual modeling on the understanding of the management of the cotton boll weevil (*Anthonomus grandis grandis*). The boll weevil is the main pest in the cotton-producing regions throughout the Americas from Southern Texas to Argentina. To date, information on boll weevil (BW) management strategies in Colombia is only available in the forms of gray literature (technical reports) and informal knowledge held by crop advisors and farmers. The conceptual model developed in this study collected that information and integrated the informal local knowledge of crop advisors and farmers with disciplinary knowledge describing management strategies. The conceptual model was conceived in a strategic planning framework for accommodating temporal-spatial scales of decision making: 1) farm (field) scale management during the cotton season and 2) a regional BW suppression strategy mainly aimed at controlling the insect populations that survived the inter-cotton season. This conceptual model provides guidelines for future research, and it can serve as a baseline for the development of quantitative models and simulations describing the decision-making process related to the management of BW in the Colombian Caribbean.

The second part of this study deepens in the understanding of the boll weevil management and applies decision analysis to assess pesticide-based strategies used at farm scale. Proactive and reactive management at farm-scale were represented as probabilistic production functions using budget partial analysis. This decision model layout was able to capture key properties of control strategies, while accounting for uncertainty about pest infestation pressure, control effectiveness and cotton yield and price. Simulation outcomes indicate that a proactive management for the BW is more efficient than a reactive approach given the current weevil infestation levels. However, farmers prefer the reactive strategy, since they have experienced seasons with low infestation pressure where no insecticide applications were required. In low infestation scenarios the proactive strategy, that requires scheduled pesticide applications in all seasons, is seen as wasteful. In seasons with high infestation pressure the expected revenues of the reactive strategy tend to decrease, mainly because more spray applications are required when fields are heavily infested by the weevil. While economic injury levels can only be applied to responsive measures, our approach of partial budget analysis under uncertainty allows us to assess and compare both responsive and preventive measures in the

same methodological framework. This framework can be extended to other non-pesticide control measures.

The fourth part of this study focuses on the assessment of economic prospects of irrigated horticultural systems. These production systems are an alternative to cotton crops for smallholders. Understanding these diversified systems require quantification of productivity and related risks for individual crops as well as an assessment of the benefits from diversification. A whole-farm decision analysis of this kind is an extension of Modern Portfolio Theory (MPT) that allows us to link the concepts of risks and returns for a multi-asset scenario (several crops or farm enterprises). Understanding this relationship is essential for identifying diversification strategies that farmers can validate and adjust to technical or economical limitations or individual preferences. This decision analysis approach can be useful in assessing other horticultural systems and for the assessment and identification of new crop options to be incorporated in diversified systems. This decision analysis can also be used to represent diversification in other whole-farm planning scenarios, e.g. when it comes to rotations of field crops, integrated livestock farms, cut-flower farming or agroforestry systems.

This study's results show the versatility of decision analysis for its application to different typologies of decision-making problems in agriculture. It provides a conceptual modeling approach that incorporates planning horizons for the decision making problems. Conceptual models outlining strategic decision-making scenarios facilitates the process of quantitative modeling because it helps to define the decision making-problem to model while offering a model reference framework. This thesis provides layouts for two of those strategic-making scenarios that are not commonly represented in the literature of applications for decision analysis but are very common in agricultural settings: production under risk and whole-farm planning and operation. Production under risk was used for modeling pest management as a special production function describing losses. This framework has the potential to provide a unified protocol for assessing benefits in pest management, specially in those cases of integrated pest management. Whole farm-planning and operation was conceived as an extension of the Modern Portfolio Theory. This thesis provides a complete protocol of decision analysis describing its application in diversified systems.

Zusammenfassung

Landwirte treffen ihre Entscheidungen im Rahmen physikalischer, biologischer, technischer, sozialer und wirtschaftlicher Bedingungen. Diese lokale Umgebung, in der ihre Nutzpflanzen angebaut, gepflegt, geerntet und gehandelt werden, wird als "Produktionssituation" bezeichnet. In einer Umgebung ausgezeichnet durch optimale Versorgung mit Wasser und Nährstoffen und ohne Ertragsverluste durch Schädlinge, Krankheiten und Unkräuter können die Pflanzen den maximalen Ertrag, d. h. den potenziellen Ertrag, erreichen. Die vorherrschenden landwirtschaftlichen Produktionssituationen sind jedoch weit vom Optimum entfernt. Im Allgemeinen wachsen Nutzpflanzen in lokalen Umgebungen, die für ihre Bedürfnisse suboptimal sind. Der Ernteertrag, der unter diesen landwirtschaftlichen Bedingungen erzielt wird, wird als tatsächlicher Ertrag einer Kulturpflanze bezeichnet. Die Differenz zwischen dem potenziellen Ertrag, der in einer perfekten Umgebung erzielt wird, und dem tatsächlichen Ertrag wird als Ertragslücke bezeichnet. Das Konzept der Ertragslücke wird häufig bei der Entwicklung und Bewertung von Modellen und Maßnahmen in tropischen landwirtschaftlichen Systemen verwendet.

Diese Arbeit trägt zum Verständnis von Produktionssituationen und Ertragslücken in landwirtschaftlichen Systemen der kolumbianischen Karibik unter Verwendung der Entscheidungsanalyse bei. Die Entscheidungsanalyse hat hinsichtlich dieses Zweckes zahlreiche Vorteile. Die Entscheidungsanalyse ist ein multidisziplinärer Ansatz, der sich mit Entscheidungsproblemen in komplexen, unsicheren und risikoreichen Umgebungen beschäftigt, mit der Absicht, eine Handlungsempfehlung zu geben. Dieser Bottom-up-Ansatz sammelt das von den Beteiligten (einschließlich der Landwirte) gesammelte Wissen und kombiniert es mit verfügbaren Felddaten und disziplinärem Fachwissen. Dieser Ansatz erlaubt die Einbeziehung aller Variablen, die für die kontextuelle Beschreibung des Problems wesentlich sind, auch wenn diese Variablen schwer zu messen sind.

Der erste Teil dieser Studie beschreibt ein konzeptionelles Modell für das Management des Baumwollkapselkäfer (*Anthonomus grandis grandis*), dem Hauptschädling für Baumwollkulturen in der kolumbianischen Karibik. Dieses konzeptionelle Modell sammelte graue Literatur, informelles lokales Wissen von Anbauberatern und Landwirten sowie disziplinäres Wissen, um einen strategischen Planungsrahmen zu generieren, der die zeitlich-räumliche Skala der Entscheidungsfindung für das Management dieses Schädlings beschreibt d.h. flächendeckendes Management und Farmkontrolle. Dieses konzeptionelle Modell bietet Richtlinien für zukünftige Forschung, insbesondere aber für die Entwicklung von quantitativen Entscheidungsmodellen für das Management des Baumwollkapselkäfers.

Der zweite Teil dieser Studie vertieft das Verständnis für das Management des Baumwollkapselkäfers und wendet die Entscheidungsanalyse an, um pestizidbasierte Strategien zu bewerten, die auf Betriebsebene eingesetzt werden. Proaktive und reaktive Managementstrategien wurden als probabilistische Produktionsfunktionen unter Verwendung der partiellen Budgetanalyse dargestellt. Dieses Entscheidungsmodell erfasst die Schlüsseleigenschaften von Bekämpfungsstrategien und berücksichtigt gleichzeitig die Unsicherheit in Bezug auf Schädlingsbefallsdruck, Bekämpfungseffektivität sowie Baumwollertrag und -preis. Die Simulationsergebnisse deuten darauf hin, dass ein proaktives

Schädlingsmanagement effizienter ist als eine reaktive Kontrolle, wenn man den aktuellen Befallsgrad des Baumwollkapselkäfers berücksichtigt. Die Landwirte bevorzugen jedoch die reaktive Strategie, da sie Saisons mit geringem Befallsdruck erlebt haben, in denen keine Insektizidanwendungen erforderlich waren. In Szenarien mit geringem Befallsdruck wird die proaktive Strategie, die planmäßige Pestizidanwendungen in allen Jahreszeiten erfordert, als Verschwendung angesehen. In Jahreszeiten mit hohem Befallsdruck sinken die erwarteten Erträge der reaktiven Strategie tendenziell, hauptsächlich weil mehr Spritzanwendungen erforderlich sind, wenn die Felder stark vom Schädling befallen sind.

Der vierte Teil dieser Studie konzentriert sich auf die Bewertung der wirtschaftlichen Perspektiven von bewässerten Gartenbausystemen. Diese Produktionssysteme stellen für Kleinbauern eine Alternative zum Baumwollanbau dar. Das Verständnis dieser diversifizierten Systeme erfordert eine Quantifizierung der Produktivität und der damit verbundenen Risiken für die einzelnen Kulturen sowie eine Bewertung der Vorteile der Diversifizierung. Eine solche Ganzbetriebs-Entscheidungsanalyse ist eine Erweiterung der Modernen Portfolio-Theorie (MPT), die in der Lage ist, die Konzepte von Risiken und Erträgen für ein Multi-Asset-Szenario (mehrere Kulturen oder landwirtschaftliche Betriebe) zu verbinden. Die Anerkennung dieser Beziehung ist wesentlich für die Identifizierung von Diversifizierungsstrategien, die Landwirte validieren und an technische oder wirtschaftliche Einschränkungen oder individuelle Präferenzen anpassen können. Dieses Planungslayout für den ganzen Betrieb ist auch nützlich, um die Diversifizierung in anderen Szenarien zu bewerten, wie z.B. Fruchtfolgen, integrierte Viehzuchtbetriebe, Schnittblumenanbau oder Agroforstsysteme.

Diese Arbeit zeigt die Vielseitigkeit der Entscheidungsanalyse für ihre Anwendung auf verschiedene Typologien von Entscheidungsproblemen in der Landwirtschaft. Sie liefert ein konzeptionelles Modellprotokoll, das Planungshorizonte für die zu lösenden Entscheidungsprobleme abgrenzt. In dieser Arbeit werden auch Entwürfe für zwei strategische Entscheidungen bereitgestellt, die in der Literatur über Anwendungen der Entscheidungsanalyse nicht häufig dargestellt werden, aber in landwirtschaftlichen Praxis sehr häufig vorkommen: Produktion unter Risiko und ganzheitliche Planung des Betriebs. Die Produktion unter Risiko wurde für die Modellierung des Pflanzenschutzes als Spezialfall einer Produktionsfunktion, die Verluste beschreibt, verwendet. Dieses Layout hat das Potenzial, ein einheitliches Protokoll für die Bewertung des Nutzens von Schädlingsbekämpfungsstrategien zu liefern, insbesondere für den Vergleich von aktiven und reaktiven Ansätzen. Die Gesamtbetriebsplanung und -führung wurde als Erweiterung der Modernen Portfoliotheorie, angewandt auf diversifizierte Systeme, konzipiert.

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I think of myself as a natural hiker having been born and bred in the Andes. In the *Rhineland*, I transformed myself into a *wanderer* that enjoys long walks along the *Rhein* in solitary or in the company of the DAAD Freundeskreis Köln. Thanks to Dennis and Yanfei who have committed their time to this organization and provide DAAD scholars with an opportunity to know our host country better, and share insightful moments.

Finally, I would like to dedicate this work to my family. We have faced many challenges, enjoyed many parties, dreamed of better times, traveled many miles, shared many stories, and spent entire lives together. We were separated during the coronavirus pandemic but now we are again together and thankfully we did not lose anyone during these uncertain times. I also want to express my deep gratitude to Lily. My anxiety rose without control during the uncertain dark days of the first pandemic winter. I experienced the so-called “writer's block” and my thesis was at a dead point. Her constant support and words of encouragement provide me with harmony and balance that allow me to find the best of me and finish my thesis. L, I hope the best for you.

“SCHÜLER.
Das sieht schon besser aus! Man sieht doch, wo und wie.

MEPHISTOPHELES.
Grau, teurer Freund, ist alle Theorie,
Und grün des Lebens goldner Baum.

SCHÜLER.
Ich schwör Euch zu, mir ist’s als wie ein Traum.
Dürft ich Euch wohl ein andermal beschweren,
Von Eurer Weisheit auf den Grund zu hören?

MEPHISTOPHELES.
Was ich vermag, soll gern geschehn.”

- -Johann Wolfgang Von Goethe, 'Faust'.

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Chapter 1

1 Introduction

1.1 Context and study relevance

Farmers make decisions within the constraints of physical, biological, technical, social and economic conditions. This local environment where their crops are planted, managed, harvested and traded is called the "production situation" (Breman and de Wit, 1983; de Vries and van Laar, 1982; Rabbinge and De Wit, 1989). The production situations are determinants of yield levels, and they are used interchangeably for describing the performance of an agricultural system. Potential yield describes an idealistic production situation where a crop grows in a perfect state of protection and supply of water and nutrients, and only limited by the yield-defining factors (radiation, temperature and genotype of the plant) (Evans and Fischer, 1999; Evans, 1993; Lobell et al., 2009; van Ittersum and Rabbinge, 1997). However, farmers can not provide a perfect supply of water and nutrients and completely eliminate losses related to pests and diseases. This production situation is called actual yield (van Ittersum and Rabbinge, 1997).

The difference between potential yield and actual yield for a specific crop is called the yield gap. Rain-fed non-fertilized crops exhibit the widest yield gap, while irrigated fertilized crops exhibit the smallest gap. In those production situations of intensive crop management, farmers have expectations of high yields and they are willing to pursue the potential yield up to the optimum economic level. This point is usually reached at approximately 80% of the potential yield. Costs of additional management over this point do not result in proportional benefits (Law of Diminishing Returns). This production situation is called exploitable potential yield or the farmland production potential (Cassman et al., 2003; Lobell et al., 2009).

In this thesis, I focused on the understanding of factors that determine production situations of agricultural systems using decision analysis. Decision analysis has numerous advantages when used for the purpose above stated. It is a multidisciplinary framework which helps decision-makers or stakeholders evaluate competing alternative actions or interventions in order to choose the preferable option (Borsuk, 2008; Hubbard, 2014; Luedeling and Shepherd, 2016). Decision analysis is a bottom-up approach that collects knowledge developed by stakeholders and combines it with available field data and disciplinary expertise (Gregory et al., 2012; Luedeling and Shepherd, 2016). This approach is able to include variables that are essential for the contextual description of the problem, even if these variables are difficult to measure (Hubbard, 2014). Data elicited from experts or available datasets is collected as probability distributions. This provides a way to include risks and uncertainties, and reflect better the reality of agricultural production situations (Luedeling and Shepherd, 2016). As a final remark, decision analysis is focused on active assessment of alternatives for improving system performance with the explicit intention to take action and assess consequences and not just studying how a system works (Gregory et al., 2012; Luedeling and Shepherd, 2016).

The case studies selected for this application of decision analysis in production situations were intensive production systems of the Sinu Valley in the Colombian Caribbean. Intensive agriculture relies heavily on the use of pesticides and chemical fertilizers to meet farmers' expectations of high yields. Since the effect of fertilizers and insecticides application follows the law of diminishing returns, these systems operate near the boundary of the exploitable potential yield. Under these conditions, variations observed in yield are mainly related to losses due to pests and diseases (Savary et al., 2016). In this production situation setting, we use decision analysis to address management problems affecting productivity (i.e. revenues) of rain-fed cotton crops and irrigated horticultural production systems. The decision problems were formulated with exploitable potential yields as a benchmark in order to discount losses due to pests and diseases. The resulting yield distribution is the actual yield that together with socio-economic variables determines the system productivity. This approach was applied to decision problems at different spatio-temporal scales.

The following sections of this chapter will provide descriptions of the application of decision analysis in the agricultural sector, the regional context of the study cases, and the organization of this thesis.

1.2 Decision-making under uncertainty in the agricultural sector

Agriculture based systems are extremely complex and vulnerable to risks and uncertainties that limit the benefits of interventions aimed to improve agricultural outcomes (Luedeling and Shepherd, 2016). Decisions in agricultural settings require attention to a range of ecological, socioeconomic, cultural, and political factors that define the productivity of agricultural systems (Singh et al., 2016). The incorporation of these factors provides decision-makers with relevant information and support for the selection of an appropriate course of action (Hardaker and Lien, 2010; Luedeling and Shepherd, 2016).

Decision analysis can provide a framework to meet the challenges of decision making in agricultural settings. This approach offers a promising way forward in supporting decision making in these settings, because it has been designed for aiding decision making on risky actions with limited research budgets or tight timelines (Hardaker and Lien, 2010; Hardaker et al., 2009; Rosenstock et al., 2017). For the purpose of implementation, this thesis presents a combination of several decision analysis concepts, procedures and tools drawn from Applied Information Economics (AIE) (Hubbard, 2014) and Agricultural Decision Analysis (ADA) (Anderson et al., 1977). This assemblage in combination with decisionSupport (a R package that facilitates decision analysis (Luedeling et al., 2020)) provides us a modeling framework for the development of decision models.

Decision models are created with the purpose to estimate the full range of plausible outcomes of particular interventions or actions. These outcomes are obtained using probabilistic simulations that include the important variables identified by the stakeholders and the uncertainty around them. Projected outcomes can be still uncertain but they offer a perspective that facilitates a rational course of action for the decision (Peterman and Anderson, 1999). In cases where the remaining uncertainty is too high to immediately decide on the most desirable decision option, decision analysis can provide guidance for what pieces of information decision makers are lacking (Luedeling et al., 2015). Calculating the value of information (Milner-Gulland and Shea, 2017) for variables within such models allows for prioritization of knowledge gaps that should most urgently be narrowed in order to improve certainty about the decision (Hubbard, 2014; Luedeling et al., 2015)

Decision models are explicitly created for representing management processes, supporting decision-making, and promoting action (implementation) in well defined contexts. These contexts or decision problem situations are described by lines of cause-consequences relationships that are specific for each problem situation. This decision-making landscape can be outlined by time-space scales that describe specific decision problems layout. The explicit description of these layouts facilitates the modeling process and representation of the management interventions. This thesis presents a hierarchical description of this decision making landscape synthesizing previous attempts to provide a typology for modeling and decision making in agriculture (Anderson et al., 1977)

1.2.1 Decision-making landscape

Formal analysis of decision-making in agriculture obviously has costs: all time and resources dedicated to think and understand the problem. Not all decisions are important or valuable enough to warrant this effort. The most common types of decision problems worthwhile this effort are:

1. Single event decisions
2. Repeated risky decisions.

Single event decisions: Formal decision analysis is needed when a decision represents a unique event of great importance that eventually will result in exclusive commitment and a significant amount of resources funneled to a single preferred course of action. These decisions are important because there is a considerable gap between the best and the worst outcome, a gap big enough that will have a significant impact on wealth. Single event decisions worth of analysis are commonly represented by investment decisions, proposing infrastructure projects, developing management plans, and designing policy frameworks (Anderson et al., 1977; Gregory et al., 2012; Hardaker et al., 2015).

Repeated risky decisions: Formal decision analysis can also be applied to decisions that do not threaten our wealth but we repetitively have to make under uncertain conditions. For these repeated risky decisions, it is possible to create a sensible strategy that could be applied time and again. The benefit from these decisions may be small, but the accumulated benefit of obtaining a better outcome every time that the decision is taken justify the investment of time and effort.

Repeated risky decisions are very common in agriculture, especially in crop protection and animal health decision problems. When dealing with diseases, not controlling a pathogen can harm the herd or the crop directly, or decrease the quality of their products. Preventing a disease to happen requires prophylactic treatments that increase production costs and reduce benefits. Because incidence and severity of a disease is uncertain and frequently on-farm assessments are not wholly reliable, farmers implement cost-effective prevention strategies that avoid or minimize losses (Hardaker et al., 2015). Analysis for repeated decisions is also the case of advisory situations or extension services where an analyst or consultant is dedicating considerable effort into devising more efficient risk-management strategies for farming activities that could be adopted by many farmers (Hardaker et al., 2015).

1.2.2 Spatio-temporal scales of decision problems

Decisions are never made in a vacuum. They are always related to some context and have consequences that will drive more actions in the future. Modeling decision problems requires awareness of this context, especially because of the practical implications for how the decision problem will be laid out (Anderson et al., 1977). For this purpose, we used an operations research and logistics (ORL) framework that provides us with a spatio-temporal scale that delineates the context of the decision problems. The resulting landscape provides us with hierarchical levels and planning horizons for the decision-making problems: policy, strategic, tactical and operational decisions (Figure 1.1). This framework was previously proposed as a unified perspective of system analysis and modeling for pests and diseases affecting crops, animals and humans. Pest management and disease problems are commonly challenged with the need for coordinated efforts of several stakeholders and public institutions at different scales that requires awareness of the extent of their responsibilities (Conway, 1984, 1977; Rabbinge et al., 1993).

Providing a decision-making landscape has broader implications than the practical side of outlining decision models and easing the work for the modeler team. It provides awareness of how actions uncertainty and decision-makers responsibility changes at different decision-making scales. Larger time and space spans are related with more uncertainties in the decision problem. Decisions with larger time-spans tend to occur at higher geographic scales, and can involve international organizations as decision makers. Policies and investment decisions require the longest planning horizon perspectives covering several decades or years, while horizons of tactical and operational decisions are usually shorter than one year (Farahani et al., 2011; Swamidass, 2000; Wernz and Deshmukh, 2012).

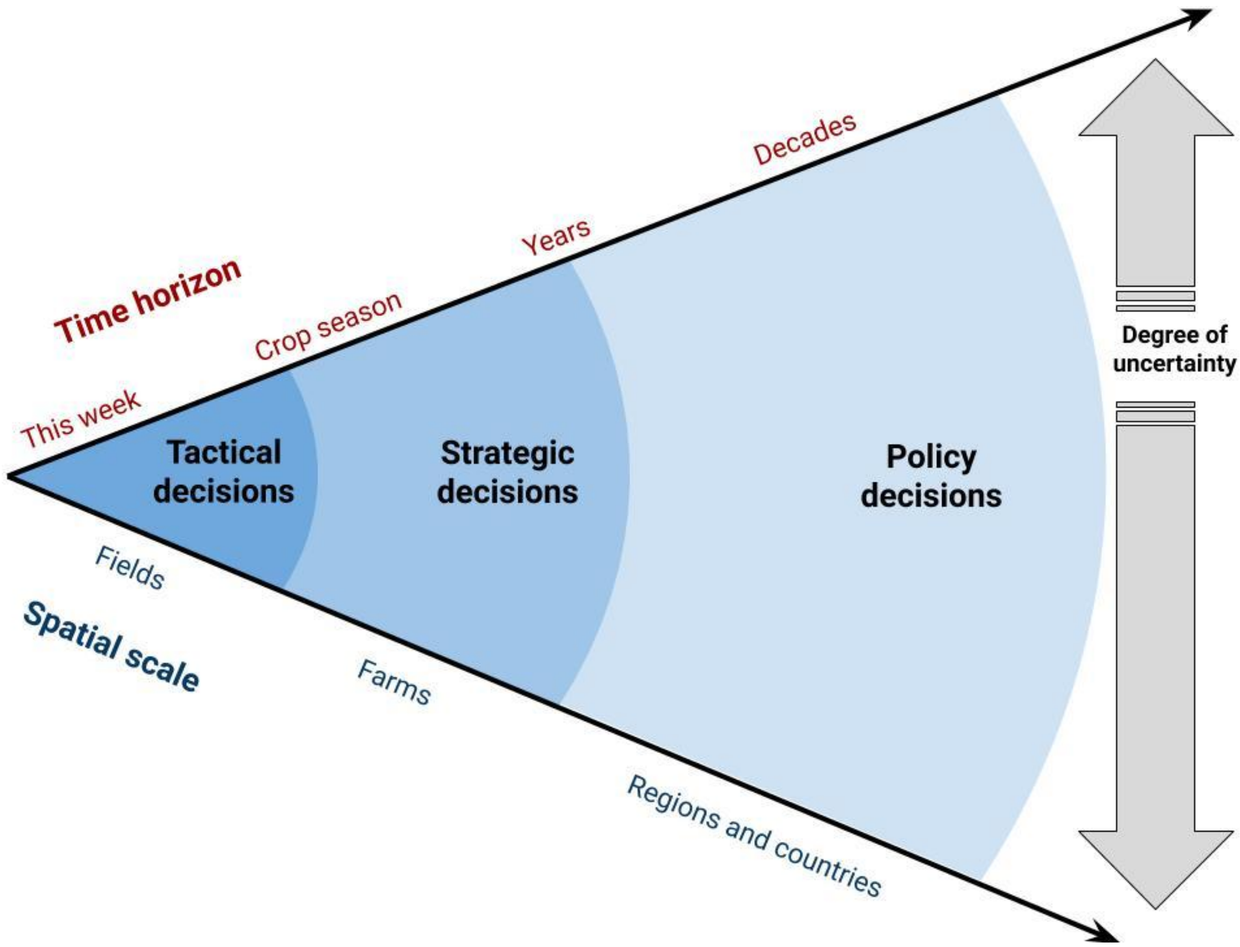


Figure 1.1. Spatio-temporal scales of decision problems in agricultural contexts. At larger scales the uncertainty increases as it is more difficult to predict events as they will occur far away in the future in heterogeneous geographic landscapes. This figure is a synthesis from previous representations (Conway, 1984; Lum, 2015; Rabbinge et al., 1993; Webb, 2019).

Each decision-making level is associated with a specific decision maker profile. Political (administrative) decisions are made by government agencies with national or regional effects on the interests and rights of private parties (Boyer, 1960). On the other side, farmers are the decision makers at the lower decision-making levels. Farm-scale management decisions are oriented to profit maximization and/or individual (household) benefits under specific socioeconomic and environmental constraints.

The next section will describe applications of decision analysis to decision problems of different scales

1.3 Policy Decisions

Governments repeatedly make decisions that have long-lasting impacts of national and regional effect. Because of their time and space dimensions, political decisions involve a high level of uncertainty (Beratan, 2007; Max-Neef, 1992; Shepherd et al., 2015), and frequently they have side effects or unintended consequences on the wider natural and social environment (Luedeling and Shepherd, 2016; Rivera-Ferre et al., 2013). These decisions are frequently based on perceived technical and economic feasibility. The decision-makers at this level often lack the tools necessary for integrating information into a forecast about possible outcomes (Peterman and Anderson, 1999).

Policy decisions problems are the interplay of a large number of variables that are intrinsically stochastic or their distribution is uncertain. In the case of agricultural settings, lack of data is very common especially in developing countries (Luedeling and Shepherd, 2016). Better policy formulation and decision making requires to overcome these difficulties and assess the effects of important factors that could jeopardize the intended outcome and fail to meet the stakeholder expectations. Decision analysis can also facilitate the stages of policy implementation and evaluation (Rosenstock et al., 2014; Shepherd et al., 2014).

Several studies showed the application of decision analysis to several problem cases of policy making and regulations. The Ugandan government policy of promoting industrial agriculture over the more diversified small-scale agriculture was assessed using decision analysis (Whitney et al., 2017). This assessment showed that industrial agriculture outperforms small-scale diversified farms in terms of energy and macronutrients but diversified systems are better at providing key vitamins and micronutrients. Decision analysis provided a recommendation that the development of Uganda's agricultural sector should consider the role of current small-scale diversified systems plays in national food and nutrition security.

Another policy and regulation agricultural area that could benefit a lot with the application of the techniques of decision analysis is pest management. **Chapter 2 of this thesis** outlines the decision analysis landscape related to the management of the cotton boll weevil in the Colombian Caribbean. This first qualitative approximation (conceptual model) of the decision-making related with this pest resembles the concept of the pest-management strategic plans developed by the United States Department of Agriculture (USDA). However, our approach goes further with the incorporation of spatio-temporal scales and how these are used for outlining the extent of quantitative decision models. In both cases, as qualitative models, they were built by knowledge elicitation during focus groups and interviews with stakeholders and collection of all the available current information about specific pests for a crop in a region.

There are additional advantages of conceiving pest management as a decision problem. The dominant paradigm in pest management is integrated pest management (IPM). The classical definition of IPM is a limited (not very functional) concept mainly used for describing control strategies at farm-scale based on the applications of chemical pesticides following the approach of economic thresholds (Hutchins, 2010; Perkins, 1980; Peterson et al., 2018; Ridgway and Lloyd, 1983). Recently, USDA has implemented a functional definition of integrated pest management that clearly separates the actions of controlling a pest from the criteria used for the assessment of the control actions (McCarl, 1981; USDA, 2019). IPM is defined as a decision-making process that identifies and reduces risks from pests and pest management related strategies. IPM is conceived as a framework able to include the uncertainties of the biology of the pest, the environmental conditions, and the available technology with the purpose to develop economically efficient pest management practices while minimizing the collateral damages related to these practices.

This framework also recognizes that an effective implementation of an IPM program requires coordination between federal agencies, universities, communities, farmers and other stakeholders. A coordinated effort must be able to address the ecological, genetic, economic and sociopolitical factors that can limit the program implementation and promote effective communication between the involved stakeholders (USDA-ARS, 2018). For this purpose, the

USDA had conceived the development of IPM Strategic Plans as the materialization of the decision making process that consolidates the available information and the needs for research in pest management at regional level on a crop basis (Murray and Jepson, 2018; Murray et al., 2019, 2018). Conceiving IPM as a decision problem of regional dimensions also facilitates the integration of another dominant paradigm of pest management, area-wide pest management. Area-wide pest management is the management of the total pest population at regional scales using control actions that are not limited to the crop season or field (Vreysen et al., 2007).

The implementation of qualitative decision models of regional extent as the IPM strategic plans, or the conceptual models using scales of decision-making presented here have potential to become guideline documents for development of policies and regulations in pest management and contribute to reach the desired ideal of pest management of becoming "integrated". These qualitative approximations can be complemented with formal decision analysis providing better understanding of the expected outcomes, uncertainties and risk of pest management strategies.

1.4 Strategic decisions

Most of the farmers' decisions worth the efforts of decision analysis are strategic decisions of the type investment (single events) or management (repeated events) decisions. Strategic management decisions include whole-farm planning and assessments of production efficiency (production under risk).

1.4.1 Long-term decisions (Investment appraisal)

Long-term decisions are perceived as risky investments because of their time span, the share of resources involved, and the uncertainty of the cash flow stream. In an investment situation, resources are laid out in the first years with the expectation that returns will be received in the future over several time periods. Several problems in agriculture qualify as investment decisions that require project appraisal. Public and private decision makers frequently engage in these kinds of decisions (Anderson et al., 1977). A public institution is interested in promoting agriculture intensification and decides to invest in a new irrigation district. A farmer as an investor is interested in buying more land or a new farm. Not all investment decisions in agriculture are related with the development of public infrastructure and real-estate acquisitions. Land uses based on perennial crops also qualify as long-term investments. Fruit and nuts orchards, grape vines, oil-palm plantations, and agroforestry interventions are some examples of agricultural production systems that must be represented as investment decisions. Some of these initiatives are mainly private but others as agroforestry interventions required mixed funding for their implementation (Do et al., 2020). However, even the private initiatives require external funding (loans) for covering establishment and/or maintenance costs during the first years of the crop when it is not able to provide any income.

The decisionSupport package (DSP), used in this thesis, contains tools for the appraisal of project investments under uncertainty. DSP provides calculations and graphical outputs representing the expected ranges (uncertainties) of net present value (NPV) and cash-flow. NPV is the most common and preferred metric for assessment of investment projects. NPV is attractive as a measure because it is able to reduce a sequence of future time payments to a single cash value that provides a global assessment of the investment and/or allows comparison of several mutually exclusive investment options. DSP was successfully applied for project appraisals in the assessment of agroforestry systems adoptions (Do et al., 2020) and investment options in honey value chains (Wafula et al., 2018).

1.4.2 Strategic management decisions

1.4.3 Whole-farm planning under risk

Decisions are not always about the risk-driven anxiety of having to choose between two options. On multiple occasions the decision is about choosing a mix of several options, each one with their own risks and uncertainties. These decisions were first described in financial analysis as part of the Modern Portfolio Theory (MPT). MPT states that owning different kinds of financial assets is less risky than just having one because in an assets portfolio, returns for each asset are additive but risks cancel each other out (Markowitz, 1959, 1952).

Each crop in a diversified production system is an element of a production portfolio, as the financial assets are elements of a financial portfolio. Each farm or production unit (irrigated fields, or greenhouses) is the physical space for these land based production portfolios. The decision to invest is determined by the expected productivity (return) and risk for the portfolio (specific combination of crops) rather than only for individual crops (Anderson et al., 1977). A smallholder dedicated to horticultural production for example, cultivates multiples crop species that provides a diversified source of income. Each one of these crop species is a discontinuous and independent production system with its own risk and uncertainties. The income and risk for this smallholder is not determined by the individual effects of the crops but for the aggregation of income and risk across all crops.

Agricultural production portfolios differ in several fundamental ways from financial portfolios. As the agricultural production portfolios are based on crop species (or animal species) with an active participation in management and marketing by the "investor", they are subjected to layers of portfolio effects associated with biological and market allocation heterogeneity.

First, for the biological (crop yield) side, there are two kinds of interactions affecting crops as portfolio elements:

1. Weak or no-interaction between the portfolio elements (crops). An example is farm crop diversification with plots of different crops planted in different sites or planting dates with the aim to deal better with climate or market prices. In this case, diversification at a biological level is analogous to that of assets in an optimal financial portfolio, and the biological performance of the portfolio is the average performance of each crop yield.

2. Strong interactions of the crop species creating ecological inter-dependencies. These ecological interactions cause the relationship between species diversity in the portfolio and the mean performance of a specific function (yield) to be nonlinear (Koellner and Schmitz, 2006). Intercropping systems and agroforestry are examples of agricultural portfolios with strong biological interactions. Some of these strong interactions can result in higher yields.

Second, the interaction between human behavior, and production and market heterogeneity generates numerous layers of portfolio effect (as the observed in biological populations and communities (Schindler et al., 2015)) on temporal scales much smaller than the scale length of financial portfolios (these portfolios use decades of trends for estimating the correlation between potential assets). This is particularly evident in farming systems based on crop species of short growing seasons. In these systems, the farmer constantly is sampling collections of new crops; selecting new cultivars from its landraces stock, new technological innovations, and markets; and assembling stocks of production situations (combinations of production means and markets). Farmers actively exploit this heterogeneity of their environment by developing stocks of asynchronous production situations, i.e. those showing contrasting traits (different planting dates, crops, or market allocations).

The decision analysis approach to diversified systems presented in this thesis has the potential to capture the wide variation of portfolio effects (biological and market heterogeneity) that affect agricultural production while maintaining the assessment of diversification under the simple and practical framework of the MPT. All complexities related to the multiple portfolio effects (interactions at different scales of the portfolio elements) are captured during the development of the probabilistic production models. **Chapter 4 of this thesis** describes a case study for the assessment of diversified systems of irrigated horticultural production using a decision analysis for whole farm planning and operation using the MPT framework.

1.4.4 Production under risk

Farms as businesses face uncertainty in price inputs, product prices and other factors that determine the quantity and quality of the output they produce. Farms produce several crops or livestock products through the control of many variables. These processes are represented by production functions. A production function measures the effect of additional inputs over the production output. Examples of production function are using more or less fertilizer, irrigating a crop, capital or labor investments or controlling a pest (Anderson et al., 1977).

Production functions usually do not incorporate uncertainty. This thesis describes a framework based on partial budget analysis that incorporates uncertainty in production functions using probabilistic measures of the production-related variables. Partial budget analysis is a formal method to estimate the expected change in monetary income from a proposed change or a new specific action in the planning or operation of the farm or its production elements (CIMMYT, 1988; Kay et al., 2019; Perrin et al., 1983).

The selected case study for the application of this framework of production under risk was the assessment of farm-scale control strategies against the cotton boll weevil in the Colombian Caribbean. A previous work used a similar decision analysis framework for the assessment of disease management strategies in crop protection (Ruett et al., 2020).

1.5 Description of the study area

The Colombian Caribbean comprised seven mainland states, i.e. Atlántico, Bolívar, Cesar, Córdoba, La Guajira, Magdalena, and Sucre. The Caribbean Plains dominate the landscape but three main mountain systems punctuate the region: Montes de María, Sierra Nevada de Santa Marta and Serranía de Perijá (Galvis, 2009). The Caribbean states account for more than 10 million people, a fifth of the entire Colombian population. Half of this population lives under the multidimensional poverty line rendering the Caribbean one of the poorest regions in Colombia (DANE, 2013). In Colombia, poverty is used to legitimize physical and structural violence against the impoverished rural people. Dominant groups use this political economy as a mechanism to legitimize the unequal distribution of wealth (Gordon et al., 2020). Extreme poverty in rural Colombia reaches 20% of the population. Rural Colombia is the scenario of "el Conflicto Colombiano", one of the longest and bloodiest civil wars in the Western Hemisphere. More than seven million internal refugees abandoned their rural settlements for small urban centers and cities with hope to find peace and security (Cuartas Ricaurte et al., 2019; Perry, 2010).

Around 40% of the Caribbean territory can be used for agriculture, but only 16% is used (>700,000 ha). This area is a fifth of the Colombian land used for agriculture (IGAC, 2012). The main crops in the Caribbean are maize, cassava, rice and cotton. These crops represent a third of the entire Colombian area under production and 70% of the Caribbean area (Aguilera et al., 2013). Crops in the Caribbean are mainly rain-fed. Precipitation is affected by two atmospheric events, the Intertropical Convergence Zone (ITCZ) and the Western Colombian Low-Level Jet (Choco Jet). The Choco Jet defines a decreasing gradient from the west side to the east and from the south to the north, with desert landscapes in the north-eastern part of the region. Córdoba and Guajira are the opposite extremes of water availability (Mesa et al., 1997; Poveda et al., 2005). The ITCZ defines the Caribbean rainfall bimodal behavior. The early rainfall season lasts from May to June and the late rainfall season lasts from August to November (Mesa et al., 1997; Restrepo et al., 2012).

Cotton production was for half a century the main agricultural activity of the Caribbean, and still today, is the major source of rural employment (Cadena Torres, 2010; Rache Cardenal, 2011). The cotton-growing area reached an acreage of 250,000 ha in the early 1990s and then declined to the current area, less than 10,000 ha (CONALGODON, 2017). Several political, economic and biophysical causes have been proposed for explaining this acreage loss. The most common causes are Colombia's economic liberalization, elimination of agricultural subsidies, increasing inflation rate, international cotton price fluctuations, and increasing production costs and yield gaps associated with climatic and biological variables (Barragán Quijano, 2010; Cadena Torres, 2010; Espinal et al., 2005).

The major cotton producing region is the valley of the Sinú River. This valley covers an area of 763,493 ha in the State of Córdoba, and geomorphologically is divided from south to north into three regions named Upper, Middle, and Lower Sinú. The Middle Sinú, the largest portion of the valley (around 70%), exhibits a wet savanna climate (Aw, according to the Köppen-Geiger climate classification) and it is dominated by flat alluvial plains frequently affected by droughts and floods. The agricultural landscape is mainly characterized by livestock ranches, and fields of cotton, corn and rice. The largest irrigation and drainage channel system of Colombia is located in this region with a potential irrigated area of 43,000 ha (IGAC, 2017; MADR et al., 2006).

The smallholders in the Middle Sinu are the most affected by the decreasing efficiency of cotton crops. Several Colombian institutions have implemented projects for promoting alternatives to cotton crops that can alleviate the conditions of the smallholders. One of the most promising alternatives for cotton diversification between smallholders is the irrigated production of horticultural crops. These production systems are concentrated in the neighboring area of the Mocari irrigation district (MID) (CVS, 2019).

1.6 Aim and outline of this thesis

The aim of this thesis is to improve the understanding of factors constraining yield and productivity in cotton production systems in the Sinu Valley and identify knowledge gaps where research efforts might be targeted. The main focus was methodological, specifically the implementation of techniques and tools associated with decision analysis for assessing the efficiency of agricultural production systems. This methodological approach gives stakeholders the opportunity to provide insights of prioritization. Study cases were selected because of their importance to farmers and stakeholders, their feasibility to be accomplished during the development of a PhD, and their typology as they represent different cases of production problems that can illustrate the versatility of the decision analysis approach.

The most challenging problem in the cotton production systems of the Colombian Caribbean is the management of the cotton boll weevil. Several studies and focus groups with farmers and stakeholders agree on the crucial importance of this problem. Evidence of its importance is manifested in national regulations issued for its control, and in the ongoing monitoring network implemented for understanding BW population dynamics. However, more than half a century of regulation has not been enough to avoid recurrent outbreaks and excessive use of insecticides. This overconsumption of insecticides is detrimental for the economic benefit of cotton farmers, but it is also an environmental and public health problem.

The first goal of this thesis is, therefore, to advance our knowledge regarding the management of the cotton boll weevil in the Colombian Caribbean. This problem persists because it is a “wicked problem” that can not be easily solved because of the associated complexity. Complex systems involve multiple actors and causes, and therefore are politically and technically complex (Peters, 2017). BW management involves multiple actors (besides farmers) interacting in a legal framework that lacks proper enforcement and understanding of the local environment, while there is limited formal understanding of the problem. For having a clear perspective of this landscape, we applied conceptual modeling based on system analysis using a previously developed protocol (Lamanda et al., 2012) and extended this concept introducing spatio-temporal scales of decision making. This scale provides us with planning horizons and very clear definitions of the decision makers profiles and for our own practical purposes boundaries for the decision problems to model quantitatively. This conceptual model describing the landscape of decision making in BW is Chapter 2 in this thesis.

As we previously described, there are two main types of strategic decisions in agriculture: investment and management. Previous applications of decision analysis are of investment type. Here in this thesis, we presented study cases of strategic management that represent problems of production under risk and whole farm planning. Production under risk represents the lowest level of strategic management and deals with the optimization of the production process.

The conceptual model of BW management identified two temporal-spatial scales for this decision problem: the area-wide management and farm-management. Area-wide management is a decision problem of the higher level, a problem of policy and regulations that involves government representatives as decision-makers. The control of the BW at the farm level on the other side is a problem of strategic management that deals with a very specific case of production optimization, avoiding losses.

The second objective of this thesis is, therefore, to assess the management strategies used for control of the BW at farm-scale, as an example of production under risk. We presented our case using partial budget analysis for laying out the decision and introducing the concepts of stochastic orderings and dominance for the assessment of the efficiency of the management alternatives. As we are using Monte Carlo simulations we proposed that pointwise comparison of the alternatives outcomes provides a quantitative assessment that facilitates the selection of the most efficient option (dominant). This procedure can be used as the primary criteria for selection of competing alternatives and only complemented by additional analysis when an option is partially dominant (it is efficient in the majority of cases).

Farming is dynamic, with opportunities to change. Decades ago, cotton was the crop with the largest acreage in Colombia. Nowadays, more and more cotton farmers, especially smallholders are pushed away by the market, the increasing occurrence of extreme climate events, and the frequent outbreaks of BW. Some smallholders decided to look for other ways of informal subsistence and others went for alternative agricultural production systems. In the Sinu Valley, one of the alternatives to cotton crops is the production of horticultural crops under irrigation. These production systems offer diversification in the dominant landscape of cotton and corn. Diversification is promoted by research institutions dedicated to agriculture in Colombia as an alternative to “traditional” commodities or industrial crops (cotton, corn, industrial cassava, sugar cane). However, this transition to horticultural crops had not been without problems. We provided support for this transition of smallholders from cotton crops to irrigated horticultural systems and used the horticultural production case as an example of whole-farm planning.

The third goal of this thesis is to provide a decision analysis model able to represent the whole-farm planning of diversified systems. Chapter 4 described the application of the Modern Portfolio Theory and its associated concept of “portfolio effect” in the decision analysis layout and developed a quantitative assessment of diversification in agriculture. This methodological approach can be applied to other diversified systems in the Caribbean and additionally can provide a theoretical framework for the efforts of the Colombian Agricultural Research Corporation (AGROSAVIA) to promote diversification between the smallholders of the Caribbean.

Chapter 2

2 Management of the cotton boll weevil (*Anthonomus grandis Boheman*) in the Colombian Caribbean: A conceptual model

An article with the same content has been published as Burbano-Figueroa, O., Sierra-Monroy, A., Grandett Martinez, L., Borgemeister, C., & Luedeling, E. (2021). Management of the Boll Weevil (Coleoptera: Curculionidae) in the Colombian Caribbean: A Conceptual Model. Journal of Integrated Pest Management, 12(1), 2021–2016. https://doi.org/10.1093/jipm/pmab009

The boll weevil (*Anthonomus grandis grandis)* is the main pest in the cotton-producing regions throughout the Americas from Southern Texas to Argentina. In the Colombian Caribbean, frequent population outbreaks have resulted in cotton planting bans in some localities and in massive applications of insecticides elsewhere (up to 15 insecticide sprays per cotton season). To date, information on boll weevil (BW) management strategies in Colombia is only available in the forms of gray literature (technical reports) and informal knowledge held by crop advisors and farmers. This study compiles this information using a standardized protocol for participatory construction of conceptual models for agricultural systems. The conceptual model developed in this study integrates the informal local knowledge of crop advisors and farmers with disciplinary knowledge describing management strategies for BW. The collected data were assessed and organized using a systems approach to facilitate the future development of quantitative models and allow visualization of knowledge gaps. The model includes the description of the biological and technical-decisional subsystems. The latter subsystem explains BW management at two temporal-spatial scales: 1) farm (field) scale management during the cotton season and 2) a regional BW suppression strategy mainly aimed at controlling the insect populations that survived the inter-cotton season. The development of this conceptual model allowed describing the current management strategies for BW and formulating hypotheses about the effectiveness of these strategies. This conceptual model provides guidelines for future research, and it can serve as a baseline for the development of quantitative models and simulations describing the decision-making process related to the management of BW in the Colombian Caribbean.

2.1 Introduction

The boll weevil (BW), *Anthonomus grandis grandis* Boheman (Coleoptera: Curculionidae), is the most limiting pest of upland cotton [*Gossypium hirsutum* L. (Malvaceae)] throughout the Americas from the Lower Rio Grande Valley (Texas) to the Argentinian Chaco (CABI, 2019; Davis et al., 2020; Grilli et al., 2012; Lanteri et al., 2003). It transformed the agricultural economy of the Southeast and East Coast of the United States in the past century following its invasion from Mexico to Texas in the 1890s (Burke et al., 1986; Robert Jone, 2006). Its introduction from the USA to cotton regions in the Caribbean and South America has caused enormous economic losses. The BW dispersed in the entire Caribbean Coast of South America in half a decade after its introduction through Tocoron (Venezuela) in 1949 and Cartagena (Colombia) in 1951 (Sierra-Monroy and Burbano-Figueroa, 2020). Three decades later, the BW was introduced to Brazil (1983) and subsequently dispersed to Paraguay (1991), Argentina (1993) and Bolivia (1997) (Scataglini et al., 2000).

Despite the importance of BW, descriptions of its dynamics and management in the tropics are scarce. For the Colombian Caribbean, the description and assessment of BW management strategies is largely limited to gray literature (Supp. file1). For the most part, these strategies are based on informal knowledge held by crop advisors and farmers. In the absence of formalized knowledge that can be used to assess management decisions, a conceptual model is a useful tool for compiling, discussing, and exchanging concepts and hypotheses, integrating the understanding of crop advisors, farmers, and academics. Conceptual models allow including local specificities of rural production systems while providing transparency and a clear flow of information that is represented in a graphical abstract of the theoretical and practical knowledge on a system (Lamanda et al., 2012; Meylan et al., 2013).

The conceptual model described here collects, organizes, and combines accumulated informal and disciplinary knowledge related to the management of *A. grandis grandis* in the Colombian Caribbean. This conceptual model is a case-study for the management of this pest in the tropics, where understanding is scarce compared with knowledge in subtropical and temperate regions. This model is also our qualitative approximation of the decision-making processes involved in the management of this pest and it outlines decision problems that future studies can examine. In order to facilitate the outlining of the decision problems, we use an operations research and logistics approach that allows us to create time horizons for the decision-making process.

2.2 Building a conceptual model

The data used for building a conceptual model were obtained from knowledge holders and published information. Focus group discussions and semi-structured interviews were conducted with knowledge holders (experts) to identify variables and parameters associated with technical operations involved in BW management. Experts participating in the initial model-building included one cotton plant physiologist, one cotton breeder, four entomologists (three with expertise in the management of BW, and one with expertise in insect ecology), and five crop advisors and/or farmers (who are responsible for a large share of the entire cotton-producing area of the Caribbean region). These experts were asked to describe how BW affects the crop, how they control the pest, and what problems limit the effectiveness of BW control in the long run. The discussion was oriented towards eliciting the main factors affecting the expected outcomes (especially yield and production costs) and providing ranges for the variables that describe the problem. The quantitative information will be used for future probabilistic simulations accompanying this qualitative description.

Published information on BW management was retrieved using Google Scholar, Agris (http://agris.fao.org/agris-search/index.do), and BAC (The Colombian Agricultural Library - https://repository.agrosavia.co/). Thesis searches mainly resulted in technical reports (gray literature) (Supp. file1). Some technical reports were obtained from local libraries or personal files. All gray literature was assessed and manually annotated for record-keeping and citation using the Sciwheel reference managing software (Sciwheel, 2021). Findings described in these papers were recorded as individual notes and discussed between the members of the field team with the support of specific experts.

Disciplinary experts and technical reports are associated with the Instituto Colombiano Agropecuario (ICA), the Corporación Colombiana de Investigación Agropecuaria (CORPOICA, today rebranded as AGROSAVIA), and the Confederación Colombiana del Algodón (CONALGADON). These organizations are affiliated with the Cotton Regional Committee (CRA) headquartered at the municipality of Cereté, Cordoba. This committee is a local initiative of the Sinú Valley farmers with monthly meetings held to discuss, propose, and evaluate all actions related to the cotton value chain. Focus group discussions, interviews, and feedback were mainly coordinated with the support of this committee.

We built our model using a previously described protocol for conceptual modeling of agroecosystems (Lamanda et al., 2012). This protocol includes the following steps:

1. Structural analysis to identify the limits of the system, subsystems, components, factors affecting the system, and the indicators for assessing system performance.
2. Functional analysis to identify the relationships between the components of the system, factors, and performance indicators.
3. Dynamic analysis to describe how the system, subsystems, and main components behave over time and to check if the structural and functional conceptual models adequately represent system dynamics.

   An operations research and logistics (ORL) approach was used for the dynamic analysis of the decision-making process associated with the technical subsystem. ORL is used for the analysis and planning of complex operations from transport and distribution of goods to operation management with the aim of accomplishing a specific goal for customers (Swamidass, 2000). This approach has been applied to several biology-based problems including pest management (Conway, 1984; Rabbinge et al., 1993).

   Under the ORL approach, the decision-making process can be considered a system in itself. This decision system wraps several dynamic processes that require organization and management at different temporal-spatial scales or planning horizons (hierarchical planning). Decisions related to the management of BW were classified into the following temporal-spatial scales: policies, strategic decisions, tactical decisions, and operational decisions.

4. Consistency analysis to assure that the conceptual model as a knowledge representation corresponds to reality. This last step is an iterative process applied regularly during the first three steps with the participation of experts. For a final consistency assessment of the conceptual model, Spanish-language versions of this document were released as preprints to elicit critiques and comments from a wider expert audience (https://doi.org/10.31220/osf.io/db8nu).

The representation of BW management was complemented with descriptions of the phenological development of the crop and pest populations and the interaction between them (damage and spatial distribution of BW in cotton fields). Additional descriptions of the model building procedures are provided in Supp. file2.

2.3 Cotton crops in Colombia

Cotton cultivars planted in Colombia belong to the species *Gossypium hirsutum* L., also known as Upland cotton (Burbano-Figueroa and Montes-Mercado, 2019). Cotton plants have an indeterminate growth habit and perhaps the most complex plant architecture of all major field crops. The basic minimal structure of a cotton plant is constituted by the main stem, and two types of branches, vegetative and fruiting branches. The main stem is made up of a series of nodes (points of leaf and bud development) and internodes (length of stem between nodes). Plant growth occurs via the production of new nodes and internodes. The first branches are generated above the fifth or sixth node. Once the first branch has reached its final size, the first flower bud is produced. Cotton flowers at anthesis are yellow (or creamy white), but petals turn pink the following day and fall off a couple of days later (McGregor, 1976; Oosterhuis and Jernstedt, 1999). As a perennial plant, cotton continuously produces flower buds, until the cotton stalks are destroyed. Cotton specialists use specific terminology to refer to the crop's reproductive structures: "squares" for flower buds, and "bolls" for post-flower fruits.

Currently, cotton is cultivated in three regions of the country: the Caribbean, the largest producer, the Upper Magdalena Valley, and the Eastern Plains. Phenological development of cotton in the Colombian growing areas exhibits spatial variation associated with soil fertility, climate (altitude), and water availability, in addition to the biological variation related to the cultivars (Burbano-Figueroa and Montes-Mercado, 2019; Burbano-Figueroa et al., 2018). Humid environmental conditions extend the vegetative period, while dry periods or droughts shorten it. Field reports of the cultivar CORPOICA M123 illustrate how the vegetative periods change across the Colombian cotton regions (Supp. Data S7). Vegetative periods in the Caribbean are shorter in the dry savanna locations (As) than in the wet savanna (Aw). Flowering dates differ between these locations by around 10 days, and similar differences are expected for boll formation (Burbano-Figueroa and Montes-Mercado, 2019; Cadena Torres et al., 2001). Modern upland cotton genotypes used in Colombia (US American and Colombian cultivars) require only short vegetation periods. Maximum expected differences in flowering times across cultivars are up to three days (Burbano-Figueroa and Montes-Mercado, 2019; CORPOICA, 2000), meaning that environmental factors (mainly rainfall) have a greater effect on phenological development than cultivar differences.

Major cotton-producing areas of the Colombian Caribbean are mainly located in the Sinú Valley (Córdoba State), and the Cesar Valley (Cesar State). The Sinú Valley is divided from south to north into three regions named Upper, Middle, and Lower Sinú Valley. It exhibits a monsoon climate (Am) in the southern part and a wet savanna climate in the north (Aw). The Cesar Valley features a dry savanna climate (Af). The local literature refers to the dry savanna regions as the 'Dry Caribbean' (Caribe Seco) and to the regions with monsoon and wet savanna climates as the 'Humid Caribbean' (Caribe Humedo). In the Caribbean, cotton is planted during the main rainy season (August to October) and harvested during the dry season (Figure 1). This conceptual model was designed for describing the BW management strategies used in these cotton-producing areas.

The Caribbean features a dry-winter tropical climate with a bimodal seasonal rainfall pattern. The dry season occurs during the northern winter. The early (April–July) and late (August–November) rainfall seasons are separated by the mid-summer drought (MSD). The bimodal seasonal rainfall pattern exhibits regional variation in length and timing of the rainy seasons and MSD (Stephenson et al., 2014; Taylor et al., 2011). In the Colombian Caribbean, the MSD is called "el Veranillo de San Juan" (Figure 1). The characteristics of the MSD define the climate of the central and northern portion of Colombia (> 2°N) and are mainly influenced by the predominance of the Caribbean low-level jets around the Southern Winter Solstice (Bendix and Lauer, 1992).

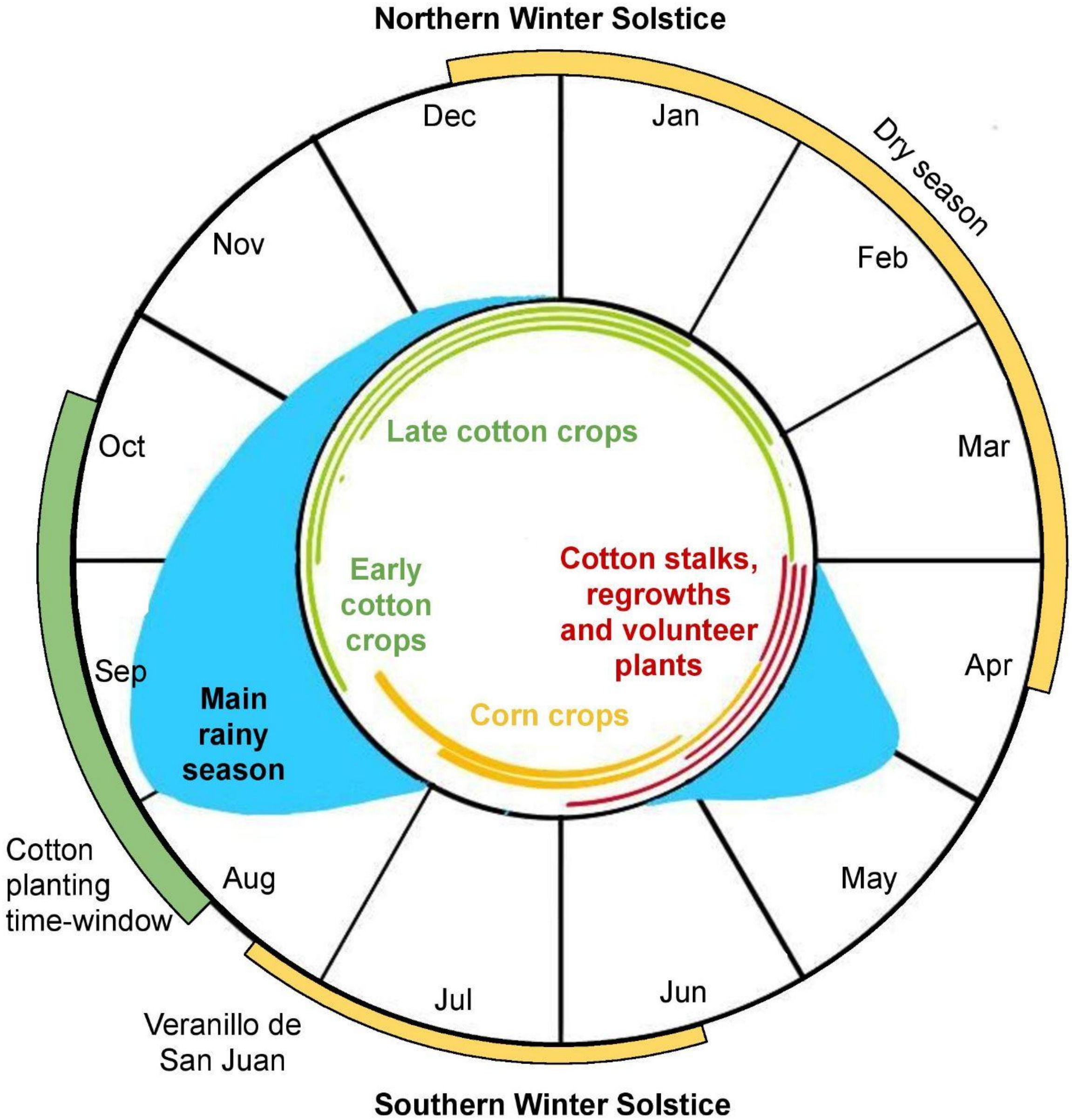


Figure 2.1 Temporal dynamics of rainfed cotton crops, stalks, regrowths and volunteer plants. These plant materials allow active reproduction of boll weevil during the entire year.

2.4 The boll weevil

At least three putative subspecies or main population clusters of the BW are recognized in North America: *grandis* (Eastern cluster), *thurberiae* (Western cluster), and an intermediate form between these two populations (Alvarado et al., 2017; Barr et al., 2013; Kuester et al., 2012; Roehrdanz, 2001; Warner, 1966; Werner, 1960). The Eastern cluster is the population distributed in the Southeast and East Coast of the USA, which uses cotton as its main host. The Eastern cluster is genetically distinguished by the predominance of the cytochrome c oxidase I (COI) mitochondrial haplotype A1. For South America, recent phylogenetic evidence suggests multiple origins for the current populations of *A. grandis*: 1) an introduced Eastern population from the USA, and 2) local populations of BW living in forests (natural environments), which are probably able to use other hosts besides cotton for reproduction

(Guzmán et al., 2007; Scataglini et al., 2006, 2000). These populations may have a taxonomic status similar to the *grandis* and *thurberiae* subspecies. *Anthonomus grandis grandis* is the most common and widespread population in the USA and South America, and it is responsible for the massive economic losses (Burke et al., 1986; Warner, 1966). All descriptions in this document refer to *A. grandis grandis* (hereafter BW).

BW undergoes complete metamorphosis, with its life cycle involving egg, larva, pupa, and adult stages. Life stages show similar morphology across tropical, subtropical, and temperate regions. The eggs of the BW are elliptical, white, and smooth (0.8 mm length and 0.5 mm width). Larvae are white with brown heads. They reach a final size of 8 mm and complete their development inside colonized fruit structures (buds or bolls). The adult is a weevil of 4-9 mm width and 7 mm length, the adult color varies from gray-brown to black, with sparse golden hairs over the elytra, and long curved protuberance on the head (rostrum) that is about half as long as the body. Mouth parts are located at the very tip. Pre-adult weevils are white, newly emerged adults are reddish, and mature adults are light brown or gray (Azambuja and Degrande, 2014; Dietz, 1891; Foster, 2009).

There are conflicting reports on the occurrence of diapause in the BW. In temperate cotton regions diapause is defined as a period of suspended reproduction that usually coincides with cold winter conditions, or with the absence of a host plant able to sustain weevils during reproduction. In the latter case, diapause can be terminated if the weevil can gain access to a proper source of food (cotton squares). The specific food dependency of BW introduces the rather vague concept of “facultative diapause” (Showler, 2010, 2009). In the tropics, however, there is no evidence that BW populations experience diapause and, at least in terms of temperature, the weevils never experience conditions that do not allow them to continue their development. As a locally appropriate alternative description of BW’s life cycle, Lobatón Garcia (1981) proposed the concept of only two distinct populations: migrating and reproductive BWs. Reproductive populations are mainly dependent on cotton. Wild hosts of the tribe Gossypieae can support BW reproduction, but they are a scattered source of food that can only sustain small populations for short periods of time (Jones et al., 1992, 1989).

Crop damage caused by BW

The high impact of the BW on cotton production systems is determined by: i) the migratory behavior of the species, which facilitates dispersal; ii) its high reproductive capacity resulting in several generations per crop season; iii) the lack of efficient natural enemies; iv) potential for rapid increases in population size from a few individuals, which can generate substantial yield losses (Stadler and Buteler, 2007); and v) high genetic variability that allows the pest to adapt to environmental changes or new environments, maintaining its high reproduction rate and capacity for causing crop damage (Leigh et al., 1996).

Boll weevils directly affect fiber yield and crop productivity via square abscission and boll damage. Cotton is a plant with indeterminate growth habit, able to compensate for losses of its reproductive structures. When a BW population is already established, however, all subsequent flower bud cohorts may directly be consumed by the weevils (INTA, 2014; Palomo Rodríguez et al., 2014). Two kinds of square damage can be identified in the field: oviposition and feeding damage. Squares with a size between 5 and 8 mm are preferred oviposition sites for the BW females (Barragan et al., 2005; Greenberg et al., 2004; Ñañez, 2012). Squares damaged by BW feeding can still follow their phenological development and reach flowering and fruiting stages. In contrast, oviposited squares suffer abscission and fall to the ground, where the insect finishes its development inside the square. Bolls are also attacked by BW, but this does not lead to abscission. Several locules can be affected by egg deposition (Barragan et al., 2005; Ñañez, 2012). The phenological development of BW takes longer in cotton bolls compared with squares (Loftin, 1946).

In Colombia, BW is endemic in the dry and wet savannas of the Caribbean Plains and in the upper portion of the inter-Andean valleys of the Magdalena and Cauca rivers. The Eastern Plains and the Patia Valley are BW-free zones (CONALGODÓN et al., 2008; ICA, 2000, 2009; Ñañez, 2012). In the Caribbean, BW is the main limiting pest of cotton crops, resulting in significant yield losses with management costs that reach up to 10% of the total production costs (Osorio-Almanza et al., 2018). Losses associated with late or inefficient control of BW have been estimated at 250-500 kg/ha of seed-cotton yield per crop season (CONALGODÓN et al., 2008; Ñañez, 2012), at current prices worth around half to one million COP/ha (154 - 308 USD/ha). The main BW control strategy in Colombia is the use of synthetic insecticides, which inflates crop production costs and negatively affects the environmental sustainability of the crop (ICA, 2010). The country has recorded an average of seven spray applications against cotton pests, 70% of which were used for controlling BW (Ñañez, 2012). Insecticide use is higher in the Sinú Valley with an average of ten spray applications and reports of up to 15 applications (Martinez Reina et al., 2018; Osorio-Almanza et al., 2018).

Biology and damage of *A. grandis grandis* in the tropics

The generation time for BW populations in the Caribbean Plains is 15-17 days (Ñañez, 2012) and 22 days in the moderate tropical climate of the Upper Cauca Valley (Morales et al., 1994), suggesting that temperature (which is negatively correlated with altitude) affects BW development and likely cotton damage in the Colombian cotton regions. Variation in BW population dynamics across latitudinal gradients has been reported for the cotton growing regions of the Americas (Loftin, 1946; Smith and Harris, 1994). The effect of temperature on the phenological development of BW has been assessed under laboratory conditions, showing that the shortest generation times are reached at 30°C, with BW development strongly affected by temperature (Figure 2) (Greenberg et al., 2005; Martins Caldeira, 2017; Spurgeon and Suh, 2017).

Attacks of *A. grandis grandis* on cotton fields in the tropics and subtropics are reported to occur in four stages that are used as criteria for designing management strategies: S1) Arrival in the cotton field: Crop damage is mainly associated with oviposition and occurs in clusters near the field margins in the absence of regrowth during the off-season period of the crop (if regrowth occurs, BWs reproduce and feed on maize pollen, maintaining a population that is homogeneously distributed in the field. Weevil adults or apical damage can be observed in the field before cotton squaring); S2) Population establishment stage: Damage is mainly associated with oviposition by migrating females and feeding and oviposition of the first BW generation that developed in the crop (S1 descendant); S3) Invasion or progression stage: Squares and flowers are attacked by the established BW population. All life cycle stages of the insect can be observed in the field; and S4) Generalization stage: the most advanced stage. The BW population has dramatically decreased the number of yellow flowers, and insecticide applications are necessary to avoid significant yield losses (Figure 3) (INTA, 2014; León Q, 1980; Lobatón Garcia, 1981). Before S1, BW adults can be observed in the cotton fields around 15 to 20 days after emergence (DAE) on the youngest leaves, and perforations occur on the plants' terminal buds.

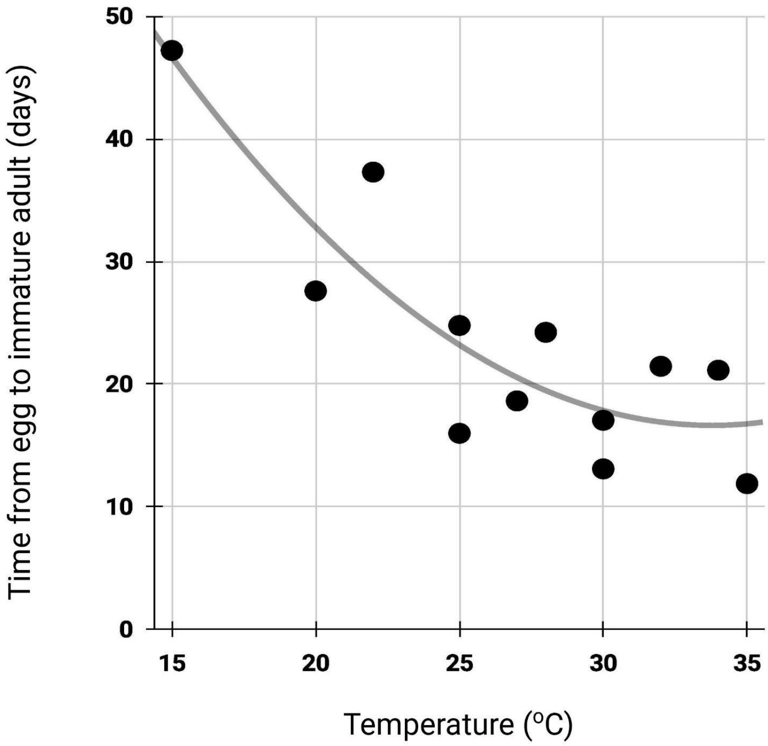


Figure 2.2. Temperature dependence of boll weevil (BW) development. At 15°C, BW requires more than 40 days to complete its life cycle. At temperatures between 30 and 35°C, BW can reach maturity after 10 to 20 days. For the Colombian Caribbean with average temperatures around 30°C the general consensus is that BW reaches adulthood after 12 days. This plot was created using data from Greenberg et al. (2005) and Martins Caldeira (2017).

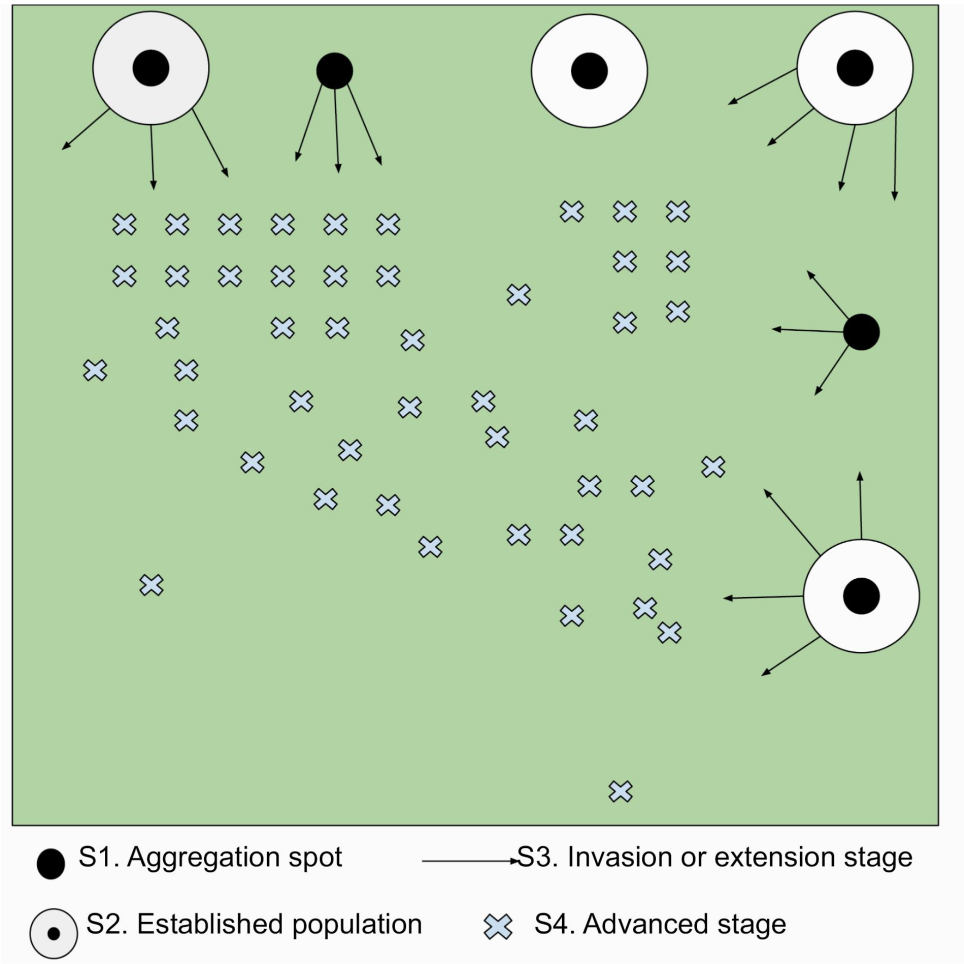


Figure 2.3. Spatial distribution of boll weevil (BW) inside a cotton field, illustrating the progression of BW development through stages S1 to S4, which are used by crop advisors and farmers in the Colombian Caribbean to describe the dynamics of BW and as an alternative to thresholds based on percentages of squares with oviposition punctures, which are not very useful for describing pests with aggregated patterns.

2.5 Decision-making landscape of BW management

We built a conceptual model that describes the BW management in the Colombian Caribbean. Two subsystems were identified: i) the biological subsystem describing the dynamics of annual cotton plant populations (crops, stalks, regrowth, and volunteer plants), the BW population dynamics, and the interaction between these two populations; and ii) the technical-decision subsystem describing the management decision landscape of BW control (Figure 4). Management strategies are implemented at two spatio-temporal scales: a regional management strategy that mainly focuses its efforts on the off-season (from March to August) and farm-scale management implemented during the cotton season (from August to March) (Table 1). Additional descriptions are provided in Supp. file3.

As this conceptual model was produced with the intention of later guiding the development of decision analysis models, we used an operations research and logistics (ORL) approach for a better understanding and definition of the decisions related to the management of BW in the Caribbean. This hierarchical framework provides us with planning horizons for the decision-making process of pest management: policy-oriented, strategic, tactical, and operational (Conway, 1984, 1977; Rabbinge et al., 1993). Policies and strategic-level decisions require the longest planning horizons, covering years or even decades, while horizons of tactical and operational decisions are usually shorter than one year (Farahani et al., 2011; Swamidass, 2000; Wernz and Deshmukh, 2012). Each decision horizon is associated with particular spatial scales and decision-making agents, whose actions can affect decision outcomes and eventually modulate the performance of the system (Table 2). Future decision analysis models can be tailored to these decision horizons with explicit definitions of temporal-spatial scales and decision makers.

Table 2.1. Elements of a conceptual model describing the management of *Anthonomus grandis grandis* in the Colombian Caribbean region.

	Off-season March - August	Cotton season August - March
Factors (Environment)		
Climate	BW populations colonized the Caribbean plains of Colombia and Venezuela. These plains exhibit savanna and monsoon tropical climates (Aw, Am, Af) that do not threaten pest survival.	
Socioeconomic factors	The majority of cotton farmers (70-80%) cultivate cotton on rented land. Enforcement of cotton stalk destruction and elimination of regrowth and volunteers on rented land requires monitoring and legal prosecution. Nowadays, farmer associations are responsible for monitoring and reporting the infractors. The regional headquarters of the Colombian agricultural agency for plant protection (ICA) are responsible for starting legal actions against the infractors. These organizations do not have enough resources and staff to accomplish these tasks. A change in the current legal framework that facilitates the enforcement of stalk destruction is required.	
Refuge	A refuge for BW is defined as locations where BW feeds during the off-season (or survives the winter in the temperate regions of the Americas). In the tropics, BW can find hosts able to support its reproductive development in these refuges, but the density of these hosts is very low. Refuge areas are a constant source of BWs where its population can not be controlled or eradicated. These populations are not considered themselves part of this system representation because control in these refuges is not technically feasible.	
System		
Biological subsystem		
Upland cotton populations	Stalks, regrowths and volunteer plants	Cotton crops
Anthonomus grandis grandis	BWs populations survive and reproduce in stalks, regrowths and volunteer plants.	BW migrating populations actively reproduce in cotton stalks, regrowths and volunteer plants. Without cotton plants, they can feed on corn pollen or other plants.
Technical subsystem		
BW management scenarios	**Area-wide management** All control measures necessary for reducing the BW population surviving during the off-season. These include but are not limited to destruction of stalks, regrowths, and volunteer plants.	**Farm-scale management** ● **Proactive strategy.** Early calendar application of insecticides aimed to avoid the infestation of cotton crops by BW. ● **Reactive strategy.** Fields are monitored for BW aggregation spots. Once detected, focused sprays over aggregation spots are started followed by field applications. Up to 15 insecticide sprays are required using this method. An estimate of 80-90% of the farmers currently use this method.
System indicators (Output)		
Yield losses	At least 20% yield losses are expected once the weevil arrives in the field, but losses can vary in response to prevalent pest density and planting date. Crops planted late in the season are challenged with bigger BW populations and lower rainfall.	
BW management costs	At the end of the lease agreement, some land tenants do not destroy the stalks after harvest and abandon their fields. ICA does not have a suitable legal framework and resources to persecute these infractors.	BW causes yield losses and pest management costs that decrease the returns to farmers. Up to a regional average of seven insecticide sprays for managing BW in a cotton season have been reported.

Table 2. Management of the cotton weevil on various spatial scales, including the actors responsible for the decision-making process.

<table>
<tr><th>Geographic scale</th><th>National</th><th>Region</th><th>Groups of farms</th><th>Field or individuals</th></tr>
<tr><td>Decision maker</td><td>ICA Department of Protection and Quarantine</td><td>Farmer Associations</td><td>Crop advisor</td><td>Farmer</td></tr>
<tr><td>Time course of actions</td><td>Long-term policies</td><td>Years</td><td>Crop season</td><td>Days to weeks</td></tr>
<tr><td rowspan="3">Decision making models conceived to represent*</td><td colspan="2">POLICY</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">STRATEGY</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">TACTICS</td></tr>
<tr><td>Main model scenarios for BW management</td><td colspan="2">Area-wide management
● Suppression</td><td colspan="2">Farm-scale management
● Proactive strategy
● Reactive strategy</td></tr>
</table>

* Models in applied ecology (pest management included) can be categorized into tactical, strategic, and policy models. These model scales are defined mainly in terms of the geographic scale and the time horizon over which they operate. Models can only be used for the scale (aim) that they were built for. Many complaints about the poor performance of a model or its lack of practical use are related to ignoring this guideline for using a specific model (Conway, 1984, 1977).

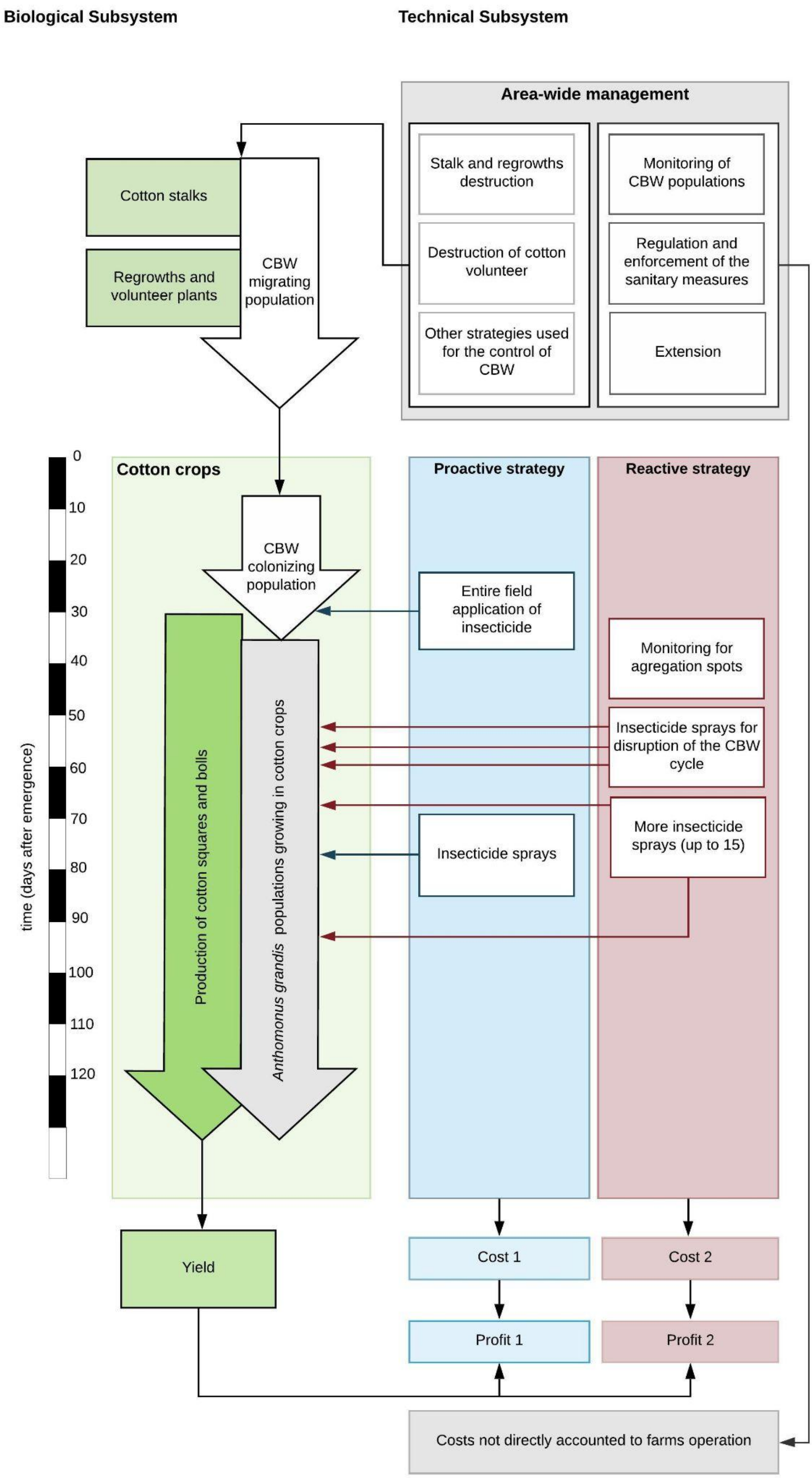

Biological Subsystem
Technical Subsystem
Area-wide management
Stalk and regrowths destruction
Destruction of cotton volunteer
Other strategies used for the control of CBW
Monitoring of CBW populations
Regulation and enforcement of the sanitary measures
Extension
Cotton stalks
Regrowths and volunteer plants
CBW migrating population
Cotton crops
CBW colonizing population
Production of cotton squares and bolls
Anthomonus grandis populations growing in cotton crops
time (days after emergence)
0
10
20
30
40
50
60
70
80
90
100
110
120
Proactive strategy
Entire field application of insecticide
Insecticide sprays
Reactive strategy
Monitoring for agregation spots
Insecticide sprays for disruption of the CBW cycle
More insecticide sprays (up to 15)
Yield
Cost 1
Cost 2
Profit 1
Profit 2
Costs not directly accounted to farms operation

Figure 2.4. Conceptual model describing the management strategies used for the control of boll weevil (BW) in the Colombian Caribbean region. Two subsystems are described: the biological subsystem that includes BW, the upland cotton crops and interactions between both components; and the technical subsystem describing management strategies at regional and farm-scale.

Based on this strategy planning framework, policy-oriented decisions, for example, are taken by national governments and implemented through strategies in time frames of decades. Pest control at the regional level requires policy decisions followed by coordinated actions of various stakeholders (Simberloff, 2003; Veitch and Clout, 2002). Political (administrative) decisions are made by the responsible government agencies with an effect on the interests and rights of private parties (Boyer, 1960). Government institutions can delegate responsibility for such initiatives to farmer organizations. However, previous assessments of regional management programs have stated that when farmers or their organizations are unable to follow the prescribed policies, policy-oriented institutions should intervene and lead the enforcement of the sanitary measures (Simberloff, 2003; Veitch and Clout, 2002). In order to effectively lead such efforts, government institutions require pest management programs with clear long-term goals, adequate provision of financial and technical resources and agreements with allied institutions to facilitate the implementation of sanitary programs (Tobin et al., 2014). A policy-oriented management scenario affects farm-scale strategies, whereas there is no influence of farm-scale strategies on policy. Government regulations related to plant protection and area-wide management are policy-oriented decisions.

For the Colombian agricultural sector, the role of the policy-oriented institution is played by the Colombian Institute of Agriculture (ICA). This institution is the plant protection and quarantine agency of the Colombian national government. It is mainly dedicated to provision of regulation and sanitary control. This institution is the decision-maker in the development of national initiatives for BW management and under legal terms solely responsible for enforcement of sanitary measures. No equivalent national, state or local agencies can legally exert this function. ICA is the key decision maker in the area-wide management of BW.

Farmers are the decision makers on the other end of the decision horizon spectrum. At farm-scale, decisions are related to profit maximization (or avoiding losses in the case of pest management) under socioeconomic and environmental constraints. Farmers develop strategies and tactics for controlling a pest using the best of their own knowledge to forecast future dynamics of pest occurrence and losses. In the next sections, we will describe the current knowledge about the state of nature for the management of the BW at area-wide and farm scales.

2.6 Management of the boll weevil

BW was successfully eradicated in North Carolina, Virginia, Georgia and Northern Texas, USA, during the 1980s and 1990s (Allen, 2008; Dickerson, 2001). Subtropical areas of the Lower Rio Grande Valley (Southern Texas) still harbor the last viable BW population in the USA (Brewer et al., 2020). The environmental conditions of the American Cotton Belt facilitated the positive outcome of the Boll Weevil Eradication Program (BWEP). Once stalks and volunteer plants are removed, there are very few or no sources of food for BW during the winter. Scarce food and freezing temperatures dramatically reduce the population size, facilitating the eradication of the remnant populations by means of cultural practices (reducing food sources) and malathion applications in the refuge areas (Hardee and Harris, 2003; Smith, 1998).

The alternative to an eradication program is a suppression program. While eradication programs aim to eliminate a pest from a defined area, the purpose of a suppression program is to reduce and control the size of the pest population (de Lima Jr et al., 2013). A suppression program includes insecticide sprays, monitoring with pheromone traps and timely execution of cultural practices. Recently, a successful BW suppression program covering 3,600 ha was implemented in the State of Goiás, Brazil (de Lima Jr et al., 2013). In the Colombian Caribbean, BW populations are persistent during the entire year, feeding on various sources without environmental restrictions. Even though a previous BW management program coordinated by ICA aimed to eradicate this pest, such attempts have remained unsuccessful and none of the current strategies in the Colombian cotton regions are designed for BW eradication.

Area-wide management of the boll weevil in the Colombian Caribbean

The purpose of area-wide management is to reduce the size of migrating populations of BW that survive in stalks and regrowths and volunteer plants, and eventually in the refuge locations. The main technical operations enforced by these regulations are destruction of stalks and elimination of volunteer cotton plants growing in fields of maize, the crop for cotton rotation (Negrete Barón et al., 2005b). There is no active management of migrating BW populations at the end of the crop season. BW populations living in the refuge sites are not targeted by any insecticide spray operations. In the tropics, this kind of intervention is considered ineffective because multiple hosts (crops and wild plants) are available for the insect. BW can survive without cotton during long periods feeding on tropical fruits (>7 months) (CONALGODÓN et al., 2008; Jimenez Mass et al., 2001). The dates for cotton planting and stalk destruction are regulated with the aim of having a cotton-free season of at least three months (Supp. file4).

Since the 1950s, several regulations and policies have been issued to enforce the area-wide control of the BW (Supp. file5). With the creation of ICA in the 1960s, all regulations are coordinated by this institution on behalf of the Colombian government (Sierra-Monroy and Burbano-Figueroa, 2020). In 2000, ICA developed the "National Plan for Boll Weevil Exclusion, Suppression and Economic Eradication" (NP-BWESE), which promoted cultural practices to control BW populations: on-schedule destruction of stalks and regrowths, planting in a specific time window, use of specific plant densities for the crop, use of cotton growth regulators and ethological control of the pest (ICA, 2000). In 2010, ICA announced the “National Plan for Establishment, Declaration and Recognition of Boll Weevil-Free and Low-Prevalence Areas" (NP-EDR-BWFLPA) based on assessments of BW population dynamics in the cotton-producing regions. This plan included a monitoring network for the states of Córdoba, Cesar, La Guajira, Magdalena, Sucre, Tolima, Valle, Cundinamarca, Cauca, Antioquia, and Huila (ICA, 2010). Recently, local initiatives for controlling the BW populations have been proposed with funding provided by the State of Córdoba. This initiative can only act as a monitoring and scouting instrument for BW populations, because it lacks a legal enforcement mechanism. All findings must be reported to ICA, which will eventually apply sanctions to the regulation infractors (Polo Montes and Álvarez, 2018).

Although cotton is a perennial plant, it is usually cultivated as an annual crop. Due to the plant’s perennial nature, cotton stalks must be destroyed at the end of the crop season. Cotton stalk destruction is a mandatory activity for all farmers and legally enforced since 1947 to prevent outbreaks of the Colombian pink bollworm (*Sacadodes pyralis* Dyar) (Sierra-Monroy and Burbano-Figueroa, 2020). The adoption of transgenic cotton cultivars expressing Cry proteins in recent decades eliminated the need to control the Colombian pink bollworm and the pink bollworm (*Pectinophora gossypiella* Saunders). Nowadays, stalk destruction only aims to control those pests (mainly BWs) that are not eliminated by the current Cry proteins (Osorio-Almanza et al., 2018).

A considerable number of farmers do not complete stalk destruction within the given time frame, and frequently the technical operations used for stalk destruction are not effective enough to prevent cotton regrowth. Enforcement of cotton stalk destruction is limited as a result of complexities related to enforcing punitive measures on rented farmland. At present, monitoring of stalk destruction is handled by farmer organizations, which then report their observations to the ICA regional headquarters. ICA does not have an effective legal framework and/or the managerial capacity to initiate legal actions against infractors on rented farmland. Officers of the regional headquarters have proposed a change in the stalk destruction enforcement with the return of the monitoring activities to ICA and sanctions applied to the landowner. Landowners, who can easily be traced and sanctioned, could be incentivized to transfer costs and efforts related to policy enforcement to the leaseholders as part of their land lease agreements (Sierra-Monroy and Burbano-Figueroa, 2020).

In this scenario, cotton plants can resume growth in April at the beginning of the following rainy season. Such surviving plants constitute a critical refuge for BW, which can feed and reproduce on these plants from late March to May. Frequently, varying numbers of stalks and volunteer plants can still be observed in June (Sierra-Monroy and Burbano-Figueroa, 2020). Under these circumstances, BW populations are only confronted with two to three months without their host crop. Such a short period of food shortage allows a sizable number of weevils to survive, facilitating the rapid buildup of a large pest population in the following cotton season (Figure 5). Additional descriptions of the intra-annual dynamics of BW populations are provided in Supp. file4).

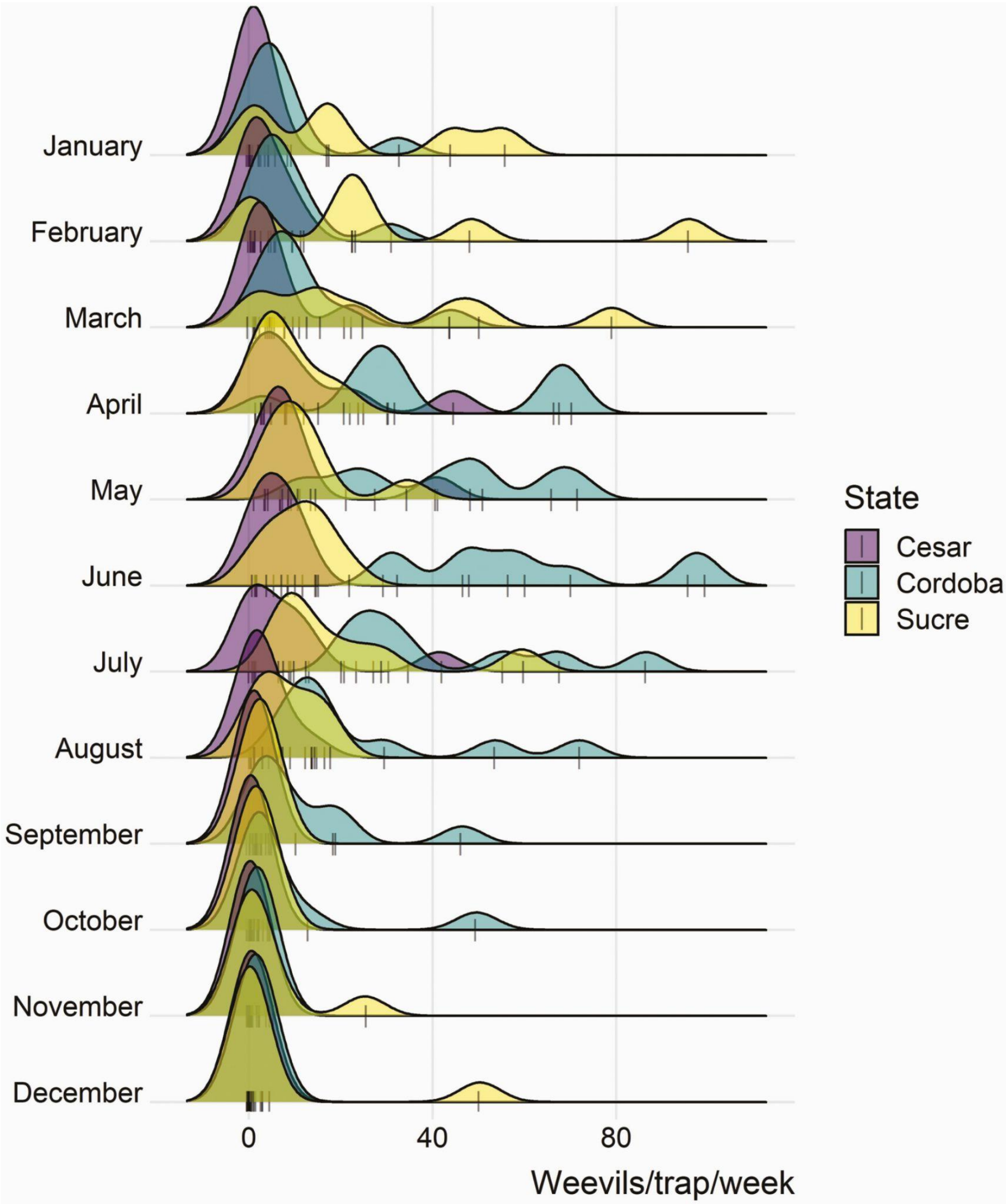


Figure 2.5. Population dynamics of migrating (dark) boll weevils (BWs) in the cotton producing areas of the Colombian Caribbean. Trap index values (migrating weevils per trap per week) were calculated from aggregated data reported by ICA for the period 2001-2012 (ICA, 2012; Pretelt et al., 2007; Villareal Pretelt et al., 2008; Villarreal Pretelt et al., 2006). Vertical lines associated with the x-axis for each month represent specific data points. Curves represent the distribution of the expected trap index for the assessed period (11 years).

Migrating BW populations are monitored using pheromone traps. Insect population sizes are estimated from the number of collected adult weevils per trap per location per week. This population estimate is called the trap index (TI) (Rummel et al., 1980). For the Caribbean, historical observations show that the midyear migrating population of BW can range from 5 to 100 TI individuals (Figure 5). The availability of cotton stalks determines the carrying capacity of the environment for supporting the BW populations. It is expected that the effective implementation of the suppression program (mainly the cotton stalk destruction) in the Caribbean will decrease the BW migrating population to 5 TI weevils. At such a population density, BW populations can feed on several crops (e.g. maize or fruit flowers), but they are only able to reproduce in a small and scattered population of available host plants.

Besides destruction of cotton stalks, some additional technical operations have been proposed for inclusion in BW management program, but not all of them have been implemented or may be effective. There is no clear evidence of the effectiveness of 'attract and control tubes' (BW-ACT) for controlling BW populations in the Caribbean (Villarreal Pretelt et al., 2005), and there are continuous claims of their ineffectiveness by farmers in other countries. Pheromone traps containing insecticide-impregnated kill strips (BW-ACT included) were designed for controlling small residual (isolated) populations, but not as the main field intervention for controlling massive migrating BW populations in a region (El-Sayed et al., 2006; Suh et al., 2009; Tewari et al., 2014). Effects of mass trapping diminish when the population density increases (Figure 6) (El-Sayed et al., 2009). BW population levels in the Caribbean region are not residual but constant, exhibiting frequent outbreaks with population densities >100 weevils/trap/week (Figure 5).

There is no certainty on the effects of the proposed technical operations, but historical data suggest that limiting access to cotton plants can decrease the migrating BW population to a density close to 10 adults/week/trap (Figure 7). The size of the mid-year migrating BW population that will colonize cotton plants during the following crop season is mainly determined by the carrying capacity of the environment. In the Caribbean, carrying capacity is mainly determined by the occurrence of cotton plants (crops, stalks, regrowths or volunteers), with no effect of the alternative feeding hosts on population size and marginal effects of the reproduction hosts considering their number and scattered distribution (Supp. file6).

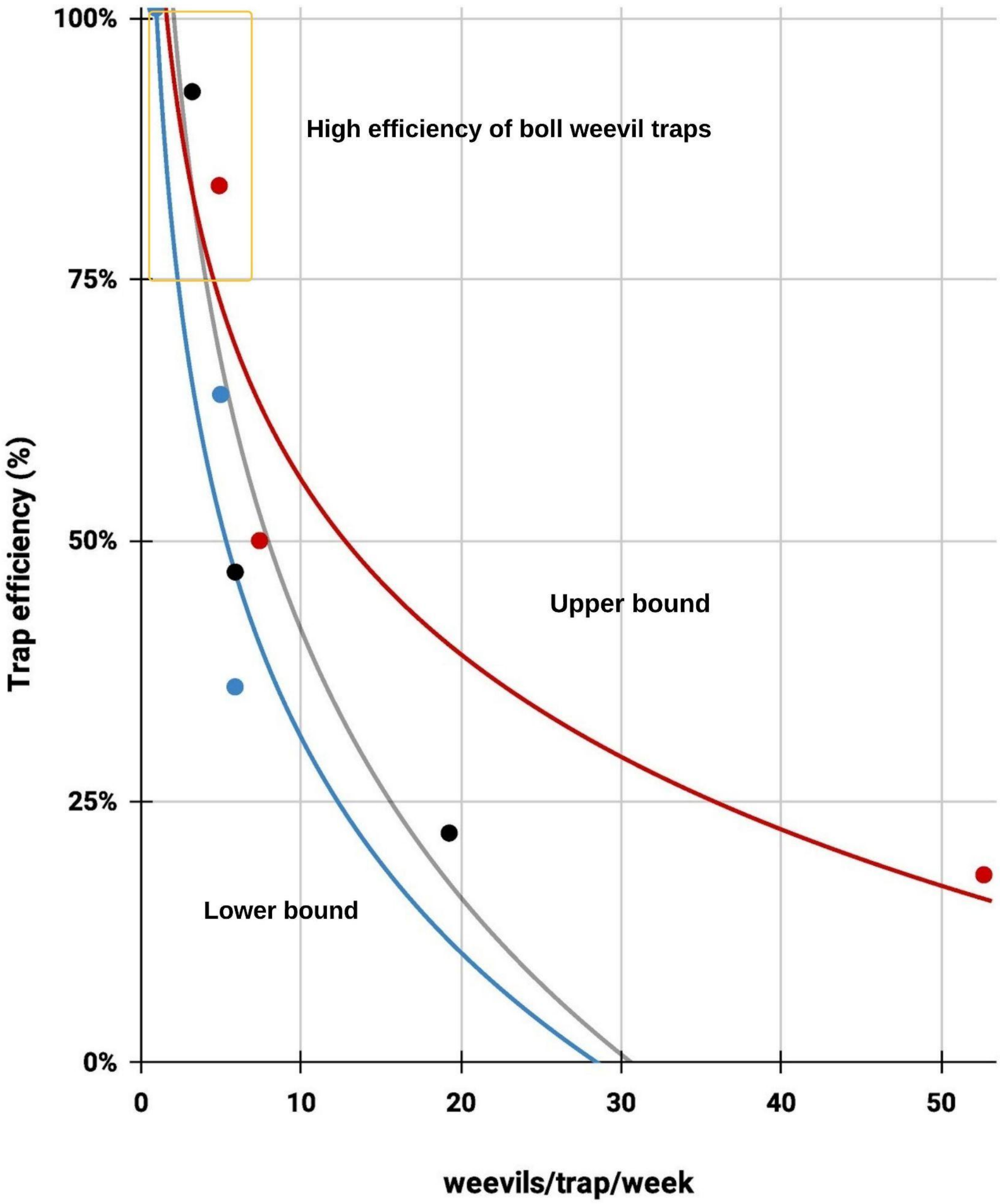


Figure 2.6. Effect of population size of overwintered boll weevils (BWs) on the effectiveness of male-baited traps (Lloyd et al., 1983, 1972). Before the synthetic grandlure, BW males were used as bait. Traps with synthetic grandlure (as the BW-ACT) are 90-100% as effective as those baited with male weevils (Hardee et al., 1974). Additional information is provided in Supp. file6.

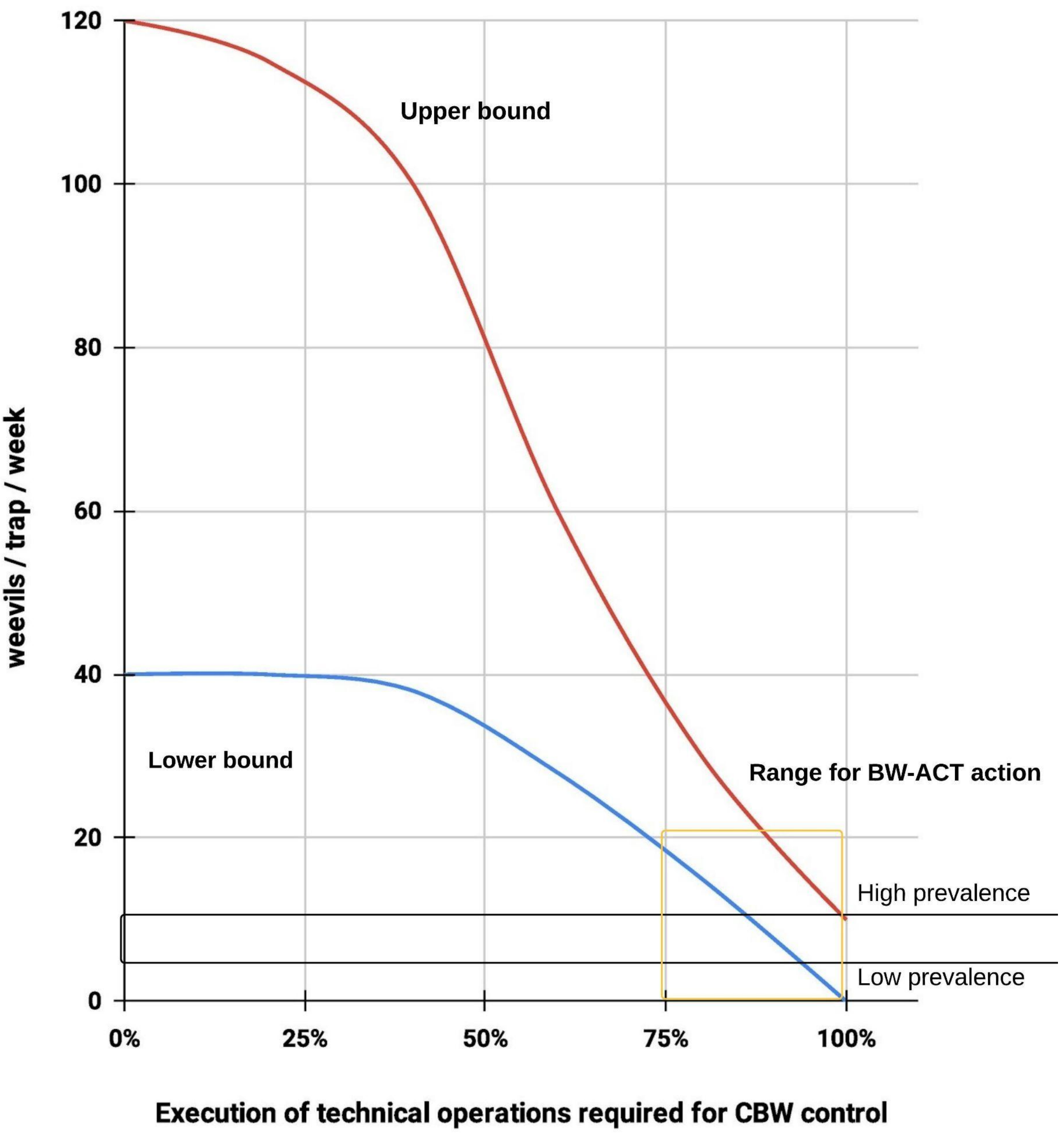


Figure 2.7. Expected outcomes for the management of migrating populations of *Anthonomus grandis grandis.* Expected changes of a midyear boll weevil (BW) migrating population in the Colombian state of Córdoba in response to the execution of all control-related technical operations with the area-wide management. The yellow dashed line represents the range where BW-ACT is effective (El-Sayed et al., 2009).

BW-ACT and other kinds of traps can be replaced by other field interventions to control the arrival of BWs to the crop and the movement to the refuge locations at the end of the season. Trap crops and scheduled insecticide sprays can be used for the same purpose. Early scheduled applications (at first square occurrence) are recommended when weevils are still circulating during the planting season (Rummel et al., 1980). Based on the historical records of migrating BW populations in the Caribbean region (Figure 5), these early applications should be a standard operation of the area-wide management program. The use of BW-ACT is enforced under the assumptions that small weevil populations arrive early in the crop season (during squaring) and the movement to the refuge locations must be controlled because those populations are responsible for crop colonization. However, field experiments in the Brazilian Cerrado suggest an alternative explanation (Arruda et al., 2020). Weevils are already present in the cotton fields very early in the season, reproducing in either cotton regrowths or plants inside the preceding crops (eg. soy and maize), and complementing their nutrition with the preceding crop. Cotton regrowths and plants are not efficiently eliminated after the adoption of herbicide-tolerant cotton cultivars. Results by Arruda et al. (2020) also suggest that the main source of field colonization is not BW populations surviving in refuges but those populations surviving in other crops. In this setting, farmers may benefit from more effective use of trap indices generated by the monitoring network, which can be used to estimate the size of the migrating BW populations before the cotton season. This, in turn, may allow insights regarding crop infestation risks and appropriate adjustments to pest management strategies.

Farm-scale management of the BW

We identified two strategies based on synthetic insecticides for the control of *A. grandis grandis* in the Colombian Caribbean: 1) early insecticide applications to keep BW migrant populations from infesting cotton fields and 2) late insecticide applications to reduce population growth rates and decrease yield losses associated with BW invasion of the crop. We called these strategic options proactive and reactive management, respectively (Supp. file7).

In the proactive strategy, insecticide sprays are applied on a calendar basis to coincide with the development of the first pinhead square (28 days after emergence (DAE)) or 1st ⅓ grown square (flower bud diameter of 6 mm). BW adults and apical meristem damage can be observed earlier than 28 DAE. These weevil populations are usually not controlled but their observation is used for triggering the pinhead square sprays. If apical damage or weevil adults are not observed before 28 DAE, insecticides are sprayed with the observation of ⅓ grown squares. The ⅓ grown square applications target the migrating females ready for oviposition in those squares of proper size and avoid the establishment of the colonizing population (S1) in the crop. Pinhead square sprays intend to control weevil populations that are already in the field in significant numbers, which can be controlled more efficiently when the cotton plants are small. Early sprays in general protect the first and early squares, which contribute most of the overall fiber yield. Later sprays are applied in response to the arrival of new migrating BW populations. These additional applications are often undertaken between 50 and 60 DAE.

The reactive strategy is composed of two field tactics. The first tactic is executed when the first BW aggregation spots are detected in the field (monitoring-based applications). Aggregation spots are defined as clusters of 5-10 plants with visible damage from oviposition and feeding (features defining the S2 attack stage). Management at this time requires gathering of punctuated squares of all plants and fallen squares on the ground and application of insecticides over the aggregation spots. These insecticide sprays are applied using a scheme that aims to disrupt the life cycle of the BW populations growing in the crop (Figure 8). The first insecticide spray aims to eliminate BW adults circulating in the field. Three more applications are scheduled every 4 days to disrupt the growth of BW in the crop. Four days is the feeding period required for a young female BW adult to start a new oviposition cycle in the savanna climate of the Caribbean (Gómez Lopez, 1981; Yepes Rodriguez, 1997). The BW population is not completely eliminated by this intervention and moves forward to the invasion phase (S3), where feeding and oviposition damage occurs in squares and bolls. The second tactic is executed during this phase. At this time, BW populations are controlled with more insecticide applications but now over the entire field (general spray applications). Between four and five applications are required from the invasion phase to harvest and two more during the harvest season to protect cotton bolls (consumed by BW when squares are absent). Farmers frequently report that ten applications are required per crop season for controlling BW and up to 15 sprays may be required for cotton seasons with high BW pressure (Osorio-Almanza et al., 2018). This strategy is the most commonly used among farmers in the Colombian Caribbean for controlling BW populations.

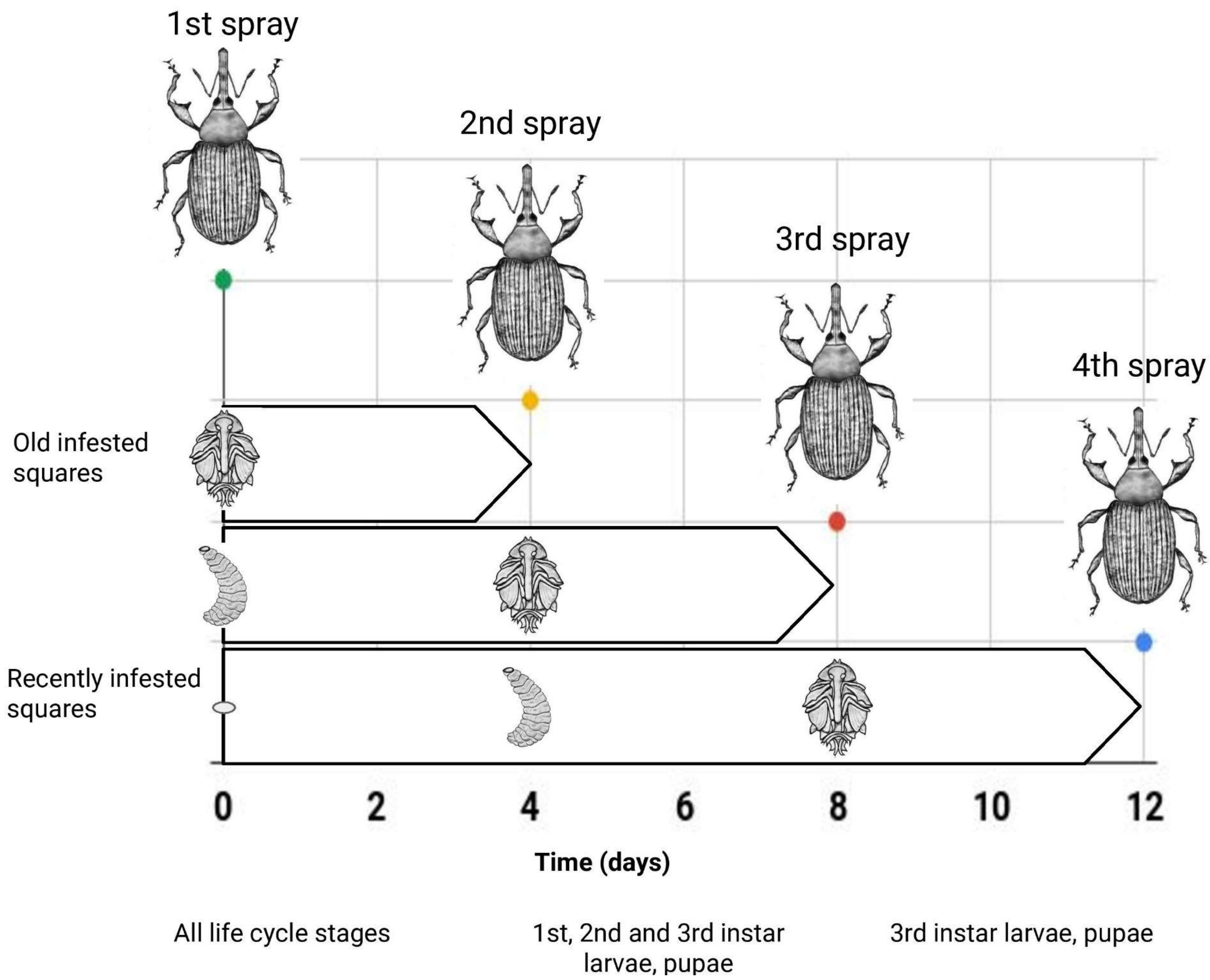


Figure 2.8. Description of the insecticide application scheme for disrupting the life cycle of the boll weevil (BW) populations in the reactive strategy.

Early-season insecticide applications of the proactive strategy may better prevent early establishment of BW populations in the crop and facilitate its management and the control of other pests. Once BW is established in the crop, it is difficult to eliminate because a large portion of its life cycle happens inside the reproductive structures of the cotton plant, where larvae are protected from environmental threats, including insecticide sprays. Monitoring-based sprays are usually recommended for pest management, but for BW calendar applications are recommended from a decisional and technical point of view (Heilman et al., 1979; Mistric and Covington, 1968; Showler and Robinson, 2005; Showler, 2012, 2004). Decisions based on monitoring require regular scouting of the crop, which translates into an increase in planning and operational costs and high risk of poor execution. In relation to yield, crop advisors and field experiments agree that reproductive structures formed during the few weeks following first squaring are responsible for a major share of the expected yield (approximately 70%). These early reproductive structures (squares mainly) are the target of the migrating BW population (S1) for oviposition and feeding.

Crop advisor interviews suggest that migrant populations of the weevil arrive to the cotton fields in the first 60 days of cotton growth. Assuming such a wide time window (12-60 DAE), we hypothesize that farmers that prefer reactive strategy have witnessed several seasons where BW did not attack the first squares and arrived later in the season and extrapolated this observation to all seasons. Under such conditions, early applications of insecticides are seen as an unnecessary cost with an uncertain effect on yield expectations. For both scenarios, there is a chance of BW populations surviving the control tactics aimed to delay the attacks or disrupt the life cycle of the pest. Reactive management is highly sensitive to allowing significant BW populations to survive, if the effectiveness of the chemical applications is compromised. Such limited effectiveness could arise from heterogeneous application of the insecticide (a common problem if applications are done manually), high precipitation after the applications, high pressure of the BW population (related to population size) or continued migration from nearby plots with uncontrolled stalk regrowths or volunteer plants (Lobatón Gonzalez and Jiménez Mass, 1984).

No field data are available to assess these strategic scenarios for the chemical management of BW. Even, to our knowledge, there was no awareness of the existence of such different strategic scenarios for controlling BW. Probabilistic simulations of these scenarios will facilitate understanding of the limitations of both chemical application strategies and help design experiments for assessing the underlying hypotheses that define the preference for a specific management strategy.

2.7 Conclusions and perspectives

The decision-making process of BW management occurs at two temporal-spatial scales:

- Regional and national scale, driven by policy-oriented decisions aimed at keeping the BW population below the economic threshold. A national suppression program for BW led by the Instituto Colombiano Agropecuario (ICA) (the government institution in charge of this decision) was implemented with very little success.
- Farm scale control of the BW operated by farmers using two types of management strategies, which we refer to here as proactive and reactive. Proactive management describes an avoidance strategy accomplished by applying insecticides early in the season, when squares are emerging. Reactive management represents monitored insecticide applications based on the detection of aggregation spots. The proactive approach is promoted as the most cost-effective strategy, reducing insecticide use and restricting crop damage.

The current area-wide management of the boll weevil requires urgent changes. The first alternative is that the area-wide management of this pest must be led and enforced directly by ICA instead of delegating responsibility for such initiatives to farmer organizations. In order to effectively lead such efforts, ICA must develop a BW management program with clear long-term goals (policy), adequate provision of financial and technical resources and an effective legal framework to enforce sanitary measures. The second alternative to this national initiative is the development of a regional management program for the Caribbean.

This initiative requires the participation of multiple national and local institutions with complementary capacities that can support ICA. Currently, the Cotton Regional Committee (CRA) is leading local actions together with national institutions with the aim to address limitations of the cotton value chain in the Caribbean. This includes the area-wide management of the boll weevil. We hope that using the framework of decision analysis under uncertainty, we can be the facilitators of this conversation.

Quantitative assessments and field data are required for estimating the uncertainties and effectiveness of the strategic and tactical options for control of BW that are implemented at regional and farm level. For area-wide management, all technical operations aim to decrease the size of the BW population, so estimating the effect of each individual technical operation and the associated costs and benefits will be a valuable contribution. Promoting the development of an effective framework for cotton stalk destruction is a priority, but further quantitative assessment of other strategies besides stalk destruction are necessary to reduce endemic BW populations. We consider that it is especially important to measure the presumed benefits of the BW-ACT devices under the current levels of BW infestation. The cost-effectiveness of the control strategies used at farm level must be estimated in order to provide a valid indicator of their technical and economic feasibility. These assessments can be obtained using quantitative models fed with probabilistic inputs provided by experts or estimated based on previous research. The development of quantitative models and simulations for the scenarios described in this paper is the subject of further research being undertaken by the authors.

Chapter 3

3 Profitability of farm-scale management strategies against the cotton boll weevil in the Tropics: Case study from the Colombian Caribbean

An article with the same content including Appendix B has been published in the Journal of Pest Science as Burbano-Figueroa, O., Sierra-Monroy, A., Whitney, C., Borgemeister, C., & Luedeling, E. Profitability of farm-scale management strategies against the boll weevil in the Tropics: Case study from the Colombian Caribbean.

Decision making in pest management is a challenging task. While pest dynamics are often quite uncertain, such decisions are often based on tenuous assumptions of certainty (economic injury levels and marginal utility approximations). To overcome such assumptions and adequately consider uncertainty, we apply decision analysis to evaluate management strategies used by farmers in the Colombian Caribbean against the cotton boll weevil (BW). We represent the decision to protect the crop using partial budget analysis. This allows us to capture key properties of BW control strategies, while accounting for uncertainty about pest infestation pressure, control effectiveness and cotton yield and price. Our results indicate that proactive management is more efficient than a reactive approach given the current BW infestation pressure. However, farmers may prefer the reactive strategy, since they have experienced seasons with low infestation pressure where no insecticide applications were required. The proactive strategy, in contrast, requires scheduled pesticide applications in all years. Results show that in seasons with high infestation pressure the expected revenues of the reactive strategy tend to decrease, mainly because more spray applications are required when fields are heavily infested by the weevil. Uncertainties related to BW arrival time to the field, BW population density and planting date appeared to have the greatest influence on the decision to protect the crop. Narrowing these key knowledge gaps may offer additional clarity on the performance of the current management strategies and provide guidance for the development of strategies to reduce insecticide use. This is particularly important for the promotion of the proactive strategy, which, under the current infestation pressure, has potential to reduce the insecticide use. While economic injury levels can only be applied to responsive measures, our approach of partial budget analysis under uncertainty allows us to assess and compare both responsive and proactive measures in the same methodological framework. This framework can be extended to other non-pesticide control measures.

3.1 Introduction

Pest management decision making is commonly addressed using economic decision levels such as economic injury levels (EILs) or marginal utility approximations. EIL is defined as "the lowest population density that will cause economic damage" (Stern et al., 1959). It is used as a framework for supporting decision making strategies at farm-scale, considering a one-season planning horizon. EIL decision making is responsive rather than preventive. It is well suited for the dynamics of occasionally occurring pests, where pesticide applications are possible after scouting and assessment. Marginal utility analysis aims to maximize profits related to the control strategy. It is described by a utility function, where an increase in profits is expected for each monetary unit invested to protect the crop (Pedigo et al., 1986). These approaches to pest control decision making are based on assumptions of certainty (Pedigo et al., 1986).

However, decision making in pest management (similar to other problems in agricultural production) is a challenging task, given that many aspects of pest dynamics and control effectiveness are uncertain. For instance, decisions on prophylactic pesticide applications are usually taken without evidence of pest presence in the field and without estimations of the expected damage caused by the pest, the efficiency of the pesticide or the future value of the crop losses. Such preventive actions cannot be assessed using an economic threshold, because they are not correlated with pest density. As they involve considerable uncertainty, they also cannot be assessed using a deterministic marginal analysis. These challenges of common pest management decision frameworks can be resolved using decision analysis methodologies (Mumford and Norton, 1984).

Pest management at farm-scale is a chain of actions that are repeated season after season. As a recurrent process, it is represented as a system of cyclical decisions. Synthesizing previous work (Anderson et al., 1977; Mumford and Norton, 1984; Norton, 1976; Pedigo et al., 1986; Waibel, 1986), the pest control decision cycle during a cropping season can be described as follows (Figure 3.1.):

1. Expected occurrence of a pest (or pest identification if it is a new pest)

2. Decision to protect the crop. A decision to protect or not to protect the crop against a specific pest based on assumptions related with the market-value of the crop, the current pest infestation pressure, the expected pest infestation levels, and the expected severity of the pest-related losses (the perceived states of the system)[1].

3. Execution of the control strategy. Once the decision-maker has decided to act, she/he will apply a previously implemented control strategy. The conventional response of a decision-maker in a management situation is to focus on the implementation of an historically well informed practice (Parma and NCEAS Working Group on Population Management, 1998; Shea et al., 2002). Each control strategy includes additional tactical and operational decisions mainly related to availability of physical resources (e.g. based on insecticide availability on local markets, or the availability of resistant cultivars) and financial resources. All strategies strive to keep pest populations under control (tactics feasibility). Strategic actions are mutually exclusive (discrete actions).

4. Forecast. All control strategies include a tactic for risk assessment based on monitoring or forecast (including mental model of farmers for signal detection or triggering of the response) of the infestation levels.

5. Implementation of control tactics. Control tactics are executed iteratively in response to perceived changes in pest infestation levels determining the economic/environmental consequences of the control strategy.

[1] Also referred to as the states of nature, the states of the decision maker´s world or scenarios.

6. Outcomes assessment. Benefits and effectiveness of the control strategy are judged on basis of the perceived infestation level and compared with outcomes observed in other farms.

7. Development and assessment of control strategies. New information about pest management tactics and operations can also be provided by other stakeholders, such as researchers or crop advisors. Usually, control strategies implemented by farmers are not updated in these seasonal cycles and can only be challenged by active learning. Active learning is the goal of initiatives involved in the adoption of new technologies by farmers (usually called extension services), and it requires the allocation of financial resources. Research and extension can provide a wide set of control strategies, identify relevant uncertainties and improve the decision rules that farmers employ in their decision-making process (Shea et al., 2002).

The second (state of the system) and third (control actions) elements of the decision cycle are the determinants of the fourth element, the expected outcomes of the strategy. These are the main elements of the farmers's decision on whether to protect the crop. This decision is represented as a utility function using partial budgeting analysis (marginal function). The expected revenues at different levels of infestation in the case of "take no action" (let the invasion run its course) can be estimated from untreated plots of field trials or historical data, or elicited from experts. The crop losses resulting from these infestation events represent the upper limit of the returns of any crop protection strategy. How much of this "potential loss" can be prevented will depend on the effectiveness of the existing control strategies (Mumford and Norton, 1984; Waibel, 1986). "Take no action" is the initial state of the system (before the intervention). It provides a baseline for the comparison of the control actions under uncertain pest infestation levels (Moore et al., 2011). As the economic outcome (return) of each control strategy changes at different pest infestation levels and crop growth stages, their comparison requires a representation of these combinations. The best overall strategy is the one able to provide the best economic results in the majority of these combinations (Waibel, 1986). This representation of the decision cycle describes the role of the farmers as managers (farmers as decision makers) and their preference for a specific strategy based on their risk perception and individual assessment of the economic consequences.

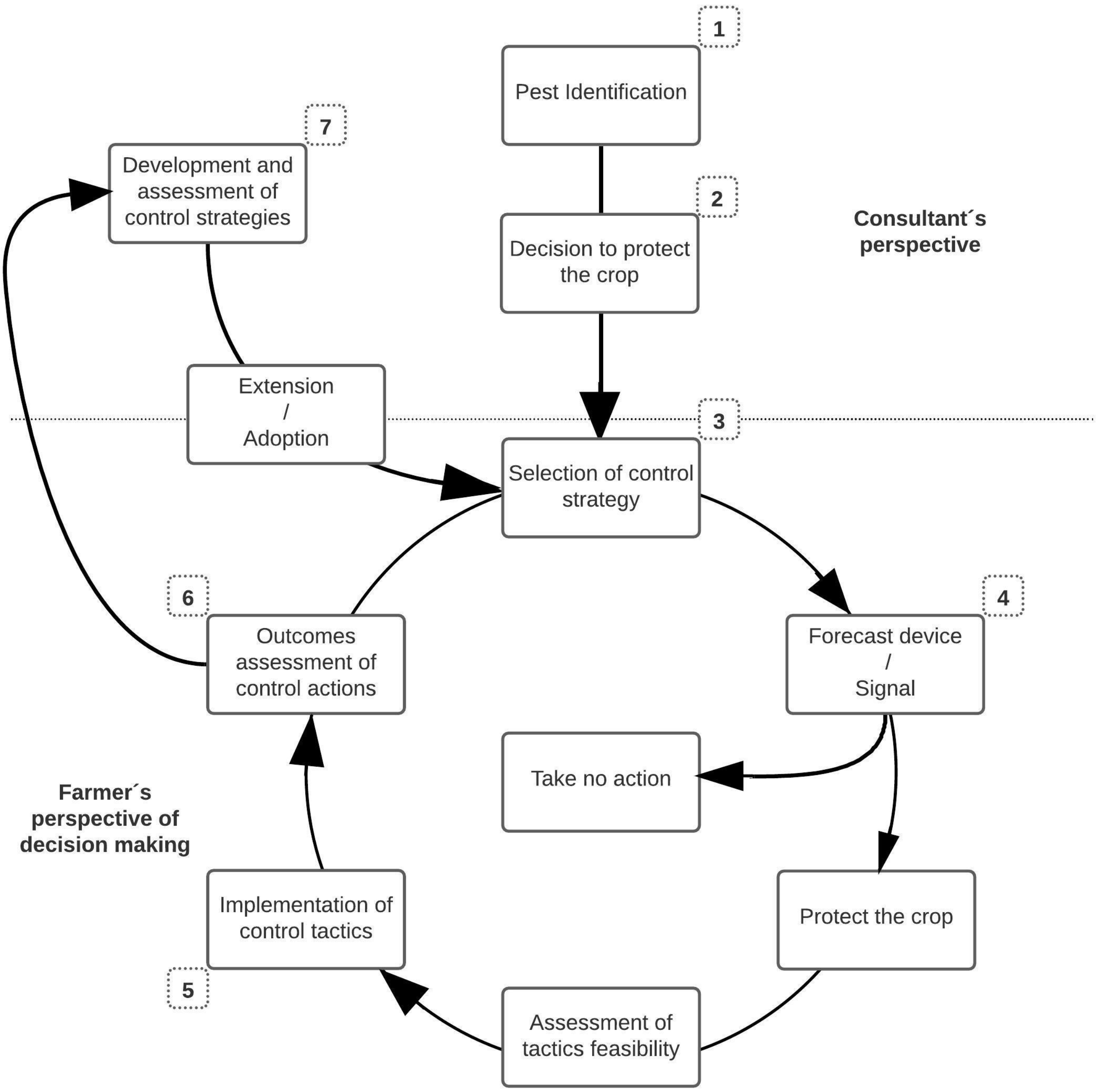


Figure 3.1. Decision making under uncertainty for pest management.

The sixth element introduces new information to the decision cycle, or comparison of the discrete actions used for pest control. These comparisons are not in the realm of the farmer's decision making perspective, but within the scope of services provided by consultants. Consultants is a broad term for all stakeholders that are linked to the pest management process in a capacity that allows them to conduct "experiments" or do research (surveys, data analysis and interpretation, comparison of control strategies, forecasts, or technical advice). The additional knowledge provided by these consultants (the consultant's perspective) can update the current beliefs of the farmers about pest control (extension services).

We use this framework to understand the control of the cotton boll weevil (BW) (*Anthonomus grandis* Boheman [Col.: Curculionidae]) at farm-scale in the Colombian Caribbean. This investigation was framed as a decision analysis under uncertainty, undertaken to assess the benefits and uncertainties of the control strategies implemented in the Colombian Caribbean. The identification of uncertainties involved in these control strategies will allow farmers and consultants to explore how these strategies can be improved. Additionally, we compare the performance of the control options, in order to estimate which strategy has the greatest potential to reduce pesticide use (while providing similar economic benefits). Options with reduced use of pesticides are preferred because the long-term objective is the development of an integrated pest management program (IPM) for this pest.

To accomplish this goal, we implemented several decision analysis concepts, procedures and tools, drawing from Agricultural Decision Analysis (ADA) (Anderson et al., 1977) and Applied Information Economics (AIE) (Hubbard, 2014). We used the framework provided by decisionSupport, an R package that facilitates decision analysis (Luedeling et al., 2020). Expert elicitation was used to provide input to the model, including uncertainties related with pest infestation levels. A probabilistic simulation based on the Monte Carlo method was used to project the outcomes of each strategy given the current pest infestation distribution. We calculated the value of information to identify decision-specific knowledge gaps of each control strategy that should be addressed by additional research (Koops, 2004). Finally, given that we are comparing the outcome of discrete strategies (actions), we used Stochastic Dominance (SD) as a measure of their efficiency. SD allows assessing risk when it is impossible to elicit utility functions for the decision makers involved (Gandhi et al., 1981; Genest et al., 2016; Levy, 2016a; Wu et al., 2017). This approach provides support for the decision making process of farmers and identifies knowledge gaps that can be considered for further research by consultants.

3.2 Methods

3.2.1 Study background

Cotton boll weevil (BW) is considered the most problematic pest of upland cotton in Colombia. The weevil arrived in South America around the middle of the 20th century, starting with two introductions via Venezuela (1949, Tocoron) and Colombia (1951, Cartagena), and colonized the entire Caribbean Plains within five years (Sierra-Monroy and Burbano-Figueroa, 2020). Currently, BW is endemic in the dry and wet savannas of the Caribbean Plains causing seed-cotton yield losses estimated between 250 to 500 kg/ha and management costs of up to 10% of the total production costs (CONALGODÓN et al., 2008; Ñañez, 2012; Osorio-Almanza et al., 2018). At farm level, BW is mainly controlled using synthetic insecticides, which increase crop production costs and cause undesirable environmental impacts (ICA, 2010). Over the past 15 years, cotton fields in Colombia were sprayed seven times per year, on average, against cotton pests (with higher values for some regions), with 70% of these applications aiming to control BW (Ñañez, 2012).

Two strategic options based on synthetic insecticides are currently implemented to control *A. grandis* at the farm level in the Colombian Caribbean: 1) proactive strategy: early insecticide applications to eliminate the BW founder population arriving to the cotton crops early in the season, and 2) reactive strategy: late insecticide applications to reduce population growth rates and decrease yield losses associated with BW invasion of the crop (Figure 3.2) (Burbano-Figueroa et al., 2019). In the proactive strategy, insecticide sprays are applied to control the early arrival of the weevils to the field, which occurs during squaring (cotton bud break stage of development prior to bloom). These applications target the migrating females (coming from the refuges) ready for oviposition on the first squares and for the establishment of the founder population in the crop. BW reactive control, in contrast, is based on a series of focused insecticide applications that are triggered by the observation of BW aggregation spots and aim to disrupt the established population (Gómez Lopez, 1981; Yepes Rodriguez, 1997). If this population is not completely eliminated, subsequent weekly field sprays are applied until the population is eliminated or the crop reaches maturity. Farmers use on average 7-10 applications per crop season, and up to 15 sprays may be required for fields exposed to high BW infestation levels (Grandett-Martinez et al., 2003; Osorio-Almanza et al., 2018). Most BW management actions applied by farmers in the Colombian Caribbean rely heavily on reactive actions to contain weevil pest populations (Burbano-Figueroa et al., 2019).

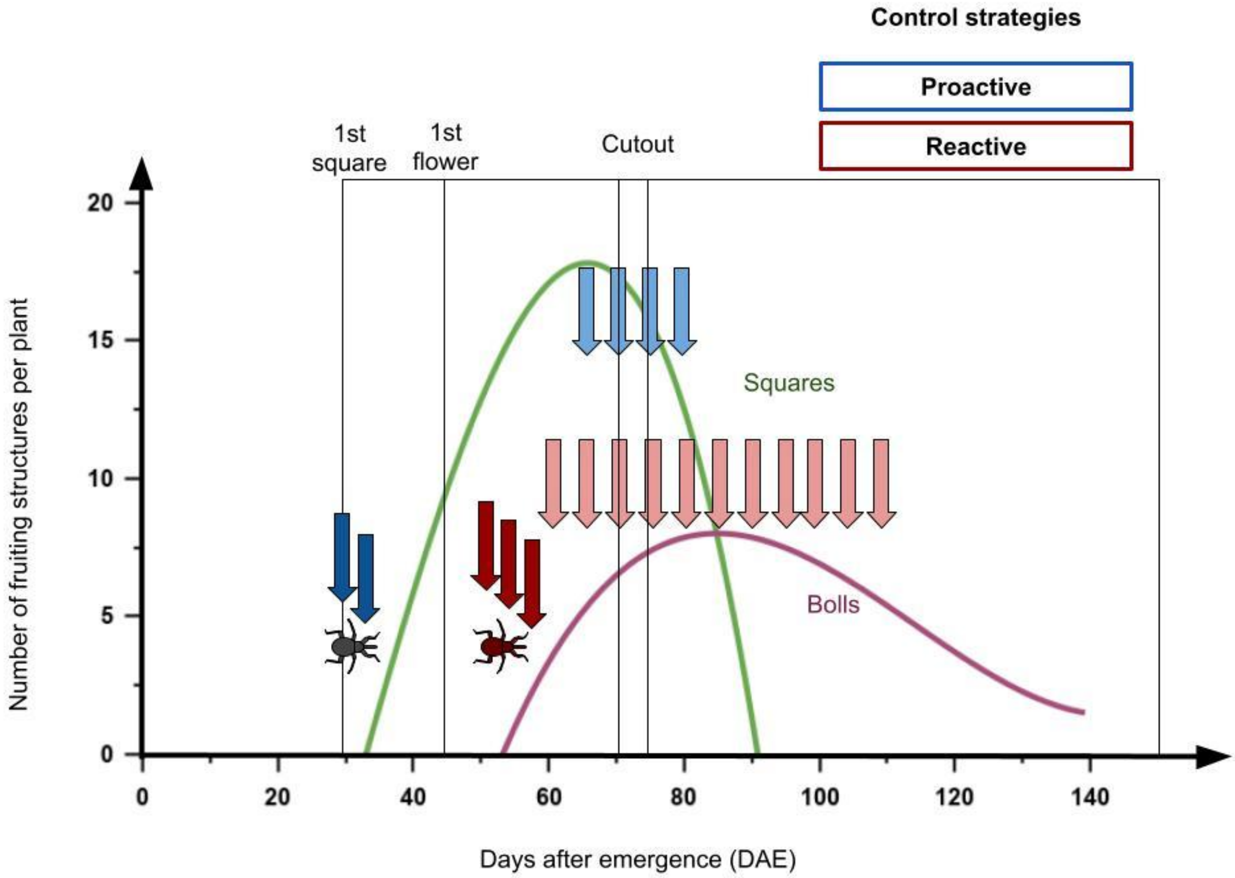


Figure 3.2. Description of strategies used for the control of the cotton boll weevil (*Anthonomus grandis*) in the Colombian Caribbean. The description of cotton phenology is based on field assays of several cultivars planted in the Sinú Valley of the Colombian Caribbean (Burbano-Figueroa and Montes-Mercado, 2019). Arrows with lighter colors represent additional insecticide applications for controlling remnant BW populations that were not eliminated in the first control operations.

3.2.2 Data source

In our previous work, we developed a conceptual model and identified variables and parameters associated with the management of BW based on information derived from focus group discussions and semi-structured interviews with knowledge holders (Burbano-Figueroa et al., 2019). The core group of experts consisted of a cotton plant physiologist, a cotton breeder, four entomologists (three with expertise in BW management, and one with expertise in insect ecology) and five crop advisors and/or farmers (who are responsible for a large share of the entire cotton producing area of the Colombian Caribbean region). Based on their inputs, we identified two scales that deal with critical issues for BW management: 1) pest management at farm-scale; and 2) issues related with the regional suppression program (Burbano-Figueroa et al. 2019).

In the present work we follow up on these findings, exploring in more detail the economic implications of the strategic scenarios used for BW management at farm scale. Besides using data from Burbano-Figueroa et al. (2019), we gathered additional information via unstructured interviews and included related technical reports, which were collected from the Biblioteca Agropecuaria de Colombia (BAC; https://repository.agrosavia.co/), a local repository, and from personal libraries of researchers associated with Turipaná Research Center – AGROSAVIA.

We received additional feedback from the Cotton Regional Committee (CRA) headquartered at the municipality of Cereté, Cordoba. CRA is a local initiative of the Sinú Valley farmers with monthly meetings for discussing, proposing and evaluating all actions related to the cotton value chain in the valley. Focus group discussions, interviews and feedback were mainly coordinated with the support of this committee. We distributed a Spanish version of this document to CRA members and their related institutions to elicit feedback.

Quantitative descriptions of parameters and variable ranges were estimated based on available technical reports or from calibrated experts. We elicited quantitative information after experts were subjected to a calibration training procedure. Training consisted of increasing the experts' awareness of concepts of probability and instruction in techniques to produce accurate estimates of confidence intervals for unknown variables that reflect the estimator's level of uncertainty (Hubbard and Millar, 2014; Luedeling and De Leeuw, 2014; Luedeling et al., 2015, 2014; Yigzaw et al., 2019). The resulting subjective probability distributions constitute explicit representations of the state of certainty about events or states of nature (the states of the decision maker's world) (Anderson et al., 1977).

3.2.3 Decision framework for assessing BW control strategies

The decision to protect the cotton crop is supported by comparing the expected return on investments in pest control with the alternative option of not controlling the pest. A farmer who chooses not to apply insecticides may suffer yield losses and consequently economic losses from insect damage. However, if they choose to protect the crop, they may spend more than the value of the crop saved, which would lead to a net economic loss. Farmers that decide not to control a pest may suffer considerable losses in years of high pest infestation (Mumford and Norton, 1984; Norton, 1976; Pedigo et al., 1986; Waibel, 1986). In this decision model framework, we assessed the effect of two strategies for BW control using the baseline scenario of "take no-action" against the pest.

The proactive strategy aims to avoid colonization of the first squares by the migrant BW population and to generally limit the extent of early colonization of the crop. This requires early applications of insecticides even if the weevils are not detected during scouting. This tactic results in the contingency of fixed cost for crop protection (insurance), which may be considered wasteful in years or scenarios with no pest occurrence. In years of high infestation, additional insecticide applications are required for protecting the new young squares until the fruiting cutout (cessation of square production). After this point, the majority of the yield share (in terms of squares) is protected and the later arriving BW populations have a limited supply of food as the squares develop into bolls. Bolls can be attacked by the weevils only when the crop is heavily infested as the result of early colonization.

In the reactive strategy, farmers scout for BW aggregation spots, which are heavily treated to control the colonizing population. Once BW aggregation spots are identified these are individually sprayed over the following weeks. Several applications are required for elimination of individuals of different ages emerging from the squares. This strategy is not completely effective and in heavily infested fields farmers must spray insecticides over the entire field several times a week. In this strategy, BW is only detected when it has already colonized the crop.

The “take no action” strategy is absent in the Sinú Valley, but it is commonly used in marginal cotton areas in the Upper Magdalena Valley. In the Sinú Valley, this strategy is reported to occur by default in years of low BW infestation in isolated cotton fields that are managed under the reactive strategy. We use “take no action” as the baseline for the comparison of management strategies. Under the assumption of no action, if a migrant BW population arrives at the crop during the squaring stage, it will consume all the available squares and reproduce freely, causing high or complete losses. Such BW infestation events constitute the scenarios where control strategies take place to generate the maximum possible benefits. How much of this "potential loss" can be prevented will depend on the effectiveness of the implemented control strategy. In terms of yield, this effectiveness is represented by the avoided yield losses. In the framework of yield gaps, the “take no action” strategy represents the “reduced yield”, the observed yield after accounting for losses related to reducing factors, in this case the damage associated with BW. The yield obtained after the implementation of pest control is the actual yield. It is not uncommon that taking no action can be a profitable action, especially in scenarios where the pest density is very low and the associated damage is economically tolerable (the economic damage threshold).

3.2.3.1 Model conceptualization and simulation

The decision model for the control strategies contains two subsystems that were used to estimate the net revenues of BW control measures:

1. A biophysical subsystem that describes the factors that define attainable cotton yield, pest infestation levels, and the interaction between cotton plants and the pest.

2. An economic subsystem represented by a production function that emphasizes the change in revenue and expenses that result from executing a specific pest control action. Production functions are represented by partial budget analysis (Kay et al., 2019, 2016). Partial budget analysis describes the additional costs of operation associated with a decision to use or not use a treatment (action or intervention) and the relationship between these costs and additional benefits (CIMMYT, 1988; Perrin et al., 1983). The production function used here is a generalization of the economic injury level concept and it is also linked to the concept of production situations that define yield levels. In this framework, the production function also illustrates the investment required for closing the current yield gaps for a specific crop facing one or multiple (biological) limiting factors (Figure 3.3).

The net revenue NR_j is defined as a function of the attainable yield Y_w, losses caused by BW L_{BW}, the effectiveness of the control strategies E_j, the cotton output price p_Y, and the control costs C_j of the tactic j (modified from (Pemsl and Waibel, 2007) (Eq.1)

$$NR_j = f(Yw,\ L_{BW}, E_j,\ C_j,\ p_Y) \quad \text{(Equation 1)}$$

The net revenue of a pest control measure is estimated as the additional net revenue relative to the baseline of no control. It is calculated from estimations of the benefits and costs of each pest control measure. For each control strategy, the benefit is defined as the avoided yield loss for a particular pest control measure.

The difference between the actual yield Y_a (Equation 2) and the yield reduced by the pest Y_{BW} (Equation 3) was used to estimate the avoided yield loss for each strategy (Equation 4).

$$Y_a = Y_w * (1 - L_{BW} * (1 - E_j)) \qquad \text{(Equation 2)}$$

$$Y_{BW} = Y_w * (1 - L_{BW}) \qquad \text{(Equation 3)}$$

$$AYL_j = Y_a - Y_{BW} \qquad \text{(Equation 4)}$$

Finally, the net revenue for each control tactic was estimated as the difference between the value of the avoided yield loss and the cost of the control strategies:

$$NR = AYL_j * p_j - C_j \qquad \text{(Equation 5)}$$

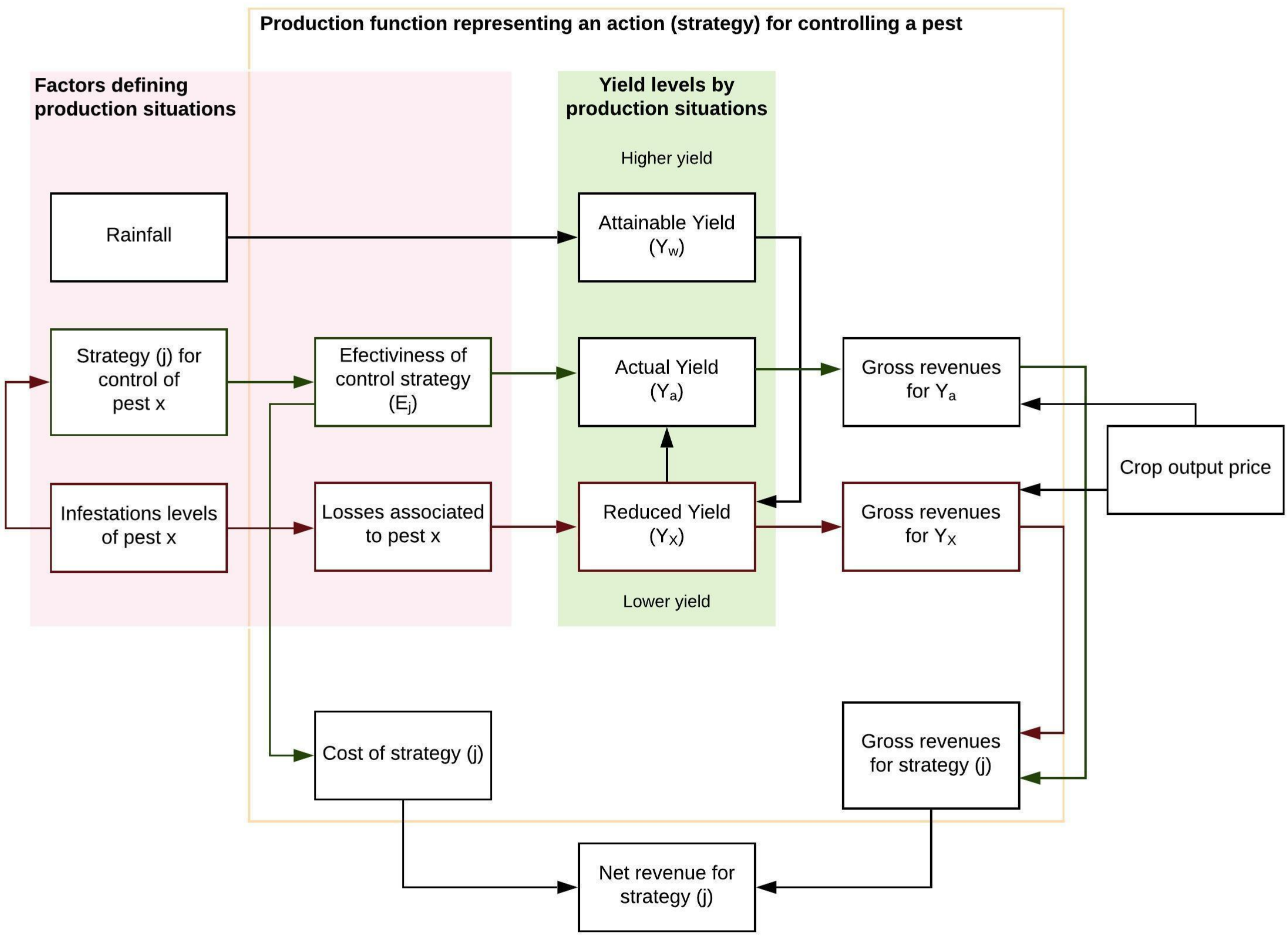


Figure 3.3. Structure of the production function representing an action (strategy) for controlling a pest in a rainfed production system.

Attainable yield was estimated as a linear function of the accumulated precipitation over a 90-day time window after planting. In the Sinú Valley, this accumulated rainfall correlates well with variation in the attainable cotton yield during the cotton season (Moreno-Moran and Burbano-Figueroa, 2017). We used the attainable yield in this simulation because cotton crops in the Colombian Caribbean are rainfed and thus exhibit widely varying yields. Planting date was included because farmers are well aware of the merits of planting early. However, planting dates of cotton are often constrained by late planting of corn (the rotational crop) in the previous season (often in response to late onset of seasonal rains) or by limitations in the availability of sowing equipment. We elicited information on the yield response to delayed planting from crop advisors.

The crop infestation by *A. grandis* was estimated as a linear function of the percentage of infected squares before the development of the first flower (55 days after emergence (DAE) and the density of the migrating BW populations at the start of the fruiting period. The level of expected crop infestation was used to estimate the expected yield losses caused by BW. The required number of pesticide applications was estimated as a function of the crop infestation levels (Grandett-Martinez et al., 2003).

3.2.3.2 Probabilistic simulation

All variables described in the stated equations are of stochastic nature, i.e. their precise values in any given year cannot be precisely predicted. To address the uncertainty that is inherent in the data, we assessed the profitability of the control options using a Monte Carlo simulation. Plausible values for all variables included in this model were defined as probability distributions, defined by distribution shape and estimated confidence intervals (provided in supplementary materials). From these distributions for all variables, we drew 10,000 sets of random samples, which were used as model inputs to compute 10,000 plausible values for the new revenue of each tactic.

To determine the sensitivity of the net revenue to the explanatory variables, we conducted Projection to Latent Structures (PLS) regression on the outputs of the Monte Carlo simulation, relating outcome variables to all uncertain model inputs. The selection of the most sensitive variables was done based on variable importance in the projection (VIP) calculation. The VIP score measures the influence of an individual input variable on the revenue (outcome) of the control strategies. Variables with a VIP score > 0.8 were considered as influential variables. For these variables, we also determined whether they had a positive or negative influence on projected revenues.

We then applied value of information analysis to determine whether collecting additional information on a certain input variable would be warranted for adding certainty to the decision on which option is preferable. We quantified the value of information by computing the expected value of perfect information (EVPI). The EVPI represents the monetary value that would hypothetically be worth investing in order to completely eliminate uncertainty on specified variables in the decision-making process (Hubbard, 2014). The EVPI can guide and underpin research priorities, especially in an environment with limited funding for additional data collection (Luedeling et al. 2015; Whitney et al. 2018). We used the EVPI to provide guidance to local research efforts for reducing the uncertainties of the implemented strategies for controlling BW (box 6 in the decision cycle). If one of these control strategies show competitive revenues and has the potential to reduce use of insecticides, reducing associated uncertainties can facilitate adoption by farmers.

3.2.4 Ranking BW control strategies with stochastic outcomes

For many decisions, decision analysis produces outcome forecasts where the distributions of plausible outcomes for the different options differ clearly enough to allow identifying the preferable course of action. Yet this is not always the case, and many analyses produce outcome distributions with strong overlap. Often such outputs also feature different distribution shapes, which complicate the decision on which decision option is preferable. The standard procedure in decision analysis indicates that at this point, additional information should be collected on high-value variables, but many decision-makers have no resources for such collection, and for many uncertainties, especially in highly stochastic contexts such as pest control, meaningful gains in certainty may be impossible. Decision analysis procedures would thus greatly benefit from improved procedures to identify a preferable option even in a context of high residual uncertainty. So far, this initial call has usually been based on the concept of expected value of the outcome variable (Luedeling et al., 2015; Ruett et al., 2020; Wafula et al., 2018; Whitney et al., 2018), but this concept is ignorant of decision-makers' attitude towards risk, which features prominently in many decision-making processes. To add nuance to the initial evaluation on which decision option should be preferred, we ranked the strategies outcomes using stochastic dominance. Stochastic dominance describes the relationship between the decision-maker's attitude toward risks and the ranking of probabilistic outcomes using stochastic orderings.

3.2.4.1 Stochastic orderings and preferences of the decision-makers

Stochastic orderings is a concept of probability theory that refers to the probabilistic comparisons of random variables, i.e., any binary relation in a set of probability distributions. Two main stochastic orderings or comparisons are used with the aim to identify differences in a pair of probability distributions. In the first comparison, one distribution in some sense attaches more probability to larger values than the other does. If the pointwise values of one distribution are larger than the values of the other one, it means that one of the two distributions *is stochastically larger* than the other one. This ranking of magnitude of distribution functions is also called strong, classical, usual or first stochastic ordering (Muller and Stoyan, 2002; Shaked and Shanthikumar, 2007; Whitt, 2014).

A second comparison is that one distribution is more spread out or dispersed than the other. If two distributions have equal means, the distribution that is more narrowly distributed or its values are concentrated is said that it *is stochastically less variable*. This ranking of distribution dispersion is also called secondary stochastic ordering, or convex order, and it is part of the inequality properties that describe distribution functions (Muller and Stoyan, 2002; Ross, 1995; Shaked and Shanthikumar, 2007).

These stochastic orderings are associated with subjective preferences and risk attitudes of the decision maker for options with increasing expectation of beneficial outcomes (Hadar et al., 1969; Levy, 2016a, 2016b; Rothschild and Stiglitz, 1970). First, any decision-maker will prefer an action whose outcome is stochastically larger in comparison with the outcome of alternative options because everyone prefers more to less. This rule of preference of the decision maker for choices with higher stochastic magnitude is called first order stochastic dominance (FSD) (Levy, 2016a, 2016b; Rothschild and Stiglitz, 1970).

The first-order stochastic dominance does not always hold for all values of the probabilistic distribution (partial order). In this case, the choice with the outcome that provides higher mean and less dispersion is considered more beneficial (higher expectations) and less risky. An averse-risk decision maker will prefer expected outcomes of this type. This rule of preference is called second order stochastic dominance (SSD) (Levy, 2016a, 2016b; Rothschild and Stiglitz, 1970).

For the second order stochastic dominance, there is an alternative scenario. The choice with the higher mean can have a larger distribution and it is perceived as a risky option. An averse-decision risk maker does not want the heavier losses associated with a wider distribution. However, an option that provides higher benefits and higher risks is preferred by risk seekers. This preference is called inverse second order stochastic dominance (ISSD) (Aaberge et al., 2013; Spiegel et al., 2018; Wu et al., 2017).

3.2.4.2 Stochastic dominance assessment

Stochastic dominance rules are commonly represented and analyzed using cumulative distribution functions (CDFs) (Figure 3.4). We plotted the outcomes of the assessed strategies as CDFs with the aim to identify the prevailed dominance between these strategies and the implications for the risk-attitude of the decision maker.

Additionally, we note here that when distributions are derived from a Monte Carlo analysis, analysts may also consider basing their evaluation on the distribution of differences between options among the model runs rather than on separate outcome projections for each option (as in Ruett et al. 2020). This pointwise difference of binary relations between probability distributions is a numerical (monetary in our case) approximation for quantifying the magnitude of the dominance between distributions regardless of the stochastic orderings or dominance rules. Stochastic orderings (and for extension dominance rules) are partial orders that represent relations in a continuous space that at least in magnitude can be captured by our proposed pointwise difference. Additionally this assessment can facilitate the discrimination between first and second-order stochastic dominance. If during this assessment, all values are positive we have a first order stochastic dominance. Alternatively, if not all values are positive, we know that a second order stochastic dominance prevails and the CDFs representation will clarify the nature of this second-order dominance.

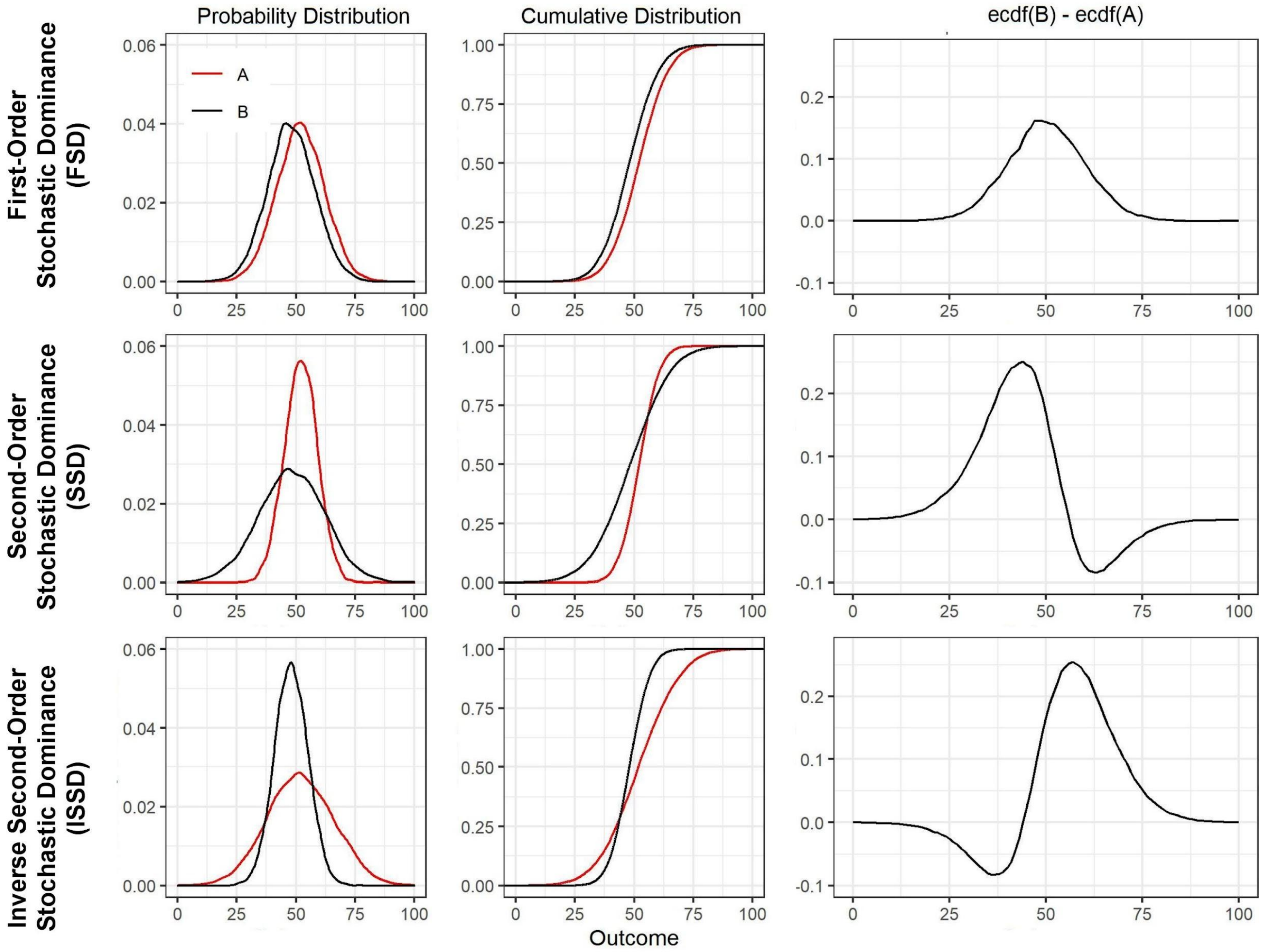


Figure 3.4. Comparing two distributions, ***A*** and ***B***, using stochastic dominance rules. In all rows, ***A*** has a higher mean than ***B***, i.e. ***A*** is the dominant option. In the first row, ***A*** is *stochastically larger* than ***B*** (FSD), and it is preferred by all decision makers (everybody wants more). In the middle row, ***A*** is less dispersed (less risky) than ***B*** (SSD), and it is preferred by averse-risk decision makers. In the third row, ***A*** is more dispersed than ***B*** (ISSD), and it is preferred by risk-seeking decision makers.

3.2.5 Software and analytical tools

Model code and analysis were implemented in the R programming language (R Core Team 2018). Monte Carlo simulations, PLS and EVPI analysis were developed with functions of the decisionSupport package (Luedeling et al. 2019). Supplementary files contain a description of R code (Supp. file8). Codes and input variables are available at https://osf.io/wv4tg/ (OSF repository: DOI 10.17605/OSF.IO/WV4TG).

3.3 Results and discussion

3.3.1 Profitability of cotton boll weevil control strategies

Model simulations revealed wide ranges of net revenues for the control options used against BW (Figure 3.5). The median net revenue of the proactive strategy was estimated at 916 thousand COP/ha with 90% confidence that the actual value lay within the range of -136 to 3436 thousand COP/ha. The chance of negative revenues for this strategy was estimated at 24%. The median net revenue of the reactive strategy was 745 thousand COP/ha with a 90% confidence range of -233 to 3090 thousand COP/ha. The chance of loss of the reactive strategy was 31%. The assessed control strategies cannot be ranked using their means and variance because of considerable overlap in revenue distributions.

For the most part of the distribution, proactive strategy revenues are stochastically larger than revenues of reactive control. The magnitude of this dominance has a media of 224 thousand COP/ha with a 90% confidence range of -100 to 808 thousand COP/ha (Figure 3.6). Simulation results were plotted as cumulative distribution functions (CDF) and the control strategies ranked using the hierarchical rules of stochastic dominance (Jiang et al., 2018; Leshno and Levy, 2004; Wu et al., 2017). Proactive control, the option with the higher mean, exhibes a wider dispersion than reactive control. In other words, proactive control dominates reactive management by ISSD, in consideration of its larger partial magnitude and wider dispersion (Figure 3.7).

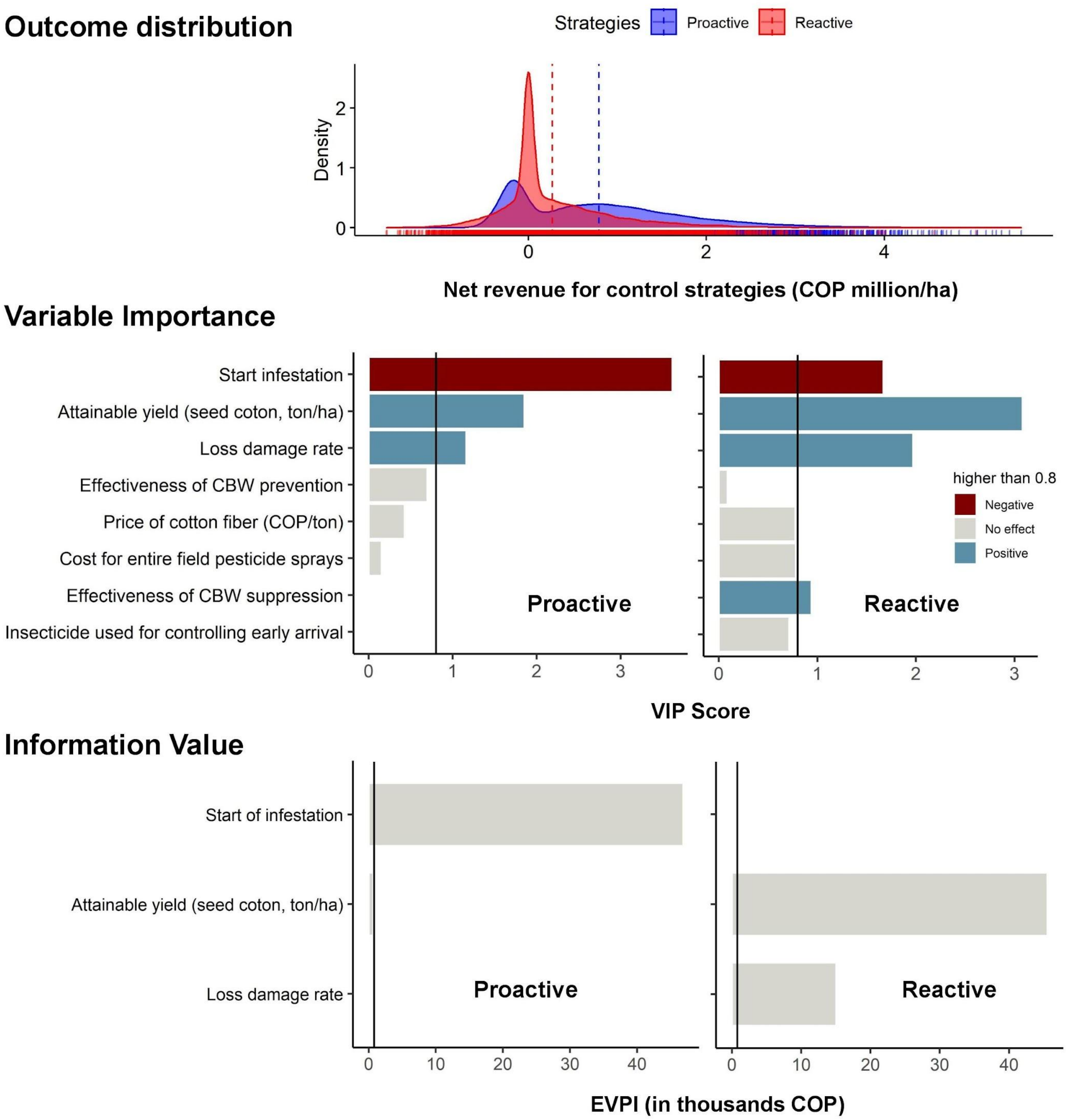


Figure 3.5. Profitability of control strategies against the Cotton Boll Weevil in the Colombian Caribbean. The panels show projected outcome distribution (first-row), important variables (determined by Projection to Latent Structures (PLS) regression; second row), and high-value variables (Expected Value of Perfect Information (EVPI); third-row). Management actions were assessed through Monte Carlo simulation based on 10,000 model runs. Vertical dashed lines the outcome distribution shows median values. In the PLS plot, blue bars indicate positive correlations of uncertain variables with the outcome variable, while dark red bars indicate negative correlations.

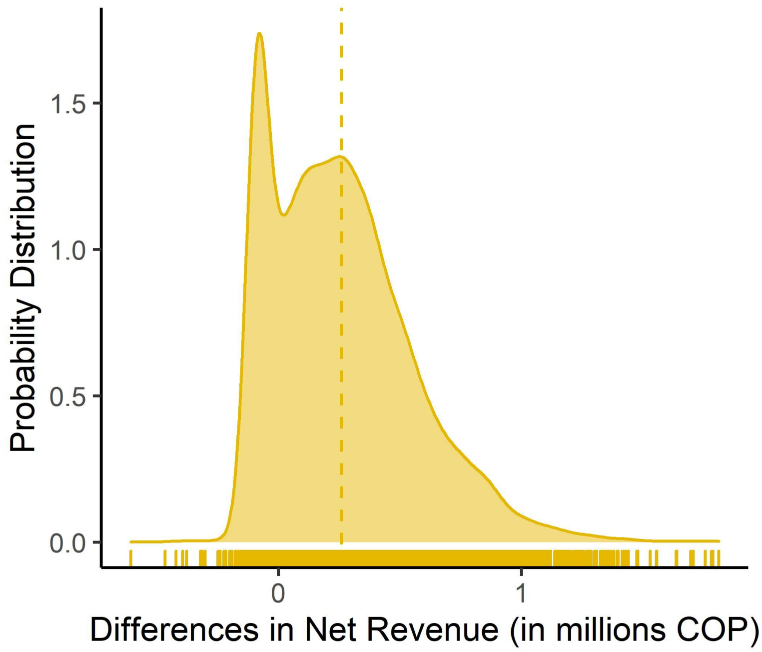


Figure 3.6. Pointwise difference in net revenues of control strategies against the Cotton Boll Weevil in the Colombian Caribbean: Proactive minus reactive values.

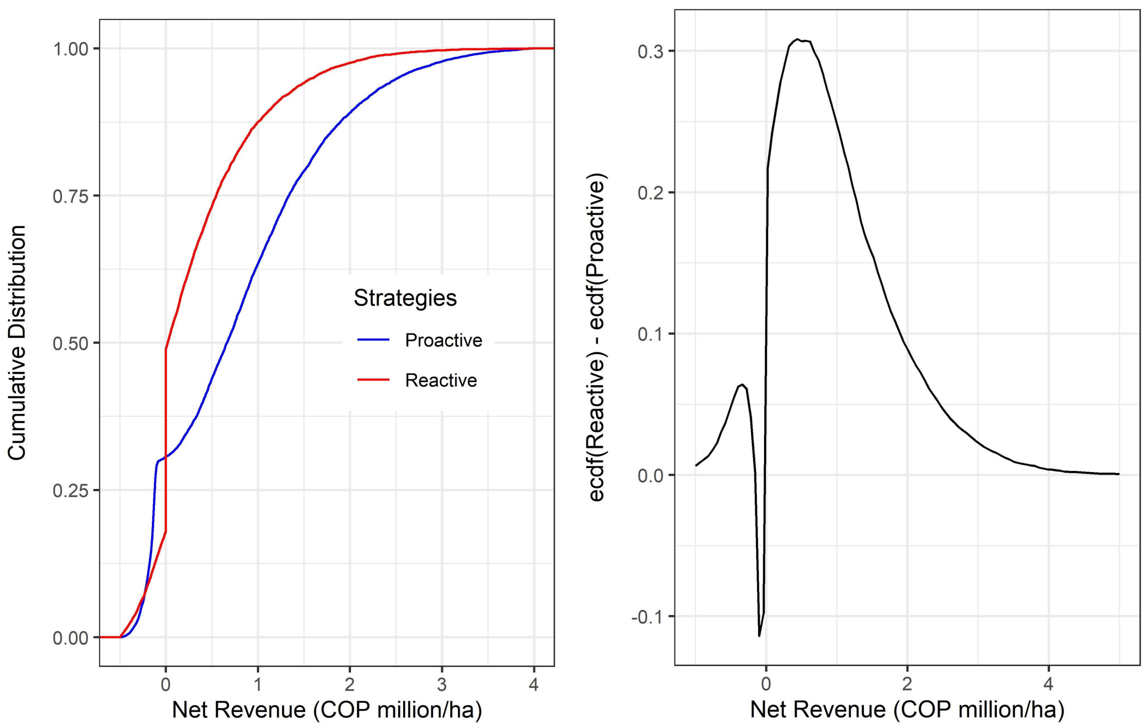


Figure 3.7. Comparison of the net revenue distributions for strategies used to control the Cotton Boll Weevil. The cumulative distributions of proactive and reactive control cross each other, indicating a lack of first stochastic dominance. Proactive management exhibits net revenue values with a higher mean and wider distribution than reactive management (inverse second-order stochastic dominance).

An alternative practical definition of dominance (or efficiency) that is used in partial budget analysis can help to clarify the advantages of the proactive over the reactive strategy. For alternative actions with similar ranges of revenue distributions, the most efficient is the one with the lower cost, because it promises similar outcomes at lower cost (CIMMYT, 1988; Perrin et al., 1983). Figure 3.8 shows the cost distribution for proactive and reactive strategies. Reactive costs have a wider distribution than proactive costs. Reactive strategy costs less than proactive control in scenarios with no or low infestation levels, where insecticides are not applied. Higher costs for the proactive strategy are expected in scenarios with large migrating BW populations. In these scenarios, crops are colonized early in the season resulting in high infestation levels that require numerous insecticide sprays for effective control. On the other hand, a proactive strategy is more effective in scenarios of large weevil populations. Insecticide sprays prevent early colonization of the crop and avoid the build-up of large weevil populations that can only occur before the cut-out (when abundant squares are available). The proactive strategy is disadvantageous when no weevil arrives early to the field and insecticides are applied without need.

Previous reports already indicated greater economic efficiency of BW proactive strategies compared with strategies based on scouting and damage thresholds (Ewig and Parencia, 1949; Mistric and Covington, 1968; Mistric and Mitchell, 1968). Scouting and damage thresholds are part of the EIL philosophy, which posits that insecticides should only be sprayed when the pest population has reached a threshold (action threshold) that is expected to cause economic losses. However, some pests, including BW, can quickly build up large populations from only a few colonizing individuals. This rapid increase in pest incidence challenges the action threshold concept. BW proactive strategies aim to avoid the colonization of the first cotton squares by female weevils via insecticide applications just before the squares are large enough to sustain developing larvae. This makes it possible to control the maximum number of adults emerging from hibernation before they can reproduce (Ewig and Parencia, 1949; Hardee and Harris, 2003; Mistric and Covington, 1968; Mistric and Mitchell, 1968). Control methods based on thresholds or monitoring allow establishment of nucleus populations that can grow rapidly, especially in warm regions such as the Colombian Caribbean, where temperature promotes fast weevil development during the entire season. Such populations can then easily reach sizes that require numerous insecticide applications.

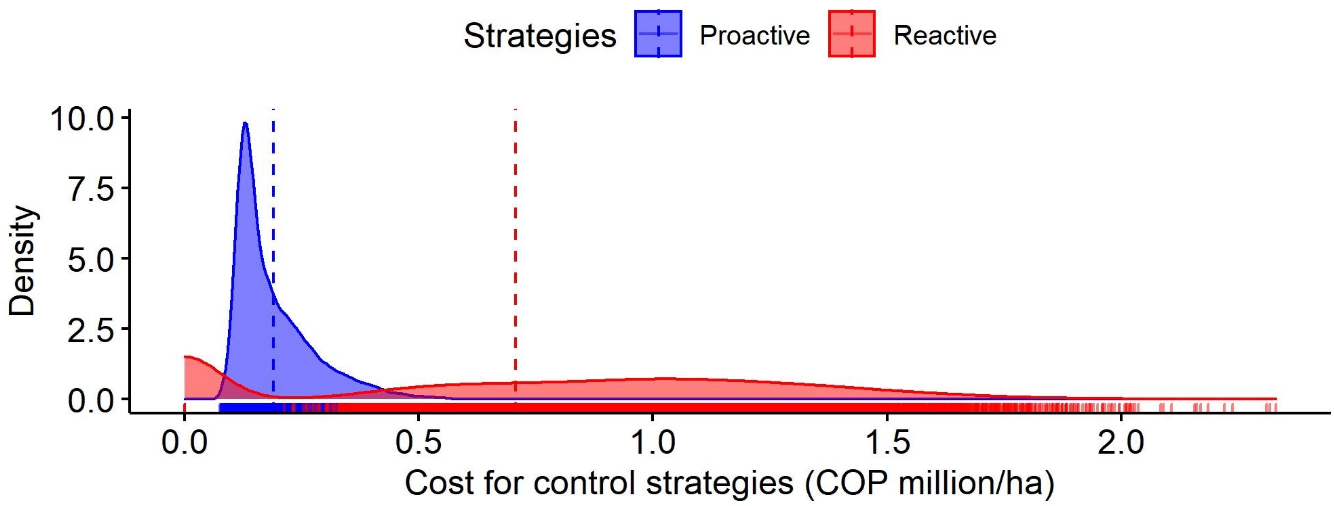


Figure 3.8. Cost distribution for the strategies used in the control of the cotton boll weevil in the Colombian Caribbean.

3.3.2 Decision-relevant uncertainties and their value of information

For both BW control strategies, VIP scores were fairly high for three variables: onset of cotton fields infestation, BW population density and cotton planting date (Figure 3.5). Infestation onset and population density are used to estimate the risk of BW colonization and the corresponding future losses. Proactive and reactive strategies use different approaches to assign values to these variables and to trigger control action against BW. Proactive strategies use prior probability distributions of the initial weevil infestation in order to forecast losses that justify scheduled application of pesticides. Reactive strategies do not use prior distributions of these variables but monitor damage in the cotton field to determine where pesticide application is justified.

proactive strategies against BW use an assumption of early arrival of the weevil to the field as rationale for calendar applications of insecticides. In the Lower Rio Grande Valley of Texas (LRGVT), before BW was eradicated, this pest was controlled by a set of proactive strategies that differed in the timing of the first spray. The standard BW proactive strategy was to apply insecticides during pinhead square formation (PHF) followed by up to 2 more applications in the following weeks. After this point, insecticide applications were triggered whenever 10% of randomly selected squares had oviposition punctures. This threshold is usually reached at the end of square production when bolls are the predominant fruiting stage (Heilman et al., 1979; Mistric and Covington, 1968; Showler and Robinson, 2005; Showler, 2004). The strategy assumed that weevils were in the field before PHF. Ambiguous field results of this strategy fostered the development of a modified control strategy (Showler, 2012, 2004). The early spraying of the alternative strategy was not triggered by the occurrence of PHF, but by the appearance of large squares (diameter of 5.5-8 mm), which was followed by continuous application at 7- to 8-d intervals while abundant large squares were still visible. This alternative strategy resulted in fewer infested squares and higher yields in comparison with spraying during the PHF phase (Showler and Robinson, 2005). The two alternative triggering signals for the start of insecticide application in the proactive strategy used in the Colombian Caribbean resemble the triggering signals used in the LRGVT.

Monitoring based on aggregation spots (as practiced in the reactive strategy in Colombia) does not appear to be practiced at all in the LRGVT or other growing regions in the US. This strategy was developed in Nicaragua and possibly introduced to Colombia in the 1980s (León Q, 1980; Lobatón Garcia, 1981). What resembles the reactive strategy used to be the "conventional" control strategy used in the Cotton Belt before the PHF sprays were introduced in the 1960s (Mistric and Mitchell, 1968). The conventional approach practiced in the Cotton Belt was based on the economic injury levels concept with an infestation rate of 10% punctured squares as the triggering point to start insecticide sprays. The conventional strategy and the reactive strategy used both monitoring for signaling the start of the insecticide sprays. The reactive strategy is informed by the detection of aggregation spots while the conventional strategy invoked a damaged squares threshold. Both strategies depend on the reliability of these detection methods and their ability to forecast future damages of economic relevance. The conventional strategy was not effectively implemented due to low adoption of scouting by farmers and economic infeasibility of monitoring by crop advisors in a region where most cotton fields were small and scattered. This failure in the implementation of monitoring in the conventional strategy resulted in heavy losses, build-up of large migrant BW populations, and numerous insecticide sprays for preventing large weevil populations from recolonize the crop (Ewig and Parencia, 1949; Mistric and Covington, 1968; Mistric and Mitchell, 1968). The conventional control strategy was also used in the Colombian Caribbean before the development of the reactive strategy. However, scouting was considered imprecise and expensive and eventually replaced by the detection of aggregation spots as the signal to start the insecticide sprays. Damage thresholds were still used to assess the effectiveness of the control of the aggregation spots and occasionally as signals for the start of entire field sprays (Bonacelly López et al., 2005).

Both strategies had non-zero EVPI for onset of field infestation, BW population density and planting date (Figure 3.5). The reactive strategy also had non-zero EVPI for rainfall variation, and effectiveness of the control strategy. Collecting additional information on the variables that have non-zero EVPI could be helpful for better determining the efficiency of the assessed strategies. We are especially interested in the promotion of the proactive strategy because it has the potential to reduce the use of synthetic insecticides. Determining the time of BW arrival to the field is important for reducing uncertainties related to this strategy. Nevertheless, consultants (as the ones assessing and developing management strategies) should not be willing to spend more than the estimated amounts (EVPI) for further investigating selected variables.

3.3.3 Probabilistic analysis

The modeling approaches we applied allowed for the incorporation of expert knowledge and elicitation of uncertainties. In this way, the model identifies and describes available options for BW pesticide-based management in the Colombian Caribbean. The uncertainties, elicited from experts for feeding the model, reflect the current state of the participants' knowledge on each pest management strategy. The model in this study presents the costs and revenues of BW management at farm-scale only. Area-wide management and other factors are also important to the wider social and ecological systems related with the control of this pest. Off-farm benefits of pest management, such as the reduction in the use of synthetic pesticides, are important from an environmental and public health perspective. They may not influence the decision-making of farmers but they are clearly of relevance, and in some cases even the motivation behind regulations that enforce certain practices, especially with regard to IPM. The results constitute a solid background for further analyses on BW control at farm-scale by assessing the effect of additional (less common or complementary) strategies carried out by farmers for BW control (Burbano-Figueroa et al., 2019). To more fully capture the current situation of BW management in the target region, assessment of the relative profitability of complementary control actions against the boll weevil, may also be needed. The holistic modeling approach demonstrated in this analysis can easily be tailored to compare other complementary farm-scale control actions and area-wide control strategies against BW.

3.4 Conclusions and recommendations

We present a standardized approach to assessing benefits of pest management strategies at farm-scale of diverse nature. We apply expert knowledge in the design and parameterization of models of costs, benefits, risks, and uncertainties of farm-scale control strategies for the cotton boll weevil. Revenue distribution of the modeled control strategies were ordered by stochastic dominance showing that under the current weevil infestation pressure, a proactive strategy is more efficient than a reactive strategy. A better understanding of uncertain factors in the proactive strategy, such as the pest infestation pressure, will facilitate its adoption. Currently, this quantification is based on a prior that assumes that the weevil will arrive early in the field in all crop seasons. This assumption results in unnecessary insecticide applications when the infestation pressure is low. Additional research should be pursued with the aim to provide a forecast tool that can eliminate this uncertainty and facilitate the adoption of a proactive strategy by all cotton farmers. The results and methods of this study promise to be useful in the assessment and design of IPM strategies.

Chapter 4

4 Crop productivity and diversification benefits in irrigated horticultural production systems

An article with the same content including Appendix C has been submitted for review to Agricultural Systems as Burbano-Figueroa, O., Sierra-Monroy, A., David-Hinestroza, A., Whitney, C., Borgemeister, C., & Luedeling, E. Crop productivity and diversification benefits in irrigated horticultural production systems.

Diversification of horticultural production systems allows farmers to cope with risks and uncertainties. Strategies aimed at raising profitability are often targeted at improving the productivity of monocultures rather than diversifying cropping systems. Horticultural production systems are often highly diversified in terms of land use and planted crops. Assessing the economic prospects of these complex systems requires quantification of productivity and related risks for individual crops as well as an assessment of the benefits from diversification. Here we demonstrate the implementation of a systematic assessment for irrigated production systems in the Sinú Valley of the Colombian Caribbean. We used participatory modeling approaches, focus group discussions and interviews to collect relevant qualitative and quantitative information from farmers. Quantitative information associated with input variables was elicited as probability distributions. Farmers were trained in estimation techniques, enabling them to provide reliable quantitative assessments of production-related variables. The model and elicited values for input variables were used to build a probabilistic simulation that allowed estimating the expected income from horticultural crops, and identifying critical risks of the irrigated production systems. Additionally we built portfolio strategies of the currently available horticultural options that can guide the farmers' decisions related to building their own suitable crop portfolio.

4.1 Introduction

Agriculture is a high-risk activity that involves complex production systems operating in environments affected by the uncertain behavior of social, economic and environmental factors (Kimura et al., 2010; OECD, 2011). Smallholder farmers in the tropics face numerous threats that often undermine their capacity for obtaining enough food and income. These challenges include frequent outbreaks of pests and diseases, extreme weather events and volatility of market prices. Farmers that depend exclusively on farm production are heavily affected by such risks, which affect their food security, nutrition, income and well-being (Harvey et al., 2014; Hertel and Rosch, 2010; McDowell and Hess, 2012; Morton, 2007; O'Brien et al., 2004).

Horticultural production systems (and other diversified agricultural systems) feature a wide range of crops. This diversity allows such production systems to cope with risks and uncertainties involved in agricultural production. Diversification is frequently promoted for many benefits related to environmental and agricultural productivity (Paut et al., 2019). However, diversification can increase system complexity due to interactions between crops, i.e. competition for resources and management effort (especially for new crop alternatives)

(Revoyron et al., 2019). Farmers and researchers must be aware of such complexity when trying to increase the productivity of these systems or trying to identify their main constraints (Figge, 2004; Paut et al., 2020).

Under a financial diversification framework, horticultural production can be seen as a problem of Modern Portfolio Theory (MPT). This theory states that owning different kinds of financial assets is less risky than just having one because in an asset portfolio, returns for each asset are additive but risks cancel each other out (Markowitz, 1959, 1952). Each crop in a horticultural production system can be considered an individual asset (an element) of a production portfolio. In a classical economic analysis, the decision to invest in each portfolio element is assessed individually based on its specific expected return and risk. If each farm or production unit is considered a physical location for a crop portfolio, the decision to invest is determined by the expected productivity (return) and risk for this portfolio or specific combination of crops rather than only for individual crops.

The distinction between the elements of the portfolio (crops) and the portfolio itself also implies a change in our perception of the decision maker, who now takes on the role of portfolio manager rather than an analyst (Figge, 2004). From the perspective of an analyst, it is important to determine the value of an asset, or in our case the productivity of a particular crop. For a portfolio manager, the decision is about which crops must be included in the portfolio to provide an expected outcome with acceptable risk. In a portfolio framework, crops that provide a lower expected benefit are attractive if they exhibit less risk.

The main aim of a portfolio strategy is to increase farmers' incomes while reducing or diversifying risks. Risks can be divided into systematic and unsystematic risks. *Systematic risks* are those that can affect all crops, for example, yield variation of different crop species in a region can be correlated when weather conditions equally affect all crops. Systematic risks can not be eliminated with the application of a portfolio strategy (Figge, 2004). *Unsystematic risks* are those risks that do not affect all crops or that are not correlated, such as the risk of crop-specific pests or diseases. This kind of risk can be reduced through a portfolio strategy. Yield is not the only source of risk for crop productivity. Sale prices of horticultural products exhibit a wide market segmentation and temporal variation related to harvest seasonality, which are unique for each crop and poorly correlated. However, market disruptions such as wars, economic recessions and global pandemics can affect sale prices for entire crop portfolios.

The development of this study was motivated by the need to support decisions at the farmer (individual) level and the institutional level. We aim to assess the risk reduction associated with crop diversification using the standard MPT framework as a case of whole-farm planning under risk. We devised an analytical framework to quantify the productivity of irrigated horticultural crops, to assess the effect of crop diversification on the risk of the production system and to provide portfolio strategies adjusted to farmer preferences. The methods presented here have scope for wider application in assessing risks involved in existing diversified systems or to project outcomes of future diversification interventions. They can guide the selection of new crops in irrigated horticultural systems and easily be extended to other regions beyond the Colombian Caribbean.

4.2 Materials and Methods

4.2.1 Description of the study area

We present the application of portfolio analysis approaches in the context of horticultural crop production in Middle Sinú Valley Colombia. The main objective of our methodology is to improve the living conditions of the local horticultural producers. The valley covers an area of 763,493 ha in the State of Córdoba, in the Colombian Caribbean. It is characterized by flat alluvial landscapes that experience periodic and recurrent events of droughts and floods. The Sinú Valley is divided from south to north into three regions named Upper, Middle, and Lower Sinú Valley. Horticultural crops are concentrated in the Middle Sinú, which includes the municipalities of Monteria, Cereté, Cíenaga de Oro, San Carlos and San Pelayo (CVS, 2019). This portion of the Valley exhibits a wet savanna climate (Aw) according to the Köppen-Geiger climate classification. Middle Sinú has the highest population density within the valley (Monteria, the state capital is located here), and the most significant horticultural production is found in the local Mocari irrigation district (MID). MID is the largest irrigation and drainage channel system of Colombia with a potential irrigation area of 43,000 ha (IGAC, 2017; MADR et al., 2006).

Horticultural crops in the Sinú Valley are grown under rainfed or irrigated conditions. Rainfed production relies on traditional and customary farming techniques and is limited to gardens or backyards of no more than 0.5 ha, usually owned by the local producer or by the producer's family. Irrigated systems require greater investment and production intensity, usually involving modern irrigation and fertilization techniques. They report higher yields than rainfed systems, and growers are more flexible in choosing planting dates, which results in greater opportunities for capturing high sale prices. The size of production units in irrigated systems is around 3 ha, much larger than on rainfed farms (Table 4.1). Around 80% of the farmers practicing irrigated horticulture are not land owners. Many hold one-year leases, with the exception of papaya growers, who often have contracts over up to 5 years. Both production systems use similar technical operations for planting, crop maintenance and management of pests and diseases. Both systems also rely on local landraces as planting material. These landraces are highly heterogeneous in terms of phenotypic traits, seed origin and quality.

The promotion of horticultural crops in the region is the responsibility of the Colombian Association for Horticultural Crops (ASOHOFRUCOL). This institution is a non-profit organization managing the resources deposited in the National Fund for Promotion of Horticultural Crops on behalf of the Colombian Ministry of Agriculture and Rural Development (MADR). In 2010 and 2011 Colombia experienced several months of extreme precipitation related to the La Niña phenomenon, resulting in floods in the Sinú Valley. These floods caused major losses, particularly in corn and cotton, which mainly affected smallholder farmers. ASOHOFRUCOL perceived this crisis as an opportunity for promoting horticultural crops in the region. As a response, they began incentivizing farmers to diversify their crop portfolios. They also made membership in farmer associations a prerequisite for access to benefits offered by MADR. In this setting, the horticultural farmers association of the Sinu valley (HORTYFRU) was founded in 2012 with 36 founder members. The association has received support for strengthening its technical capabilities mainly from the Colombian Corporation for Agricultural Research (AGROSAVIA). These interventions have helped farmers overcome low profits and losses (David Hinestroza, 2020). However, farmers still face uncertainties related to production costs, yield-reducing factors and sale prices.

A varied array of agricultural systems thrive in the diverse Colombian landscapes. AGROSAVIA addresses this heterogeneity through the organizational concept of 'Innovation Networks' (IN). INs are nationwide teams of researchers associated with specific production systems. Horticultural crops are the main focus of the IN for horticultural and aromatic crops. These INs are challenged by the complexity of prioritizing research gaps and developing interventions for diversified production systems with very limited resources available for research and innovation. Currently, the IN for vegetable and aromatic crops lacks support for assessing new cultivars and promoting their adoption.

4.2.2 Model development

We developed a decision model at whole-farm scale that is able to estimate benefits, risks and uncertainties of diversified production systems. The model was built using a three-step strategy: Conceptual modeling of whole-farm planning and operation, a probabilistic model to estimate the productivity of individual crops at plot scale in a multi-year operation, and a portfolio analysis to assess and identify diversification strategies that suit farmers' risk-preferences (Figure 4.1). The model development process was framed as a participatory approach. This approach allows us to capture all main factors (physical and economic) affecting the performance of irrigated horticultural production in the Sinú Valley.

4.2.3 Knowledge gathering and elicitation

The data used in this study were elicited from five focus group discussions and additional semi-structured interviews conducted with members of the farmers' association HORTIFRU-Cereté. Additional information was collected from technical reports and journal articles. Twelve farmers were involved as the core group of experts, providing inputs and feedback and validating outputs for each of the model development stages (Figure 4.1).

During the development of the conceptual model (first stage) experts provided qualitative descriptions of the current understanding of whole-farm planning and operation, market constraints that define the production system, and the crops that are grown. Graphical representations of the system were validated by the experts.

At the second stage of model development, experts provided quantitative approximations of all model variables covering specified costs, benefits and risks for whole-farm planning and operation, as well as for the production of specific crops. We elicited this information after experts were subjected to calibration training. Training consisted of increasing awareness of concepts of probability and instruction in techniques to produce accurate estimates of confidence intervals for unknown variables, which reflect the estimator's level of uncertainty (Hubbard and Millar, 2014; Hubbard, 2010; Hubbard Decision Research, 2015; Luedeling and De Leeuw, 2014; Luedeling et al., 2015, 2014; Yigzaw et al., 2019). The resulting subjective probability distributions represent uncertainty explicitly as probabilities of events or states of nature (the states of the decision maker's world) (Anderson et al., 1977). Crop productivity models and inputs were additionally validated by two crop advisors, and drafts of the findings were shared with researchers at AGROSAVIA for additional feedback.

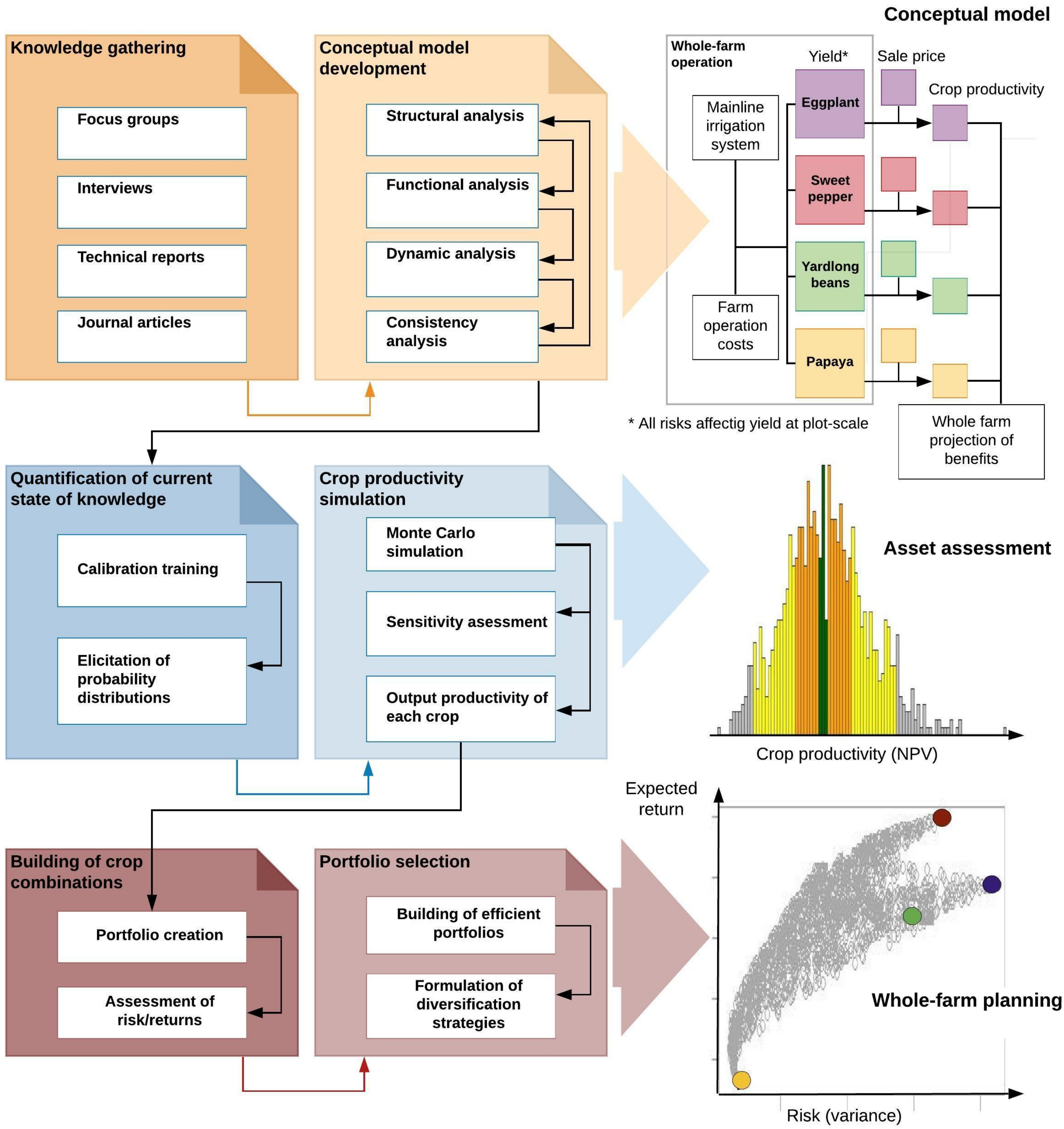


Figure 4.1. Model development process to study whole-farm planning under risk and the benefits of crop diversification. This decision analysis includes three main stages: conceptual modeling (yellow boxes) asset-based risk analysis (blue boxes), and portfolio risk analysis (red boxes). The first stage provides a qualitative description of the current understanding of system processes and functions. The second and third stages are quantitative assessments. The second stage aims to assess the productivity of each crop (assets) while the third stage measures the benefits of diversification and provides strategies for reducing risk at the whole-farm scale.

At the final stage, experts assessed the technical and economic feasibility of crop combinations and suggested crop combinations that fitted their own preferences. We use these preferences and the MPT framework to formalize diversification strategies aimed to reduce risk at the whole-farm scale.

4.2.4 Conceptual modeling

The irrigated horticultural production systems of the Sinu Valley (IHPSs-SV) are intensive market-oriented farms, with crop sales constituting the main source of household income. We built a conceptual model by explicitly identifying all important factors and relationships affecting the production systems, as well as variables associated with the operation of the farm or with the production of specific crops (plot scale) (Figure 4.2) (Lamanda et al. 2012). This framework combined the farmers' understanding of the system with disciplinary and theoretical knowledge held by researchers or contained in technical documents. The conceptual model development included the following steps:

(i) structural analysis to identify the boundaries of the system, sub-systems, components, factors affecting the system and indicators for assessing system performance.

(ii) functional analysis to identify the relationships between the components of the system, influencing factors and performance indicators.

(iii) dynamic analysis to describe how the system, sub-systems, and main components behave over time and to check if the structural and functional representations of the conceptual model are able to represent system dynamics.

(iv) consistency analysis to ensure that the conceptual model as a knowledge representation corresponds to reality. This last step is an iterative process applied regularly during the first three steps with the participation of experts.

Variables provided by stakeholders were organized into those belonging to the financial, technical and biological subsystems.

Farmers reported that crop yields are not affected by rainfall variations but several pests and diseases are responsible for considerable yield losses (Table 4.2). The exploitable potential yield was estimated as the upper quartile of the reported yield distributions. From this value, losses related with pests and diseases were discounted and weighted with the reported effectiveness of control strategies. The resulting yield distribution resembles the yield ranges reported by the farmers and is considered the actual yield. Losses were estimated as continuous distributions of risk probability (frequency) and risk magnitude (percentage yield loss) of pests and diseases for each crop, using farmers as key experts. Risk magnitudes were estimated as the perceived losses from the potential yield estimates. Farmers involved with this research reached consensus over the highest yield that is possible and considered biological constraints (pests and diseases) as the main causes of the observed variation.

Costs were assigned to two spatial scales:

Farm or production unit costs are mainly fixed costs incurred during the operation of the farm, which are not directly related to crop production. They include investment costs related to the irrigation mainline system, expenses for its maintenance, payments for water rights (MID) and land leasing.

Crop production costs are directly related to crop production and mainly variable costs. They were estimated as aggregate values of hired labour, costs related to land preparation, plant material (seed and seedling production), pest management (insects, diseases and weeds), fertilization, harvesting and energy (diesel pumps). Costs related to the irrigation zones were also included here, because they varied between crops, since the irrigation zone layout is adjusted to the density crop.

Crop sale prices were estimated as the monthly values in the high and low seasons for each crop and an estimate of how much of the harvested product can be sold during the high-price season.

Table 4.1. Description of the irrigated horticultural production systems of the Sinú Valley (IHPS-SV).

<table>
<tr><th>System components</th><th colspan="4">Description</th></tr>
<tr><td>Production unit</td><td colspan="4">The standard irrigation system serves an area of 3 hectares divided into 0.5-hectare plots. For each plot, specific arrays of irrigation lines are established according to the plant density and water requirements of the crop (irrigation zones). The irrigation mainline system is maintained annually, which we considered as a cost associated with the whole-farm operation. We discounted costs and revenues related to each crop based on the length of the production cycle.</td></tr>
<tr><td rowspan="7">Sub-systems</td><td>Crop option</td><td>Scientific name</td><td>Local designation</td><td>Description of plant material*</td></tr>
<tr><td>Eggplant</td><td>Solanum melongena</td><td>Berenjena</td><td>Varieties obtained by mass selection from farmers' landraces have been released (Cadena et al., 2011), but landraces still dominate the planting material landscape. Landraces exhibit a wide variation of phenotypic traits (yield, fruit quality and pest resistance) (Cadena Torres et al., 2011)</td></tr>
<tr><td rowspan="3">Sweet pepper</td><td>Non-pungent Annuum pepper species**</td><td>Aji dulce</td><td rowspan="3">Cultivars of two sweet pepper species are cultivated in the Caribbean, and they collectively are called “aji topito” and “aji chino”. Landraces of C. chinense are most commonly cultivated (Correa et al., 2019).</td></tr>
<tr><td>Capsicum chinense</td><td>Aji topito</td></tr>
<tr><td>Capsicum annuum</td><td>Aji chino</td></tr>
<tr><td>Papaya</td><td>Carica papaya</td><td>Papaya</td><td>The varieties Hawaiana, Tainung, and Maradol are available in the region. Tainung is the most widely planted cultivar.</td></tr>
<tr><td>Yardlong beans</td><td>Vigna unguiculata subsp. sesquipedalis</td><td>Habichuela larga</td><td>No particular varieties are reported and currently no germplasm collections or breeding programs are in development. No landraces are distinguished*** .</td></tr>
</table>

* Cultivar is used here as a general classification of plant populations used by farmers or growers. Landrace is used for designating plant populations bred (mass selection) and propagated by the farmers but not formally registered. Variety is used to designate registered cultivars that under the Colombian regulation must show as a population a stable common set of phenotypic traits.

** *C. chinense* and *C. annuum* are part of the *C. annuum* complex or Annuum Group (Tripodi, 2019). The term ‘sweet peppers’ is commonly used in American English for designating non-pungent cultivars of *C. annuum* that are not bell pepper cultivars (Grossum cultivar group). In the Caribbean and South America, a broad definition is used that includes non-pungent cultivars of the Annuum Group.

*** Yardlong beans are widely distributed in the US Southeast and the Caribbean. They were introduced from Southwest Asia during the Columbian exchange and by Chinese workers during the transcontinental railroad construction (Herniter et al., 2020; Perrino et al., 2008).

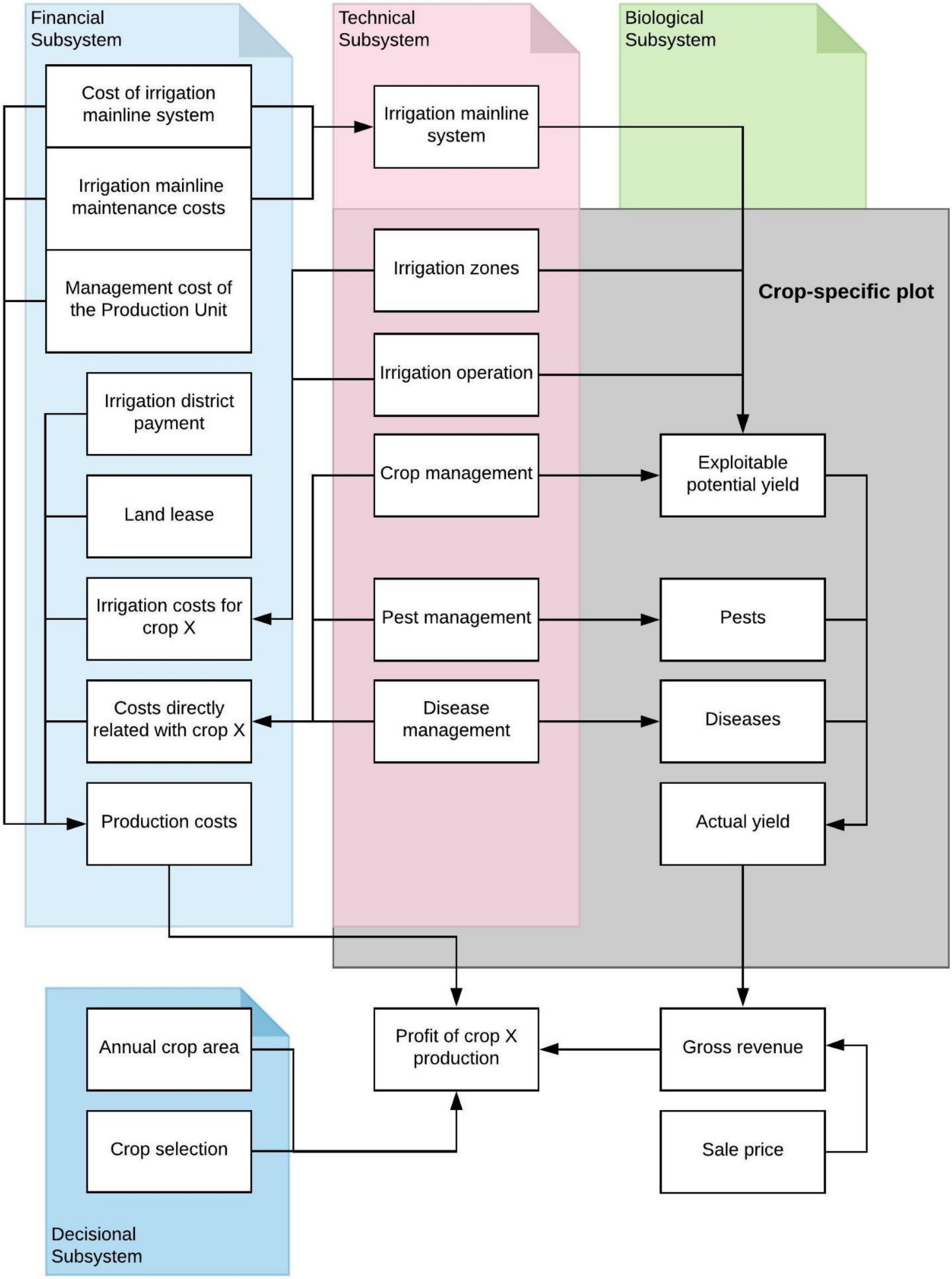

Financial Subsystem
Technical Subsystem
Biological Subsystem
Cost of irrigation mainline system
Irrigation mainline maintenance costs
Management cost of the Production Unit
Irrigation district payment
Land lease
Irrigation costs for crop X
Costs directly related with crop X
Production costs
Irrigation mainline system
Irrigation zones
Irrigation operation
Crop management
Pest management
Disease management
Crop-specific plot
Exploitable potential yield
Pests
Diseases
Actual yield
Annual crop area
Crop selection
Decisional Subsystem
Profit of crop X production
Gross revenue
Sale price

Figure 4.2. Conceptual model for assessing crop productivity in the irrigated horticultural production systems of the Sinú Valley. Crop options are eggplant, sweet pepper, yardlong beans and papaya. The model also included technical elements and costs related to the operation of the whole farm or the irrigation field, which are discounted based on the gross revenue in proportion to the duration of the production cycle.

Table 4.2. The main biological yield-reducing factors for the crops incorporated in the irrigated horticultural production systems of the Sinú Valley.

Yield reducing factors	
Eggplant diseases and pests	
Fruit rot	A common disease during the rainy season that caused damage before and after harvest (stored fruits). Experimental evidence suggests that the causal agent is Phytophthora.
Wilt pathogens	Decline and death are very common in the rainy season. These are associated with bacterial and fungal pathogens: Ralstonia, Phytophthora, and Fusarium are the reported pathogens, with Ralstonia the most limiting one.
Bean-spider mites	*Tetranychus ludeni* is the main pest of eggplant in the region. Local eggplant landraces exhibit field resistance against this pest.
Sweet pepper diseases and pests	
Damping-off	Collapse and death of pepper plants associated with soil-borne pathogens. Severity increases when fields become flooded.
Leafroll chlorosis	Unknown cause. Symptoms suggest infection by virus.
Broad mites	*Poliphagotarsonemus spp*. (Acaro blanco) is a ubiquitous pest attacking crops the entire year.
Yardlong bean diseases and pests	
Leaf rust	Unidentified pathogen, probably a species of the genus Uromyces.
Root rot	*Fusarium, Sclerotium and Pythium*
Leafhoppers	*Empoasca sp* (Lorito verde) reduces the crop season by up to 2 months. This pest is possibly associated with transmission of a virus that causes chlorosis and leaf curling.
Weevils	Unidentified pest causing flower bud damage, flower losses and black spots on beans, which make them unmarketable.
Papaya diseases and pests	
Anthracnose	Constant fruit damage throughout the year, with greater impact during the rainy season.
Variola	Black spot disease of papaya caused by Asperisporium caricae
Leafhoppers	*Empoasca papayae* causes defoliation and yield loss through leaf area loss and transmission of the bunchy top disease

4.2.5 Crop productivity simulation

We rewrote the resulting conceptual model as a set of equations outlining the major relationships that determine the productivity of each individual crop. This mathematical model reflects the best available understanding of the system, combining experience and expertise of the model development team (analysts) and the experts. We coded this mathematical model as a function in the R programming language (R Core Team, 2018) using the decisionSupport package (Luedeling et al., 2020). All formulas and scripts are available in Supp. file9. The model was parameterized with the elicited probability distributions and ran 10,000 times as a probabilistic Monte Carlo simulation. Each run provided one possible outcome. The totality of all model runs generated a probability distribution that illustrates the plausible outcomes given the experts' current state of uncertainty (Luedeling et al., 2020).

Crop productivity models were used to quantify the annual economic outcome for each crop by calculating the Net Present Value (NPV) and cash flow over a 5-year period. This time period is commonly used in the region for accounting depreciation of the irrigation system. Crop productivity was estimated on the basis of planting one hectare per year. NPV and crop productivity were plotted as cumulative distribution function (Supp. file10).

We applied Projection to Latent Structures (PLS) regression as a sensitivity analysis to identify critical uncertain input variables that were strongly related to variation in the NPV (Luedeling and Gassner, 2012). The most sensitive variables were selected based on the variable importance in the projection (VIP). The VIP score measures the influence of an individual input variable on the NPV (outcome) of the crop options. Variables with a VIP score above 0.8 were considered as influential variables. For these variables, we also determined whether they had a positive or negative influence on project outcomes.

4.2.6 Designing efficient crop combinations

4.2.6.1 Diversified agricultural systems as a case of Modern Portfolio Theory

We applied the Modern Portfolio Theory (Markowitz, 1959, 1952) framework to assess diversification in agricultural settings. MPT is a systematic method of minimizing risk for given levels of expected revenues for different financial assets. For the case of a diversified agricultural system, each individual crop behaves like a financial asset, and risks are represented by the uncertainty related with outbreaks of pests and diseases and environmental factors affecting yield, as well as sudden variation in market prices. All these uncertainties were previously captured by our probabilistic crop productivity models. We use MPT for providing a global assessment of how these risks affect productivity at the whole-farm scale and how optimal combinations of crops (based on land allocation) can decrease risk.

In this framework, we considered that the goal of a farmer is to plant an optimal combination of crops for a specific irrigated land area X, being only limited by access to financial resources and market, with irrigation limiting the effect of environmental factors (in the tropics the main source of environmental variation is rainfall). In this setting, x_i is the variable describing the farmer planting decision associated with each crop. This decision value is the proportion of $i$area per year that is planted with crop , relative to the total planted area, where $i = 1,, n,$ and

$$. \sum_i x_i = X$$

The expected economic return of a portfolio with two or more crops (assets), R_p is the resulting sum across the expected economic returns for all crops, r_i, weighted by the land proportion assigned to each crop, x_i.

$$R_p = \sum_i x_i * r_i.$$

with r_i as the annuities for each crop or land use option.

The risk (standard deviation) of economic returns for each crop combination (portfolio), σ_p, was quantified as:

$$\sigma_p = \sum_i \sum_j x_i * x_i * \rho_{i.j} * s_i * s_i$$

where i and j are the indices for each crop option; x_i is the proportion of land occupied by a specific crop; s_i is the standard deviation of economic returns for each crop option; and $\rho_{i.j}$ is the coefficient of correlation between the economic returns for crop options i and j. Diversification benefits decrease (higher risk) when the crop productivities used in each combination are correlated ($\rho_{i.j} = 1$).

4.2.6.2 Portfolio creation and risk-return assessment

For the development of the MPT model, we calculated an efficient portfolio of horticultural crops using mean values and variances of productivity estimates for each crop. Productivity was calculated as annuities from the resulting NPV values returned by the crop productivity model.

We defined the efficient frontier of the portfolios as the maximum mean economic revenue for a given level of risk (variance) of crop combinations. The optimal portfolio is defined as the one that maximizes economic revenue while featuring low risk. We simulated crop productivity values and risks for 10,000 possible portfolios of crop combinations. All portfolio calculations were implemented in the R environment (R Core Team, 2018) using the PortfolioAnalytics package (Peterson et al., 2015). Related portfolio figures were also obtained with this package (Supp. file11).

4.3 Results and discussion

4.3.1 Profitability of single-crop options

Model simulation outcomes of the crop options were plotted as cumulative distribution functions (CDF) of economic return over a 5-year period (NPV) and as multi-factor productivity (MFP). A wide variation of expected return values was observed for the crop options, while a narrow range of possible values was observed for their multi-factor productivity (Figure 4.3). Yardlong beans were the least profitable option on an acreage basis, whereas all other crops appeared similarly profitable based on means and confidence intervals of annuities (Table 4.3). Among these three crops, sweet pepper is the most favorable option based on its dominance over the other crops (better outcomes for most parts of the distribution curve) while papaya appeared like the least efficient option (Figure 4.3, Bottom panel).

In terms of productivity, MFP values of the crop options range from 0.5 to 3, with sweet pepper being the most favourable option based on dominance (Figure 4.3, Right panel). For all crops, MFP values showed rather similar distributions, whereas economic returns on an acreage basis (partial factor productivity) exhibited considerable differences between yardlong beans and the other crop options. This discrepancy is related with the resulting intensification of irrigated systems. In intensive agricultural systems, crop productivity is not strongly dependent on land but also on additional inputs such as capital, labour and services (Echevarria, 1998; Fuglie and Rada, 2013; Fuglie et al., 2016). Under local conditions in the study area, comparisons of crop productivity on an acreage basis differ from those based on the total account of all inputs. Yardlong beans are the option that requires the lowest investment per hectare, but their rate of return to inputs is comparable to the other crops.

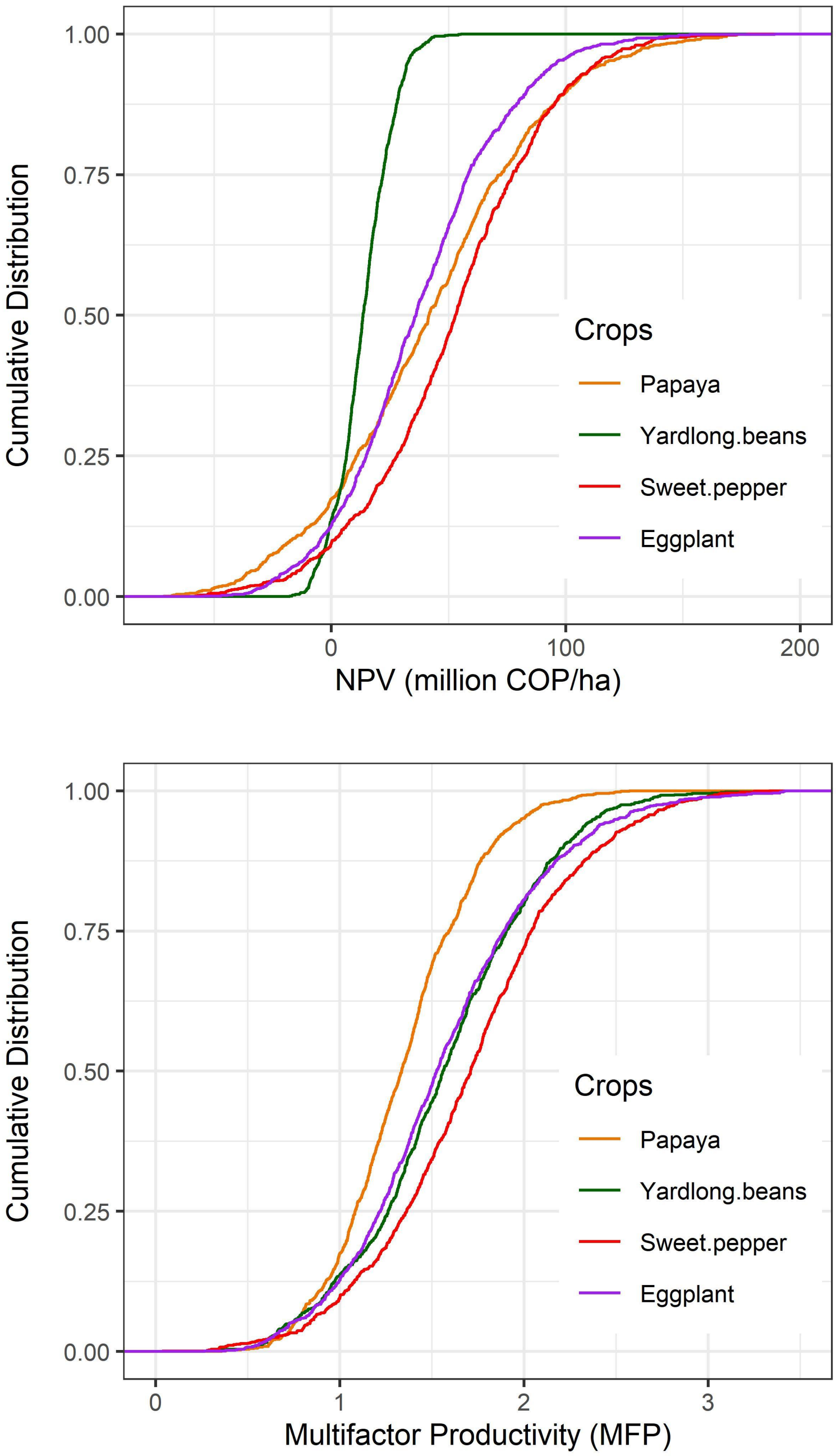


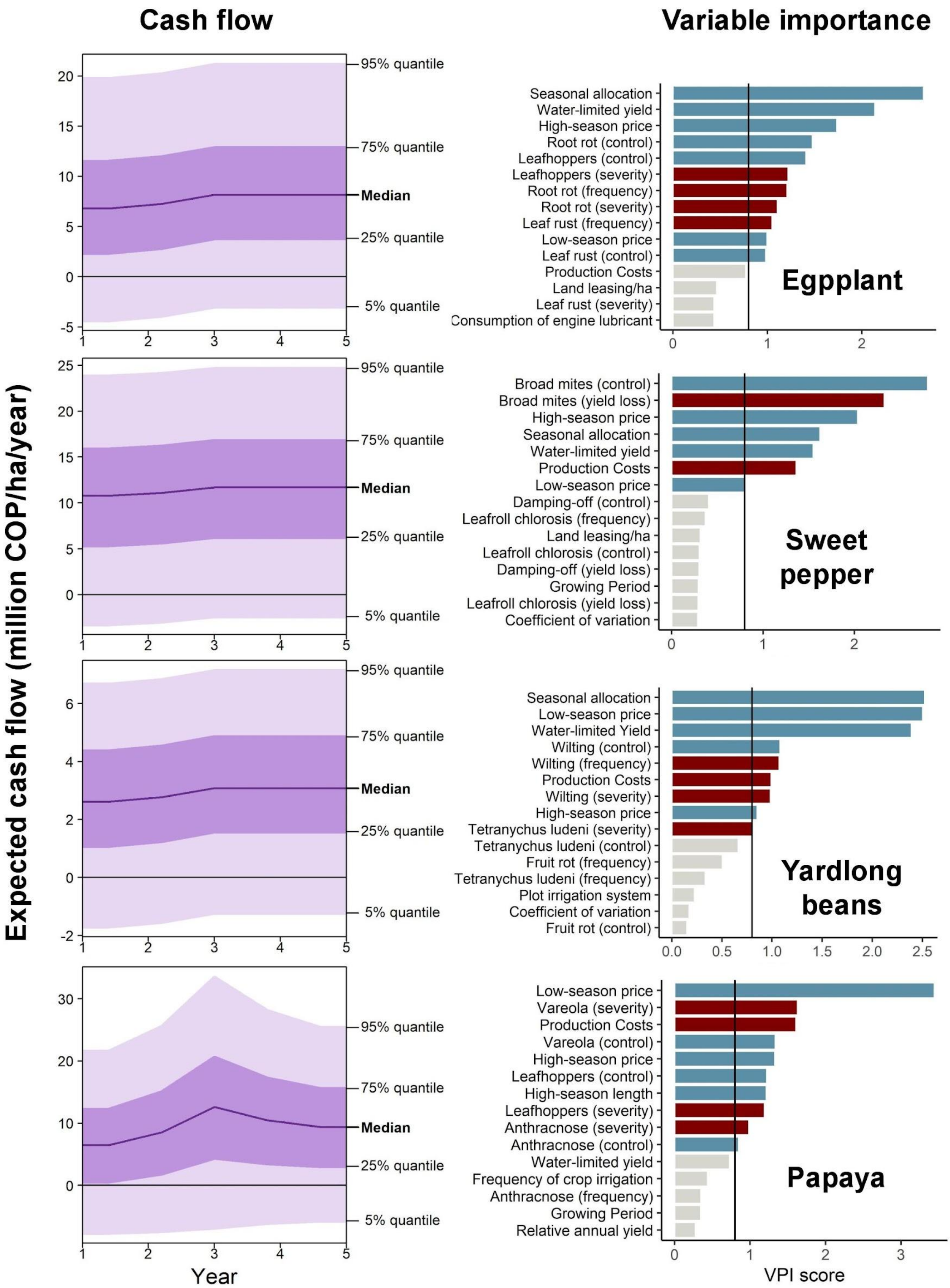
Figure 4.3. Model results for crops of the irrigated horticultural production system of the Sinú Valley, Córdoba, Colombia. Results were produced through Monte Carlo simulation (with 10,000 model runs) with a time horizon of five years. **Top panel:** Projected economic returns for each crop, expressed as net present value (NPV) in Colombian pesos (COP).Bottom panel: **Multifactor Productivity,** i.e. the ratio of expected gross revenues to all production costs.

Table 4.3. Description of projected annual returns for crops used in the irrigated horticultural production systems of the Sinú Valley, Córdoba, Colombia.

Single-crop options	Annual return (million COP/ha)				CV(%)
	Mean	95% confidence interval		SD	
Sweet pepper	11.95	-2.99	26.26	8.91	74.5
Papaya	9.76	-7.28	27	10.42	106.74
Eggplant	8.75	-4.07	22.18	7.96	90.99
Yardlong beans	3.19	-1.57	7.52	2.74	85.87

4.3.2 Sensitive variables

PLS regression analysis identified several variables that strongly influenced the projected net present value (NPV) of each crop (Figure 4.4). VIP scores revealed that the crop profit distribution was negatively influenced by yield-reducing factors and, with the exception of yardlong beans, by production costs. Monthly prices, seasonal product allocation, control of pests and diseases, and potential yield were the most uncertain variables that were positively associated with crop productivity. Yield-related variables alone did not account for the entire projected variation in productivity and justify our pursuit of assessing diversification in horticultural systems using a holistic approach to measure productivity. Previous reports have stated that crop productivity in the tropics is undermined by frequent outbreaks of pests and diseases, extreme weather events and high volatility of market prices (Harvey et al., 2014; Hertel and Rosch, 2010; McDowell and Hess, 2012; Morton, 2007; O'Brien et al., 2004).



Cash flow
Variable importance
Expected cash flow (million COP/ha/year)
95% quantile
75% quantile
Median
25% quantile
5% quantile
Year
Egpplant
Seasonal allocation
Water-limited yield
High-season price
Root rot (control)
Leafhoppers (control)
Leafhoppers (severity)
Root rot (frequency)
Root rot (severity)
Leaf rust (frequency)
Low-season price
Leaf rust (control)
Production Costs
Land leasing/ha
Leaf rust (severity)
Consumption of engine lubricant
Sweet pepper
Broad mites (control)
Broad mites (yield loss)
High-season price
Seasonal allocation
Water-limited yield
Production Costs
Low-season price
Damping-off (control)
Leafroll chlorosis (frequency)
Land leasing/ha
Leafroll chlorosis (control)
Damping-off (yield loss)
Growing Period
Leafroll chlorosis (yield loss)
Coefficient of variation
Yardlong beans
Seasonal allocation
Low-season price
Water-limited Yield
Wilting (control)
Wilting (frequency)
Production Costs
Wilting (severity)
High-season price
Tetranychus ludeni (severity)
Tetranychus ludeni (control)
Fruit rot (frequency)
Tetranychus ludeni (frequency)
Plot irrigation system
Coefficient of variation
Fruit rot (control)
Papaya
Low-season price
Vareola (severity)
Production Costs
Vareola (control)
High-season price
Leafhoppers (control)
High-season length
Leafhoppers (severity)
Anthracnose (severity)
Anthracnose (control)
Water-limited yield
Frequency of crop irrigation
Anthracnose (frequency)
Growing Period
Relative annual yield
VPI score

Figure 4.4. Model results for eggplant production in the irrigated horticultural production systems of the Sinú Valley, Córdoba, Colombia. Results were produced through Monte Carlo simulation (with 10,000 model runs) with a time horizon of five years. **Cash flow:** distribution of modeled annual net cash flow over a time horizon of 5 years (left). **Variable Importance:** The most important variables (determined by PLS regression; right) are shown (VIP>0.8; black vertical line), with correlations of variables with crop profitability characterized as positive (blue), negative (red) or unimportant (gray).

4.3.3 Probabilistic analysis of crop productivity

The implementation of our probabilistic model for the estimation of crop productivity allows overcoming the previously described limitations of data availability for horticultural crops that have often required conceiving risk as an exclusive function of yield (Paut et al., 2019). In our study, farmers were subjected to calibration training, which raised their capability to serve as experts who can provide estimates of quantitative inputs for the crop productivity model. The crops and their cultivars (landraces) included in this study have limited distribution and market presence and are substantially under-researched. Data describing these crops is scarce and funding for research is limited. Using farmers as knowledge providers is a feasible cost-effective option for collecting data and developing models that can be used to assess risk and uncertainties and develop effective interventions. We must highlight the importance of considering economic benefits and their variability when developing horticultural crop portfolios, which arises from the high price volatility related with fresh products and the major significance of risk and uncertainty in horticultural production.

4.3.4 Building horticultural crop portfolios

The optimal diversified portfolio selected among all combinations of crop options assessed in this study obtained a risk of 5.75 standard deviations (SD) and an expected income of COP 10.5 million. This risk level is two times greater than the risk of the single option with the lowest value (yardlong beans with an SD of ± 2.74), but lower than the risk of the other options alone (Figure 4.5).

A portfolio with all 4 options was not considered suitable by the core group of experts. All farmers considered eggplant and sweet peppers attractive crop options but experts were divided regarding yardlong beans and papayas. Farmers with limited access to financial resources preferred yardlong beans because of low establishment costs and short vegetative periods (3 months), which allow them to generate income and revenues that can be invested in eggplants and sweet pepper. However, there are drawbacks for yardlong beans as they require more managerial attention and labor input, without concurrent prospects of high returns. On the other hand, as establishment and production costs for papaya are higher, only farmers with some level of financial security are able to incorporate papaya as a crop option. Papaya trees are planted with the purpose of having a constant source of income throughout the year and the prospect of larger acreages as the market for papaya is not locally constrained.

For serving the goals of farmers with different crop preferences, we calculated additional portfolio combinations. Portfolio option 1 is adjusted to suit farmers with limited means and resources who favor the production of yardlong beans. Combinations for portfolio option 1 that accomplish the purpose of maximizing returns while decreasing risk are 0% yardlong beans, 58% sweet pepper and 42% eggplant. The low returns of yardlong beans drive the MPT algorithm to its exclusion from the optimal portfolio. However, it is possible to build portfolio combinations over the efficient frontier that include yardlong beans. Figure 4.6 illustrates these crop combinations over the efficient frontier, with yardlong beans dominating among the combinations with the lowest level of risk (SD) and economic return. We do not think of Portfolio 1 as a fixed strategy but a dynamic one that can be adjusted for the availability of resources (as well as for farmers' risk preferences). This consideration resembles the practical decision rule of the farmers planting yardlong beans as a way to build capital for planting eggplants or sweet peppers. Portfolio option 2 includes papayas and addresses the interests of farmers with substantial resources. For these farmers, with the current information, the best strategy is to plant equal acreages of the three crops.

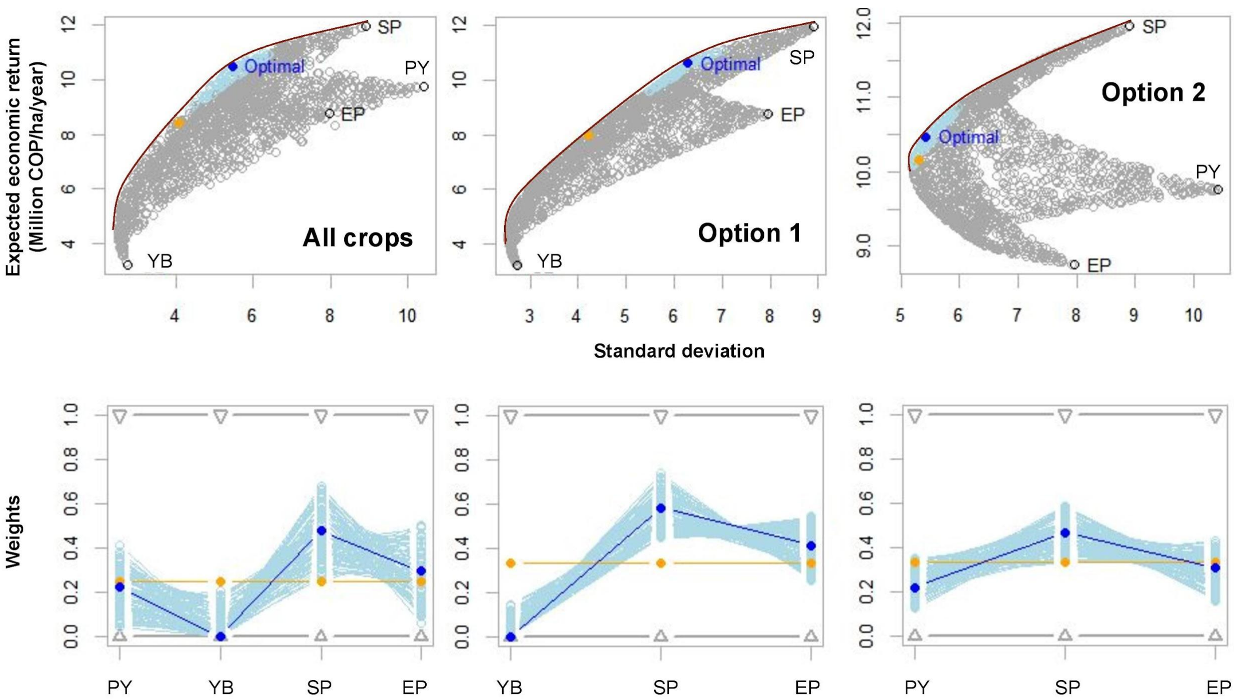


Figure 4.5. Risk-return combinations (upper panels) and structured land composition for the optimal portfolio (lower panels) for portfolio strategies designed for the irrigated horticultural production systems of the Sinú Valley, Córdoba, Colombia. The crops included are eggplants (EP), sweet pepper (SP), papaya (PY), and yardlong beans (YB). The 'All crops' portfolio includes all 4 crops. However, farmers have divergent preferences for yardlong beans and papaya. Options 1 and 2 represent portfolios that accommodate these preferences. Option 1 is a portfolio strategy for farmers who prefer yardlong beans and have limited resources (which exclude adopting papaya). Option 2 is a portfolio for farmers who are willing and able to include papaya in their farms. The dark blue dot describes the optimal portfolio that accomplishes the goals of maximizing returns at the lowest risk. The light blue aggregation around this point described 100 neighboring points adjacent to the optimal combination. In the lower panel, these neighboring points are represented as lines. Yellow dots and lines represent equal-area combinations of all crops.

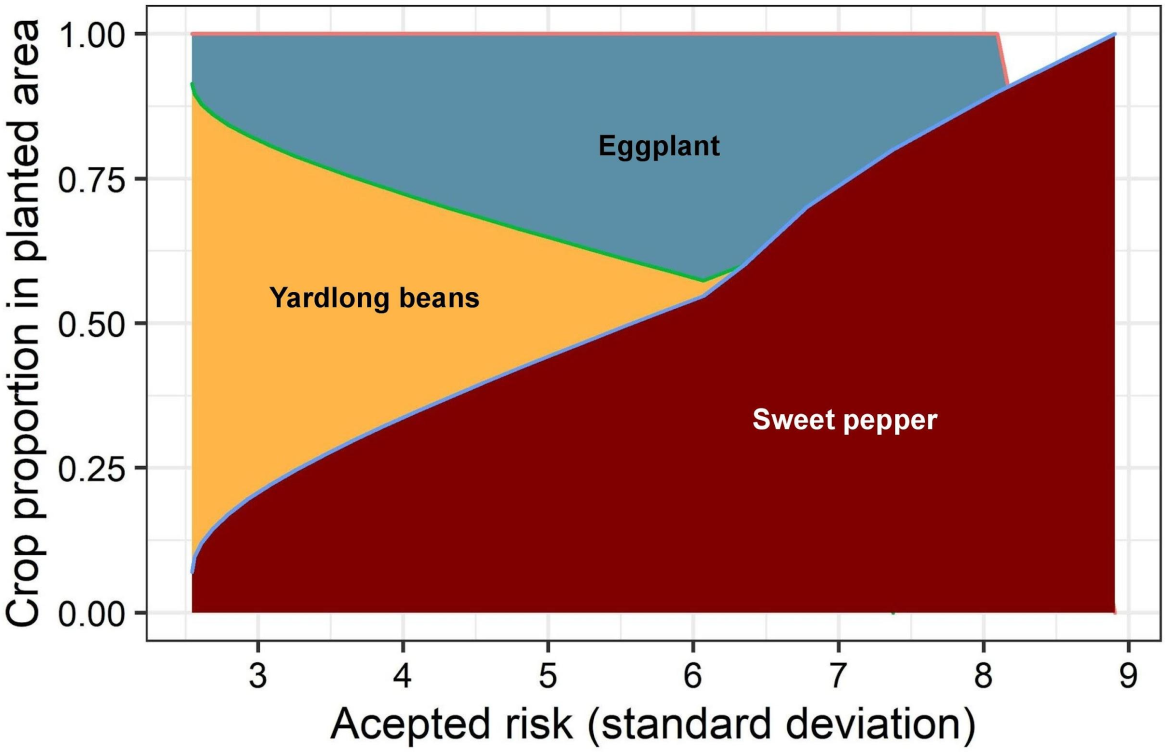


Figure 4.6. Structural land composition of the efficient frontier for a strategic portfolio option of crops with contrasting levels of risk. Crop combinations are based on yardlong beans, eggplant, and sweet pepper. This portfolio strategy describes the replacement of yardlong bean acreage in favor of crops with higher expected economic returns as the farmer gets access to more resources or is willing to accept higher levels of risk.

4.3.5 Whole-farm planning and diversification under uncertainty

We presented an approach for assessing diversification benefits in horticultural production systems using MPT as a framework. This whole-farm decision analysis introduced the dual-objective strategy of maximizing returns and decreasing risk in the generation of diversification strategies that are adjusted to farmers' resource availability or preferences. Our results showed that risk, defined as the standard deviation of crop productivity, can be greatly reduced through diversification.

Our approach allows us to incorporate the main sources of risks and uncertainties related to yield and market variables that affect the productivity of individual assets (crops) and provides tools for addressing the widespread lack of data in horticultural production systems. Our productivity models capture uncertainty related to unsystematic risks that are commonly ignored during yield estimations, such as risks arising due to pests and diseases. Farmers were also able to describe seasonal price variation for horticultural products, which in our case study of irrigated systems are key considerations when farmers choose planting dates and harvest seasons. Rather than considering systematic changes (e.g. extreme weather events or market phenomena that affect all crops), a portfolio strategy addresses such unsystematic risks, whose effects vary among crops.

Using the portfolio theory, we were able to formalize the decision rules that farmers follow in designing crop combinations, and we managed to formulate clear strategies for diversification that are attuned to resource availability and risk preferences. We aim to extend this decision analysis approach in collaboration with our partners to include potential new crop options that can be promoted for adoption in the Colombian Caribbean.

4.4 Conclusions

By using a three-stage strategy for decision analysis under uncertainty, we managed to assess crop productivity and diversification benefits of horticultural systems. This whole-farm decision analysis is an extension of Modern Portfolio Theory that allows us to link the concepts of risks and returns for a multi-asset scenario (several crops or farm enterprises). The understanding of this relationship allows us to measure the benefits of diversification in agricultural production and to identify diversification strategies that maximize returns while reducing risks. Validation of these strategies by farmers allowed us to adjust them to technical or economical limitations or individual preferences. We expect our decision analysis approach to prove useful in assessing other horticultural systems but also for the assessment and identification of new crop options to be incorporated in diversified systems. This decision analysis can also be used to represent diversification in other whole-farm planning scenarios, e.g. when it comes to rotations of field crops, integrated livestock farms, cut-flower farming or agroforestry systems.

Chapter 5

5 Final discussion and concluding remarks

Many governments and policies aim to increase farmer incomes through interventions in agricultural systems. Farmers' income can be increased in three ways: (i) more yield per land unit and more sales at constant price; (ii) higher price for sales and/or reduction of production costs with constant yield; and (iii) change of the agricultural system by shifting to higher value crops or stepping out of farming due to high production costs (Barrett et al., 2018; Dorward et al., 2009; Peter Timmer, 1988; Reardon and Timmer, 2014). The first option implies that higher incomes are reached by filling the crop yield gaps and increasing sales (improvement of the production frontier). The second pathway implies reduction in the production costs through the adoption of technological developments (price frontier). The third option requires the search and implementation of a new production alternative. Frequently, this third option includes perennial crops and then implies improved incomes associated with long-term investments (Bogdanović and Hadžić, 2019).

Interventions that aim to improve farmer incomes are decision problems of management, planning or shifting to better production systems in agricultural settings. Previous works illustrated the application of decision analysis for the assessment of alternative production systems in the search for better incomes (Do et al., 2020). Here in this thesis, the decision analysis approach was extended to planning and management strategies in agriculture. This study provides valuable knowledge for analysts and consultants seeking to apply decision analysis in the diverse problems of agricultural systems. For the case studies presented here, this thesis offers conceptual frameworks for future additional research, quantitative assessment of the available options, and identification of knowledge gaps that will facilitate the implementation of future interventions.

The first research goal of this study was to advance our understanding of management of the cotton boll weevil (BW) (*Anthonomus grandis*) in the Colombian Caribbean (Chapter 2). The conceptual modeling approach identified two temporal-spatial scales for the management of the BW: 1) farm (field) scale management during the cotton season and 2) a BW suppression strategy for controlling the insect populations at regional scale. The development of this conceptual model allowed describing the current management strategies for BW and formulating hypotheses about the effectiveness of these strategies. This conceptual model provides guidelines for future research work, and it is a baseline for the development of quantitative models and simulations describing the decision-making process related with management of BW in the Colombian Caribbean.

Chapter 2 also demonstrates the importance of participatory modeling and brings forward an addition to a previous standardized protocol for conceptual modeling. The built conceptual model was able to formalize local knowledge and elicit information that was not previously collected using traditional interview and econometric methods. This study provides an extension of a standardized protocol for conceptual modeling that includes spatio-temporal scales of decision-making problems in agriculture. These scales are particularly relevant in the definition of planning horizons that are necessary in the development of strategic plans for pest management and the outlining of decision problems. Strategic plans for pest management are currently used by the US Department of Agriculture (USDA) for addressing pest control at state or regional level with the intention to conceive integrated pest management (IPM) as a decision making process (Murray and Jepson, 2018; Murray et al., 2019, 2018). The protocol presented here offers a systematic approach for this endeavor with a clear definition of decision-making scales and decision problems that later can be addressed with quantitative tools of decision analysis.

Chapter 3 complements the conceptual model that describes the management of BW by applying decision analysis to assess control strategies used by farmers during the crop season. Two strategic options based on synthetic insecticides are currently implemented to control *A. grandis* at the farm level in the Colombian Caribbean: 1) Proactive strategy: early insecticide applications to eliminate the BW founder population arriving to the cotton crops early in the season, and 2) Reactive strategy: late insecticide applications to reduce population growth rates and decrease yield losses associated with BW invasion of the crop. Our results indicate that a proactive approach is more efficient than reactive management given the current BW infestation pressure. However, farmers may prefer the reactive strategy, since they have experienced seasons with low infestation pressure where no insecticide applications were required. The proactive strategy, in contrast, requires scheduled pesticide applications in all years. Results show that in seasons with high infestation pressure the expected revenues of the reactive strategy tend to decrease, mainly because more spray applications are required when fields are heavily infested by the weevil. Uncertainties related to BW arrival time to the field, BW population density and planting date appeared to have the greatest influence on the decision to protect the crop. Narrowing these key knowledge gaps may offer additional clarity on the performance of the current management strategies and provide guidance for the development of strategies to reduce insecticide use. This is particularly important for the promotion of the proactive strategy, which, under the current infestation pressure, has potential to reduce the insecticide use.

The accomplishment of this second goal (Chapter 3), also provided an opportunity for the application of decision analysis in the assessment of pest management strategies. Pest management decisions are commonly addressed using economic decision levels or marginal utility approximations. These decision approaches are based on assumptions of certainty and clearly ignore the uncertainties associated with pest infestation pressure, control effectiveness, cotton yield and fiber price. The economic injury level (EIL) is the most popular method of decision making in pest management between entomologists. Besides ignoring uncertainty, this method has another difficulty. EIL was designed as a method of reducing insecticides in management cases where there was correlation between crop damage, pest density and the amount of insecticide applied. EILs was widely promoted as the main pillar of the IPM framework becoming synonymous concepts. However, there is a flaw in the prevalence of EILs in pest management (specially in crop protection), and that is to ignore that frequently prophylactic measures are the most efficient option to control a pest. Decisions based on prophylactic pesticide applications are usually taken without evidence of pest presence in the field, without estimations of the expected damage provoked by the pest, the efficiency of the pesticide or the future value of the crop losses. Such preventive actions cannot be assessed using an economic threshold, because they are not correlated with pest density. As they involve considerable uncertainty, they also cannot be assessed using a deterministic marginal analysis. These flaws of the common pest management decision frameworks can be solved with use of decision analysis methodologies (Mumford and

Norton, 1984). Chapter 3 describes the implementation of a partial budget analysis under uncertainty approach able to assess and compare both proactive and reactive measures in the same methodological framework. This framework can be extended to other non-pesticide control measures such as biological control.

In the last decade, there has been a transition from cotton crops to other production systems motivated by removal of subsidies on cotton crops, changes in the weather pattern, and frequent outbreaks of BW. Smallholders are the majority of the population transitioning to other crops or other informal ways of subsistence. In the Sinu Valley, several local institutions have promoted the transition to horticultural crops under irrigation. These production systems offer diversification, intensive land use and better incomes. This presented a framework for supporting decision making in diversified systems as an example of whole-farm planning using Modern Portfolio Theory (Markowitz, 1959). This special case of decision analysis requires the implementation of a three-stages strategy for decision analysis that is able to quantify crop productivity and estimate benefits of diversified systems. This decision analysis strategy includes: conceptual modeling, individual crop-based risk analysis, and portfolio risk analysis. The first stage provides a qualitative description of the current understanding of the system processes and functions. The second and third stages are quantitative assessments. The second stage aims to assess the productivity of each crop while the third stage measures the benefits of diversification and provides strategies for reducing risk at the whole-farm scale. This decision analysis approach has the potential to be used in the assessment of other horticultural systems, and identification of new crop options that can be incorporated in the diversification strategies of these systems. This decision analysis can also be used to represent diversification in other whole-farm planning scenarios such as rotations of field crops, integrated livestock farms, cut-flower farming or agroforestry systems.

Decision analysis can also provide a bottom-up approach for the efforts of the Colombian Agricultural Research Corporation (AGROSAVIA) to promote interdisciplinary work and stakeholder participation at the local and regional level. AGROSAVIA is aimed to support the needs of farmers in Colombia but it is challenged by the size and landscape of the country (AGROSAVIA, 2020). Colombia has a mainland area slightly larger than the combined areas of Germany, France, Belgium and the Netherlands. The presence of the Andean Mountains generates a highly heterogeneous landscape that results in diversity of agroecological niches and distinctive regional cultures and identities (Safford and Palacios, 2001). To overcome these challenges and maximize their impact as the leading institution of the Colombian national system for agricultural research, AGROSAVIA implemented an organization model based on innovation networks (IN) (Restrepo Ibiza and Gómez Badel, 2019). This organizational model aims to connect scientists of 23 research centers and stations for working together in national strategic issues of agricultural value chains while regional and local stakeholders are invited to participate. However, stakeholder participation is still low and frequently the conversation is dominated by a small number of participants. Information is collected as lists of common issues and prioritized by consensus without qualitative description of the problem or quantitative approximations. There is another issue with those innovation networks involved with horticultural crops (INs for vegetable and aromatic crops, roots and tubers, and tropical fruits). Horticulture is commonly practiced in diversified systems with distinctive regional characteristics, and management, from homegardens to intensive irrigated production systems. These diversified systems exhibit structural complexity, species diversity (frequently landraces), outputs of varied nature, and tremendous variability from farm to farm. Planning interventions in these systems and prioritizing what to research with minimal funding is the bottleneck of a national research program trying to understand the local needs. Decision analysis has potential to link these issues and provide a practical approach for addressing this complexity and increasing engagement of local stakeholders by capturing their understanding of the problem and their foresight of possible solutions.

Supplemental Data

Supplementary file S1. Gray literature related with the boll weevil management in Colombia

Definition of gray literature

Gray literature refers to documents produced by different government, business, and higher education and research organizations that are not indexed by commercial publishers. Gray literature is a vital resource in scholarly communication, research, and development, policy making in business, industry, and governance. It provides considerable contents of evidence, argument, innovation, and understanding in different subject areas, of science, engineering, health, social sciences, education, arts, and humanities (J. Adams et al., 2016; Garousi et al., 2019; Mahood et al., 2014). Gray literature and information are the main literature sources that describe interventions in public health and development by governmental and non-governmental organizations (R. J. Adams et al., 2016; Farace and Schöpfel, 2010; Franks et al., 2012; Pappas and Williams, 2011).

Gray legal literature

Documents related with laws and regulations are a specific type of gray literature. Gray legal literature includes documents produced by government, academics, business and industry that provide information about laws and regulations and their implementation at international, federal, state, and/or local level (Rucinski, 2015).

For this work, the legal gray literature is represented by all regulations and associated technical reports released by the Instituto Colombiano Agropecuario (ICA). A compilation of the historical gray legal literature related to the BW was provided by a former study (Sierra-Monroy and Burbano-Figueroa, 2020). This study covered 80 years of regulations aimed to control BW, and compiled gray literature describing laws, regulations and implementation of sanitary measures aimed to control cotton pests in Colombia, mainly BW.

Digital archives

Gray literature is difficult to find and retrieve but the development of institutional digital archives have allowed access to massive collections of gray literature. Digital Archives are repositories of digital information with social, economic, cultural, and intellectual value created with the purpose of preservation and long-term accessibility. These archives contain digitized and born-digital material (Awasthi, 2021).

For the regional context of this work, the information related with the weevil management is mainly described in technical reports associated with several Colombian institutions. Currently, a great proportion of these files are available in an institutional DSpace repository, the Digital Agricultural Library (the Biblioteca Digital Agropecuaria). This repository is an initiative taken at the BAC (The Colombian Agricultural Library - https://repository.agrosavia.co/), Colombia, to digitize and preserve technical reports produced by the Corporación Colombiana de Investigación Agropecuaria (CORPOICA, today rebranded as AGROSAVIA), ICA and other Colombian institutions that are associated with rural production. More than 20,000 reports and 300 videos have been indexed until now. The Digital Agricultural Library is the official repository of gray literature for the institutions linked to the Colombian National System for Agricultural Innovation (SNIA), and serves as distributor for literature produced by AGROSAVIA[2]

[2] Acronyms of institutions
ICA: Instituto Colombiano Agropecuario (Colombian Institute for Agriculture)
AGROSAVIA: Corporación Colombiana de Investigación Agropecuaria (Colombian Corporation for Agricultural Research)
SNIA: Sistema Nacional de Innovación Agropecuaria (National System for Agricultural Innovation)

Supplementary file S2. Data collection and development of the conceptual model

Description of the study area

This conceptual model was designed for describing the BW management strategies used in the cotton-producing areas of the Colombian Caribbean, specifically in the Sinú Valley (Córdoba State) and the Cesar Valley (Cesar State). The Sinú Valley is divided from south to north into three regions, namely the Upper, Middle and Lower Sinú Valleys. It exhibits a monsoon climate (Am) in the southern part and a wet savanna climate in the north (Aw). The Cesar Valley features a dry savanna climate (Af) in the northern part and wet savanna climate (Aw) in the south. The local literature refers to the dry savanna regions as the 'Dry Caribbean' (Caribe Seco) and to the regions with monsoon and wet savanna climates as the 'Humid Caribbean' (Caribe Humedo).

Data collection

The data used for building the conceptual model were obtained from two sources: knowledge holders and published information. Focus group discussions and semi-structured interviews were conducted with knowledge experts to identify variables and parameters associated with technical operations involved in BW management. Experts participating in the initial model-building included one cotton plant physiologist, one cotton breeder, four entomologists (three with expertise in the management of BW, and one with expertise in insect ecology) and five crop advisors and/or farmers (who are responsible for a large share of the entire cotton-producing area of the Caribbean region). These experts were asked to describe how BW affects the crop, how they control the pest, and what problems limit the effectiveness of BW control in the long run. The discussion was oriented towards eliciting the main factors affecting the expected outcome (especially yield and production costs) and to provide ranges for the variables that describe the problem.

Formally and informally published information on BW management was obtained through literature research. First, we used the keywords *Anthonomus grandis* and "algodón" (cotton in Spanish) as search terms in Google, Google Scholar, Agris (http://agris.fao.org/agris-search/index.do) and BAC (The Colombian Agricultural Library - https://repository.agrosavia.co/). These searches mainly resulted in technical reports (grey literature). Some technical reports and theses were obtained from local libraries or personal files. All grey literature were assessed and manually annotated for record and citation using the F1000 Workspace reference managing software. We then focused on scientific publications by entering specific search strings describing biological processes and BW management in Google Scholar. Findings described in these papers were recorded as individual notes and discussed between the members of the field team with the support of specific knowledge experts.

The first version of the conceptual model was released in Spanish language to elicit feedback from a wider audience of experts and stakeholders (https://doi.org/10.31220/osf.io/db8nu, Version 2). After this pre-release, a description of the role of the government agencies in the development of management strategies and policies was included in the dynamic structure of the conceptual model. For a better understanding of these information, an operations research approach was used for separating management-related decisions based on their time framework. Pre-release copies of the model versions were distributed via email to additional key experts.

Disciplinary knowledge experts and technical reports are associated with ICA, CORPOICA (today AGROSAVIA), and the Confederación Colombiana del Algodón (CONALGADON). Crop advisors belong to the farmer organizations registered by the local office of CONALGODON. ICA is the agency responsible for the regulation and enforcement of pest control measures and quarantines under the national authority of the Colombian Ministry of Agriculture and Rural Development. AGROSAVIA is the Colombian Agricultural Research Corporation, a state-owned enterprise composed of 13 research centers devoted to research, development and innovation for the agricultural and livestock sector. AGROSAVIA is a decentralized institution funded by the Ministry of Agriculture and Rural Development. CONALGODON is the Colombian cotton association representing farmers and ginners in the country. These organizations are affiliated with the Cotton Regional Committee (CRA) headquartered at the municipality of Cereté, Cordoba. This committee is a local initiative of the Sinú Valley farmers with monthly meetings for discussing, proposing and evaluating all actions related to the cotton value chain in the Sinú Valley. Focus group discussions, interviews and feedback were mainly coordinated with the support of this committee.

Building of the conceptual model

From information obtained during data collection, we built a model using a previously described protocol for conceptual modeling of agro-ecosystems (Lamanda et al., 2012).

This protocol includes the following steps:

1. Structural analysis to identify the limits of the system, sub-systems, components, factors affecting the system and the indicators for assessing system performance.
2. Functional analysis to identify the relationships between the components of the system, factors and performance indicators.

3. Dynamic analysis to describe how the system, sub-systems and main components behave over time and to check if the structural and functional conceptual models adequately represent system dynamics. Management scenarios were identified via analysis of the temporal-spatial scales of the technical subsystem.

   An operations research and logistics (ORL) approach was used for the dynamic analysis of the decision-making process associated with the technical subsystem. ORL is used for analysis and planning of complex operations from transport and distribution of goods to operation management with the aim of accomplishing a specific goal for customers (Swamidass, 2000). This approach has been applied to several biology-based problems including pest management (Conway, 1984; Rabbinge et al., 1993).

   Under the ORL approach, the decision-making process can be considered a system in itself. This decisional system wraps several dynamic processes that require organization and management at different temporal-spatial scales or planning horizons (hierarchical planning). Decisions related to the management of BW were classified into the following temporal-spatial scales: policies, strategic, tactical and operational decisions.

Policies and strategic-level decisions require the longest planning horizon perspectives, covering decades or years, while horizons of tactical and operational decisions are usually shorter than one year (Farahani et al., 2011; Swamidass, 2000; Wernz and Deshmukh, 2012). Each decision level is associated with particular decision-making agents, whose actions can affect decision outcomes and eventually modulate the performance of the system (Table 2).

4. Consistency analysis assures that the conceptual model as a knowledge representation corresponds to reality. This last step is an iterative process applied regularly during the first three steps with the participation of knowledge experts. For a final consistency assessment of the conceptual model, Spanish-language versions of this document have been released as preprints for receiving critiques and comments from a wider expert audience (https://doi.org/10.31220/osf.io/db8nu). During this step we identified limitations of the first model versions for accounting decision-makers' responsibility at different scales. There was special emphasis in the role of ICA in the current legal and institutional framework. This framework was assessed, analyzed and published as an independent paper (Sierra-Monroy and Burbano-Figueroa, 2020). However, we were not able to have a hierarchical representation of the decision-making process, especially the separation between those decisions considered individual (farmer) responsibility and those communal actions under regulation. At this point, we introduced the ORL approach as an extension of the conceptual model protocol developed by Lamanda et al (2012). This hierarchical scale provided us with a standard framework for the outline of decision-making scenarios.

Supplementary file S3. Elements of a conceptual model describing the management of *Anthonomus grandis grandis* in the Colombian Caribbean

Table S3. Structural representation of elements during the off and cotton season (See also Figure S3.1)

<table>
<tr><th rowspan="2">Time (year)</th><th>Off- season</th><th>Cotton season</th></tr>
<tr><th>March - August</th><th>August - March</th></tr>
<tr><td colspan="3">Factors</td></tr>
<tr><td>Environmental factors</td><td colspan="2">Savanna and monsoon tropical climates (Aw, Am, Af) that do not threaten pest survival</td></tr>
<tr><td>Socioeconomic factors</td><td colspan="2">The main proportion (70%) of cotton crops are on rented land, making it difficult for farmers to commit to the destruction of stalks, regrowths and volunteeers. ICA (the Colombian agricultural agency) has a mission to promote and enforce agricultural health but lacks a proper legal framework and technical and financial resources to ensure that all cotton farmers destroy stalks and volunteer plants at the right time (KE21).</td></tr>
<tr><td>Refuge areas</td><td colspan="2">A refuge area for BW is defined as locations where BW can feed during the inter-cotton season. In some refuge areas, BW can find hosts able to support its reproductive development, but these are scarce. A constant source of BWs are refuge areas where populations cannot be controlled or eradicated (CONALGODÓN et al., 2008). These populations are not considered part of this system analysis because economical and technical limitations limit weevil control directly in the refuge areas. Feeding hosts include guineo manzano (a banana landrace), mango, mataratón (Gliricidia sepium), coconut trees, plantains, guayaba dulce (a Psidium guajava landrace) and several grass species (Figures S3.2 and S3.3). These plants allow BW populations to survive for extended periods. BWs can also survive for three months feeding on corn pollen. Corn is the preferred rotational crop for cotton (Jimenez Mass et al., 2001) (LGM).</td></tr>
<tr><td colspan="3">System</td></tr>
<tr><td colspan="3">Biological subsystem</td></tr>
<tr><td>Anthonomus grandis grandis</td><td>BW populations survive and reproduce in regrowths from stalks and volunteer plants.</td><td>BW populations living in refuge areas and interseason cotton populations arrive to cotton crops where they can reproduce and dramatically increase their population size (KE22)</td></tr>
<tr><td>Upland cotton populations</td><td>Cotton regrowths, sprouts from living stalks, and volunteer plants</td><td>Cotton crops (KE22)</td></tr>
<tr><td colspan="3">Technical subsystem</td></tr>
<tr><td rowspan="2">BW management scenarios</td><td rowspan="2">Suppression. All measures necessary to reduce the BW population surviving during the intercotton season. These include, but are not limited to, destruction of stalks, regrowths, and volunteer plants. Insecticide sprays over these plants are recommended with the aim to decrease the BW population (AOB, KE22, KE23).</td><td>Proactive management. Avoiding the infestation of cotton crops by BW. Early insecticide applications on fixed dates (AOB)</td></tr>
<tr><td rowspan="2">Reactive management. "Business as usual". Reducing the growth rate of the BW population. Monitored insecticide applications. Up to 15 insecticides sprays are required using this method, which is applied by an estimated 90% of farmers (AOB, KE22, KE23)</td></tr>
<tr><td></td><td>Stalks are not destroyed immediately after harvest and persist until mid-year. In May 2010, an acreage of 10.000 ha of cotton stalks were reported as not destroyed (Arbelaez Farfán, 2012).</td></tr>
<tr><td colspan="3">System indicators</td></tr>
<tr><td>Yield losses</td><td colspan="2">Yield losses related to BW change according to pest pressure, prevalence for a particular year and planting date. Late planting dates lead to larger BW populations whose control requires more insecticide sprays (AOB, KE22).</td></tr>
<tr><td>BW management costs</td><td>It is not clear who is responsible for the cost of destroying stalks at the end of the cotton season. At the end of the lease agreement, some land tenants do not destroy the stalks immediately after harvest, leaving this task to the land owner. ICA does not have a precise legal framework and technical capacity for persecuting these infractors (KE21, KE22).</td><td>BW is one of the main limitations of cotton productivity in the Caribbean region because of pest management costs and yield losses. A regional average of up to 7 insecticide sprays for managing BW in a cotton season has been reported (KE21, KE22).</td></tr>
</table>

* These experts were interviewed for the development of the conceptual model: Anibal Ochoa Bedoya (AOB), Liliana Grandett Martinez (LMG). KE are identification codes for anonymized knowledge-experts.

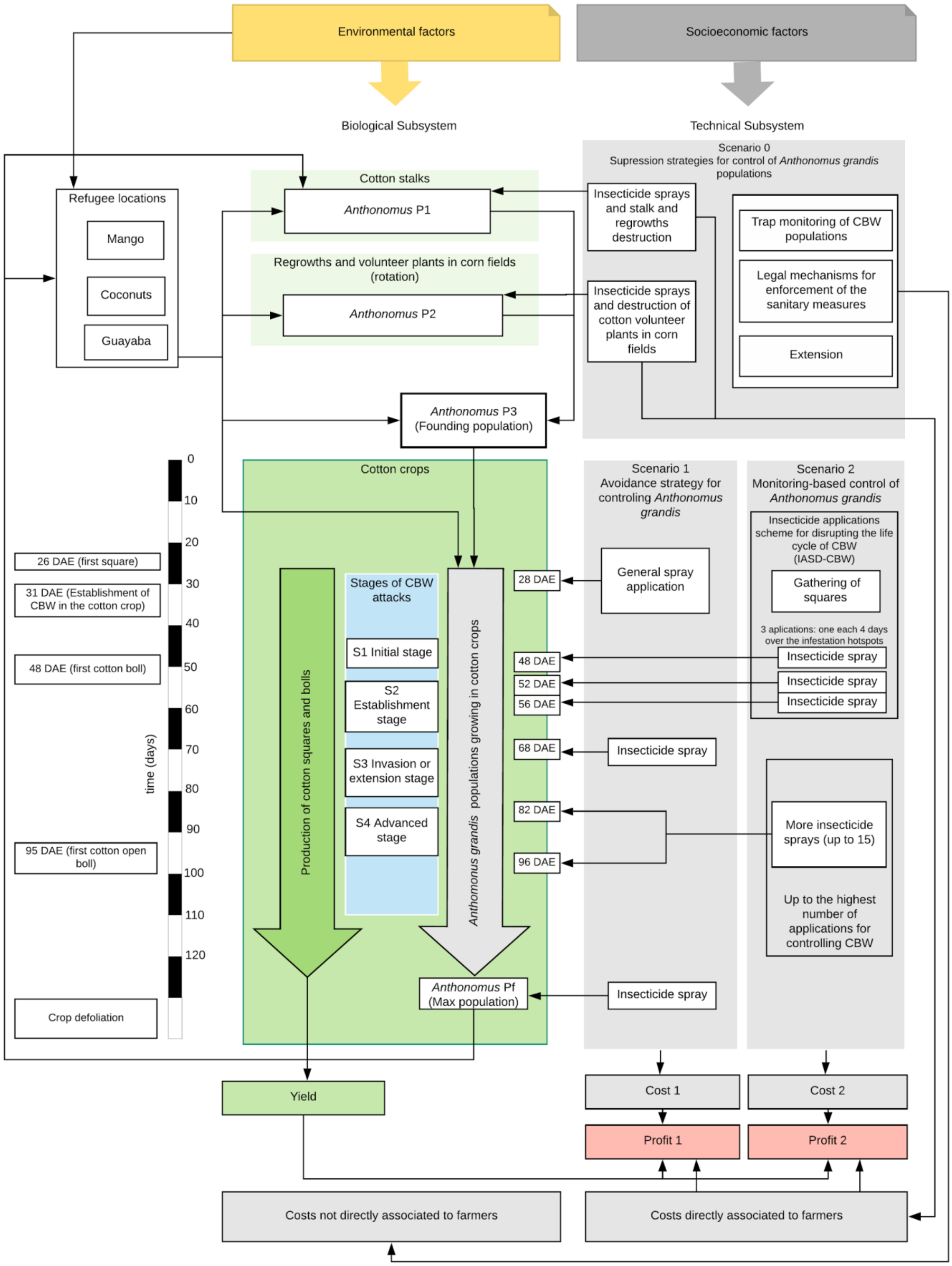


Figure S3.1 Graphic detailed representation of the management of BW in the Colombian Caribbean

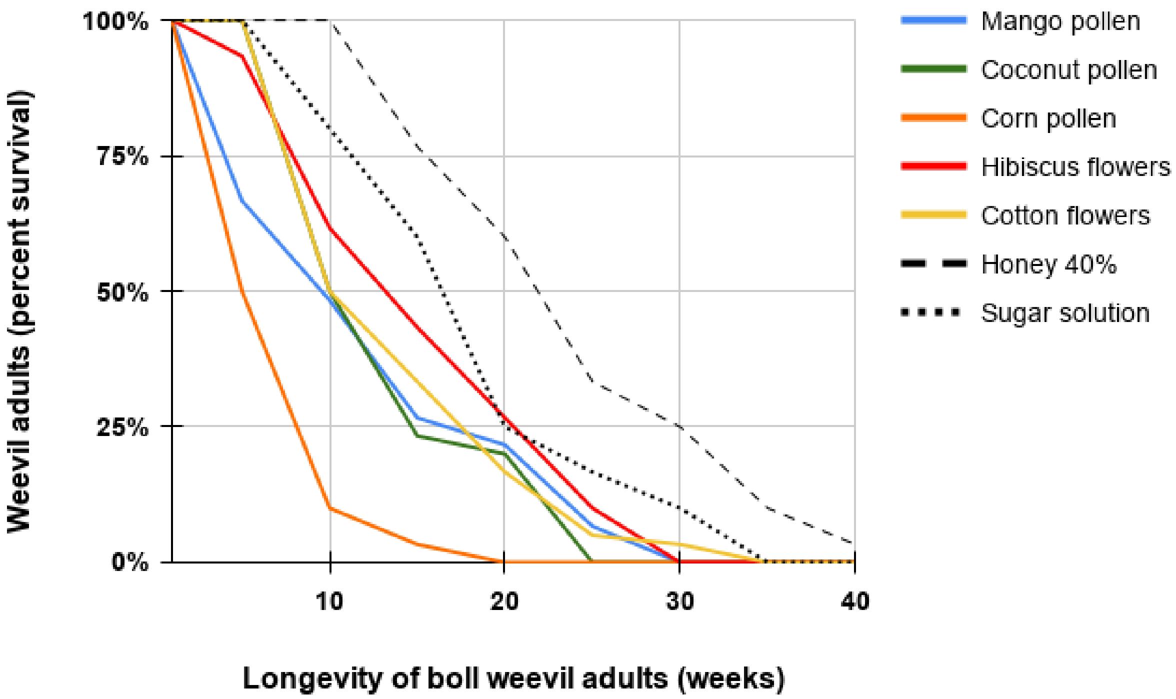


Figure S3.2 Boll weevil (BW) adults survival curves. Adults were reared in continual presence of various food sources. This assay provided evidence that BW adults reared from cotton in the Sinú Valley have the potential to live for periods up to six months on a continuous supply of *Hibiscus* or cotton flowers, mango or coconut pollen, and up to three months on corn pollen. The figure was created from data originally reported by (Jimenez Mass et al., 2001). A similar essay conducted in the Lower Rio Grande Valley showed that BW adults have the potential to live up to nine months on a continuous supply of cotton flower buds (squares), and up to four months on *Hibiscus rosasinensis* L. buds (Chandler and Wright, 1991). Weevils from northeastern Mexico were able to survive more than two months on pollen mixture (bee pellets), cotton and bud flowers, and flowers of *Opuntia lindheimeri* and *Abutilon hypoleucum* (Jones et al., 1993)

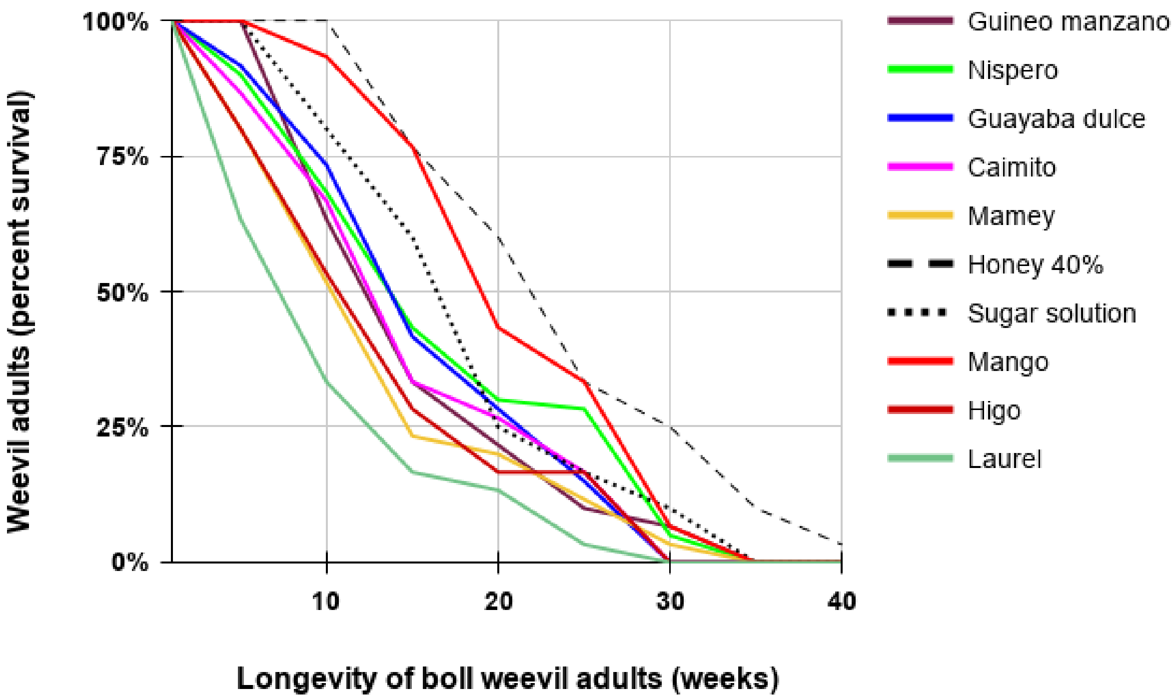


Figure S3.3 Boll weevil (BW) adults survival curves. Adults were reared in continual presence of various locally available fruits. This assay provided evidence that BW adults reared from cotton in the Sinú Valley have the potential to live for periods up to seven months on a continuous supply of guineo manzano (a banana landrace), níspero costeño (*Manilkara* spp.), guayaba dulce (landraces and hybrids of *Psidium guajava*), caimito (*Pouteria caimito*), mamey (*Mammea americana*), mango, higos and laurel (*Ficus* spp). The figure was created from data originally reported by (Jimenez Mass et al., 2001).

Supplementary file S4. Temporal dynamics of boll weevil populations throughout the year

<table>
<tr><th rowspan="2">Subsystem</th><th rowspan="2">Component</th><th rowspan="2">State variable (or parameter)</th><th rowspan="2">Variable description</th><th colspan="4">Year</th><th rowspan="2">Source</th></tr>
<tr><th>1st Quarter</th><th>2nd Quarter</th><th>3rd Quarter</th><th>4th Quarter</th></tr>
<tr><td rowspan="7">Anthonomus grandis grandis</td><td rowspan="4">BW populations during the intercotton season</td><td>BW refuge population</td><td>Several feeding hosts allow BW to survive in the environment when cotton is not available. These hosts do not support BW reproduction.</td><td colspan="4">Refuge locations</td><td rowspan="5">AOB, KE24</td></tr>
<tr><td>P1</td><td>BW populations actively reproducing in cotton stalks and regrowths</td><td colspan="2">Cotton stalks and regrowths</td><td></td><td></td></tr>
<tr><td>P2</td><td>BW populations surviving in cotton volunteer plants growing in corn fields (rotational crop)</td><td></td><td>Cotton volunteer plants - Corn crops</td><td></td><td></td></tr>
<tr><td>P3</td><td>BW migrant population in midyear. This population will colonize cotton crops in the following season. This population is the aggregate of weevils located in the refuges, and the migrating populations from P1 and P2.</td><td colspan="2"></td><td>BW migrating population</td><td></td></tr>
<tr><td>Weevil populations growing in the cotton crops</td><td>Parameters describing population dynamics of BW growing in cotton</td><td>Populations growing in cotton crops from P3. This population is actively reproducing in the cotton reproductive structures.</td><td colspan="2"></td><td colspan="2">Cotton crops</td></tr>
<tr><td rowspan="2">Migrating (circulating) population of BWs at state and regional scale</td><td>Cotton-producing regions</td><td rowspan="2">This population can be estimated from the data on population dynamics collected by ICA and CONALGODON using pheromone traps (with an exception for the cotton season, when the crop is more attractive). These records can be converted to trap indices as representations of population density. Traps are distributed as a ratio of one per 100 ha or one per 50 ha.</td><td colspan="2">P1 and P2 can be calculated from the trap data and estimates of the weevil population that can survive in cotton stalks and volunteer plants.</td><td colspan="2">Weevils are strongly attracted to the crop. The size of this population can be estimated from simulations using expert knowledge and previous models.</td><td>ICA</td></tr>
<tr><td>Regions where cotton is not longer cultivated</td><td colspan="4">Trap data is used by ICA for assessment of BW free areas in the country or areas with low BW prevalence. This population density is a proxy for the size of the populations surviving in the refuge locations or the carrying capacity of the environment for this pest.</td><td>ICA</td></tr>
</table>

Supplementary file S5. Regulatory framework for the control of boll weevil

Since its creation in 1963, ICA is the agency responsible for the regulation and enforcement of pest control measures and quarantines under the national authority of the Colombian Ministry of Agriculture and Rural Development.

Cotton stalk destruction has been regulated since 1947 (Decreto 040028, 1947; Decreto 313, 1950), even before ICA was created. Cotton stalk destruction (CSD) was mandatory in the two weeks following the cotton harvest. In 1955, the Cotton Development Institute (IFA) (the entity responsible for crop sanitation before ICA was established) decreed that a fraction of the value of the harvested cotton should be retained by gathering centers (10%) and farmer organizations (8%) until the CSD was verified (Decreto 1659, 1955). In 1964, fixed dates were established for CSD, with March 15th being the CSD deadline for the Caribbean (Decreto 331 1964, Resolución 00723, 1964). A mandatory pest management program for BW was initiated in 1994 (Resolución 2072, 1994), prohibiting application of chemical insecticides before cotton budding, and enforcing CSD, complemented by attract and control tubes (BW-ACT) (Sierra-Monroy and Burbano-Figueroa, 2020).

In 1999, the ICA offices of each state were authorized to issue local regulations related to CSD, and farmer organizations were commissioned to collect the 10% fee deposit used as guarantee of the CSD (Resolución 00372, 1999). Up to today, under this provision, ICA state offices issue regulations for each cotton season and establish dates for registering farmers, cotton seed sales, start of the cotton season, and CSD (ICA, 2009).

A decade ago, ICA established prevalence thresholds that are used for categorizing cotton producing areas where BW is endemic (ICA, 2009). Areas with more than 12.5 weevils/trap/week were classified as high-prevalence while areas with less than 5 weevils/trap/week were classified as low-prevalence. Areas without reports of BW over 5 years are considered weevil-free (ICA, 2009). These ICA-defined thresholds are shown in Figure 6.

Supplementary file S6. Mass trappings of boll weevils

Males of the genus *Anthonomus* emit an aggregation pheromone composed of up to seven components commonly called grandlure (Tewari et al., 2014). The glandlure blend for *Anthonomus grandis grandi*s is a four-component pheromone: (1R-cis)-1-methyl-2-(1-methylethenyl) cyclobutaneethanol; (Z)-2-(3,3-dimethylcyclohexylidene) ethanol; (Z)-(3,3-dimethylcyclohexylidene) acetaldehyde; and (E)-(3,3 dimethylcyclohexylidene) acetaldehyde (Gueldner et al., 1971; Hardee et al., 1972; Tumlinson et al., 1969, 1968).

The release of the synthetic grandlure for BW allowed the development of pheromone-based traps (PBT) (Coppedge et al., 1973; Hardee et al., 1972). Pheromone-based traps are essential tools in BW suppression and eradication programs (Dickerson, 1986). They are used for detection, population estimation, mass trapping and guiding insecticide applications (El-Sayed et al., 2006; Suh et al., 2009; Tewari et al., 2014). Addition of insecticides or adhesive surfaces can achieve up to a threefold increase in the capture efficiency of these pheromone traps (Villavaso et al., 1998).

The efficacy of PBT for mass-trapping of BW is ambiguous (Boyd et al., 1973; Daxl et al., 1995; Fuchs and Minzenmayer, 1992; Hardee et al., 1971; Karner and Goodson, 1993; Langston, 1995; Showler, 2003; Villavaso et al., 1998). However, this ambiguity is explained by the higher efficiency of PBT at low levels of BW population density and absence or reduced competition of cotton plants. Mass trapping is effective for BW control during the off-season for scattered populations located in refuges (isolation and low population density) (El-Sayed et al., 2006; Showler, 2007) or at the start of the crop season (when competition with volatiles of cotton plants is reduced) if BW population density is low (Ridgway et al., 1990; Sonenshine, 2017).

Several types of traps were assessed for the development of the BW PBTs with different purposes (Tewari et al., 2014). In Colombia, BW attract and control tubes (BW-ACT), wing traps and sticky baits have been assessed and used for decreasing the size of BW populations (mass trapping) (ICA, 2009). Hardee or scout traps, the most effective designs for monitoring (Hardee et al., 1996), are used by ICA´s BW monitoring network. ICA enforces the use of BW-ACT every season on all cotton farms as a standard operation for controlling BW, before cotton budding and after the CSD is completed (ICA, 2009). Interviewed experts and farmers question this enforcement considering the high price and the poor performance of these devices. Field evidence suggests that implementation of BW-ACT does not have impacts on BW populations or cotton yield (Villarreal Pretelt et al., 2005). This outcome is expected considering the high population density of BW in the Caribbean that severely limits the efficiency of PBT.

Supplementary file S7. Temporal dynamics of cotton, *Anthonomus grandis grandis* and pest management during the cotton season

<table>
<tr><th>Components</th><th>State variables or parameters</th><th>Description</th><th colspan="5">Phenological development of cotton plants in relation to BW occurrence</th><th>Source</th></tr>
<tr><td colspan="9">Biological subsystem</td></tr>
<tr><td rowspan="6">Cotton crop</td><td rowspan="6">Cotton development (DAE)*</td><td>Phenological events / Colombia regions</td><td>First square</td><td>First white flower</td><td colspan="2">Boll opening (estimates are based on multi location trials of cultivar M123)</td><td>Total vegetative development</td><td rowspan="6">(Burbano-Figueroa et al., 2018) (Burbano-Figueroa and Montes-Mercado, 2019) (Burbano-Figueroa, 2019)</td></tr>
<tr><td>Caribbean dry savanna</td><td>25</td><td>44</td><td colspan="2">97</td><td>120-130</td></tr>
<tr><td>Upper Magdalena Valley</td><td>27-35</td><td>46</td><td colspan="2">98</td><td>120-130</td></tr>
<tr><td>Eastern Plains</td><td></td><td>54</td><td colspan="2">100</td><td>130-145</td></tr>
<tr><td>Sinú Valley</td><td>25-35</td><td>52-58</td><td colspan="2">105-112</td><td>135-145</td></tr>
<tr><td>Upper Cauca Valley</td><td></td><td>59</td><td colspan="2">122-125</td><td>145-152</td></tr>
<tr><td rowspan="3">Anthonomus grandis grandis</td><td rowspan="2">BW populations</td><td rowspan="2">Demographic changes in the insect population</td><td colspan="2">Immigrant populations</td><td>Established populations</td><td>Resident populations</td><td>Emigrant populations</td><td></td></tr>
<tr><td colspan="5">BW populations arrive at the crop in a time window between 28 and 60 DAE, depending on the carrying capacity of the environment during the inter-cotton season. The population growth rate and size are only limited by the availability of squares and bolls. At low densities, weevils prefer squares over bolls. Trap index data suggest that the destruction of the cotton stalks induces the emigration of the BW populations to the refuge locations.</td><td rowspan="2">KE2
KE23</td></tr>
<tr><td>BW damage</td><td>The BW population increases its size proportionally to the available squares. Damage is proportional to the size of the BW population.</td><td colspan="2">Early feeding damage on tender cotton terminals before the occurrence of squares.

Both sexes of BWs start to feed on pollen from squares causing damage by feeding and oviposition.</td><td colspan="2">The growing BW populations cause damage in squares, flowers and bolls. BW populations exhibit linear growth proportional to the available reproductive structures.</td><td>Oviposition and feeding damage decrease concomitantly with lower egg-laying rate of BW females.</td></tr>
</table>

			S1. Initial stage	S2. Establishment stage	S3. Invasion or extension stage	S4. Advanced stage	Migration	
	Spatio-temporal BW dynamics	Spatio-temporal changes of the BW populations when they are attacking cotton crops	Development of aggregation spots. BW attacks begin along the field margins with prevalence of oviposition damage. Damage varies from several squares attacked in a single plant to clusters of several plants (between 5 - 10) showing damage in multiple squares.	Establishment of BW population in the aggregation spots. Feeding and oviposition damage is observed in the aggregation spots. This damage is mainly caused by the first BW generation born and matured in the cotton crop (S1). It is possible to see some adults causing damage to the squares or feeding on flowers.	This is a critical stage for the management of BW in scenario 2. The BW population growth rate cannot be controlled using cultural practices. During this stage, damage occurs in squares and flowers and all BW life cycle stages are observable in the field. Adults can easily be spotted, especially in the flowers when they have reached a density of one BW individual per five flowers.	All life cycle stages of BW are observed in the field. Flowers contain more than 1 BW adult. Significant yield losses or total loss.	Migration of BW populations to refuge locations.	(León Q, 1980) (Gómez Lopez, 1981) (Gómez, 1993)
Technical subsystem								
Proactive management. Avoiding infestation of cotton crops by BW	Technical Operations (TO)	Calendar insecticide sprays to avoid or delay the arrival of migrant BW (colonizing) population to the cotton crop	1-2 whole-field insecticide sprays	5 - 6 whole-field insecticide sprays			Defoliation	AOB LGM KE22 (Jiménez Mass, 1981) (Negrete Barón et al., 2005a)
	Event related with the decision to start a TO		Insecticide sprays are applied with the appearance of the first square	Additional insecticide sprays are applied when the BW population is establishing			Cotton boll opening and harvest	
	Time (DAE) when the TO is developed		approx. 28 DAE	approx. 68 DAE			120 - 150 DAE	

Reactive management. Reducing the growth rate of the BW population	Technical Operations (TO)	Insecticide sprays based on the detection and control of aggregation spots (IHS).	Scouting	When aggregation spots are detected, the insecticide application scheme for disrupting the BW life cycle (IASD-BW) is applied. This scheme includes three insecticide sprays every 4 days directly over the IHS followed by as many whole-field insecticide sprays as necessary. Additionally, gathering fallen squares is necessary.	Up to 15 insecticide sprays	Defoliation	AOB KE22 LGM (León Q, 1980) (Gómez Lopez, 1981)
	Event related with the decision to start a TO			Occurrence of BW aggregation spots	BW adults feeding on flowers	Cotton boll opening and harvest	
	Time (DAE) when the TO is developed			48 DAE	82 DAE	120 - 150 DAE	

*DAE: Days after emergence

Supplementary file S8. R-script describing control strategies used against the boll weevil in the Colombian Caribbean

We employed the decisionSupportR package (Luedeling et al., 2020) (Luedeling, Goehring, and Schiffers 2019) and its functions to develop the model and to perform probabilistic simulations.

We defined sample values for all variables by generating a make_variables function to select randomly from each variable in the file describing their probability distribution functions (`"PDF.csv"`).

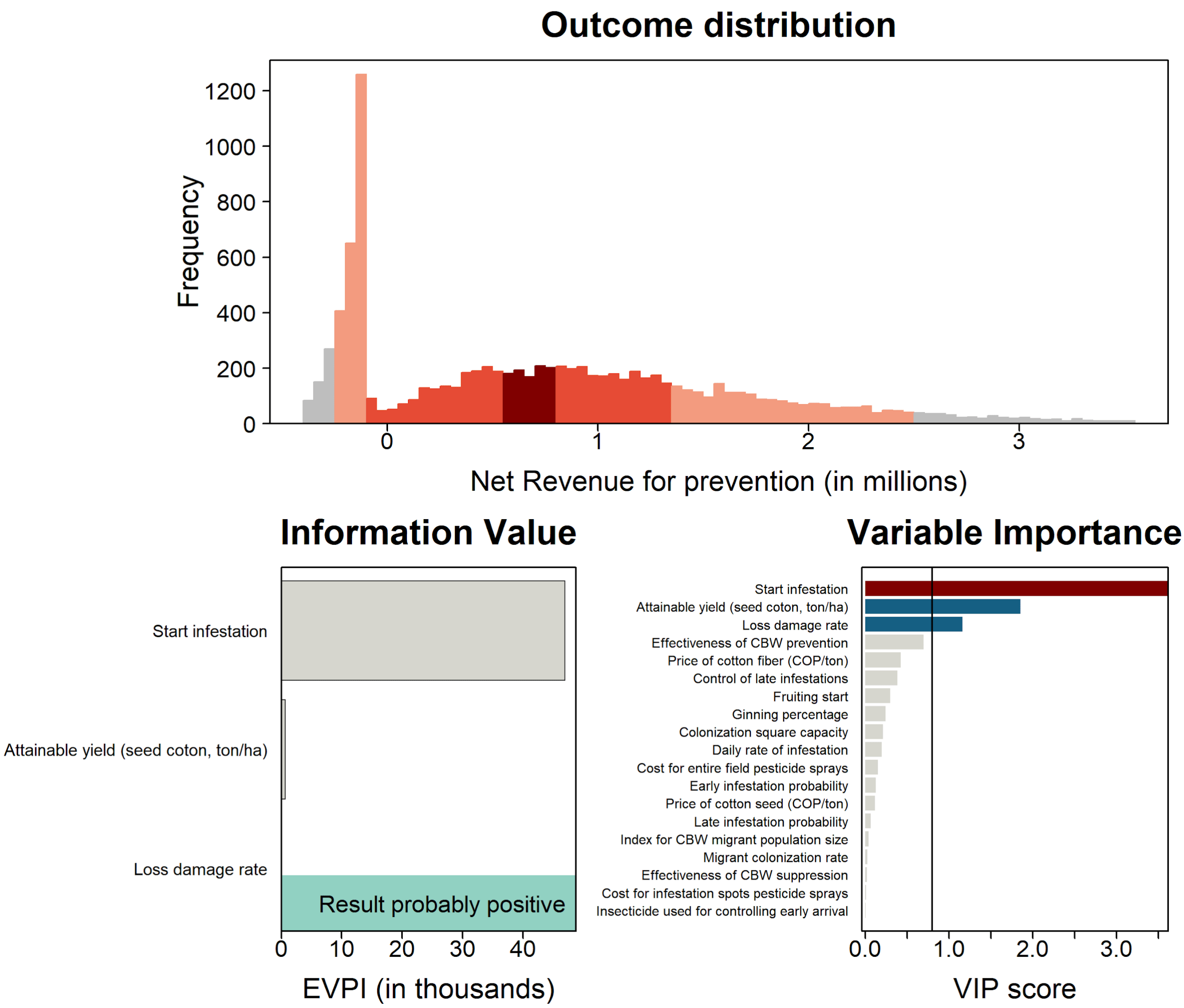
The `make_variables` function is used to generate one random value for each variable in the `"PDF.csv"` file. These values are not used in the simulation, but they are used for testing of the model code and troubleshooting purposes.

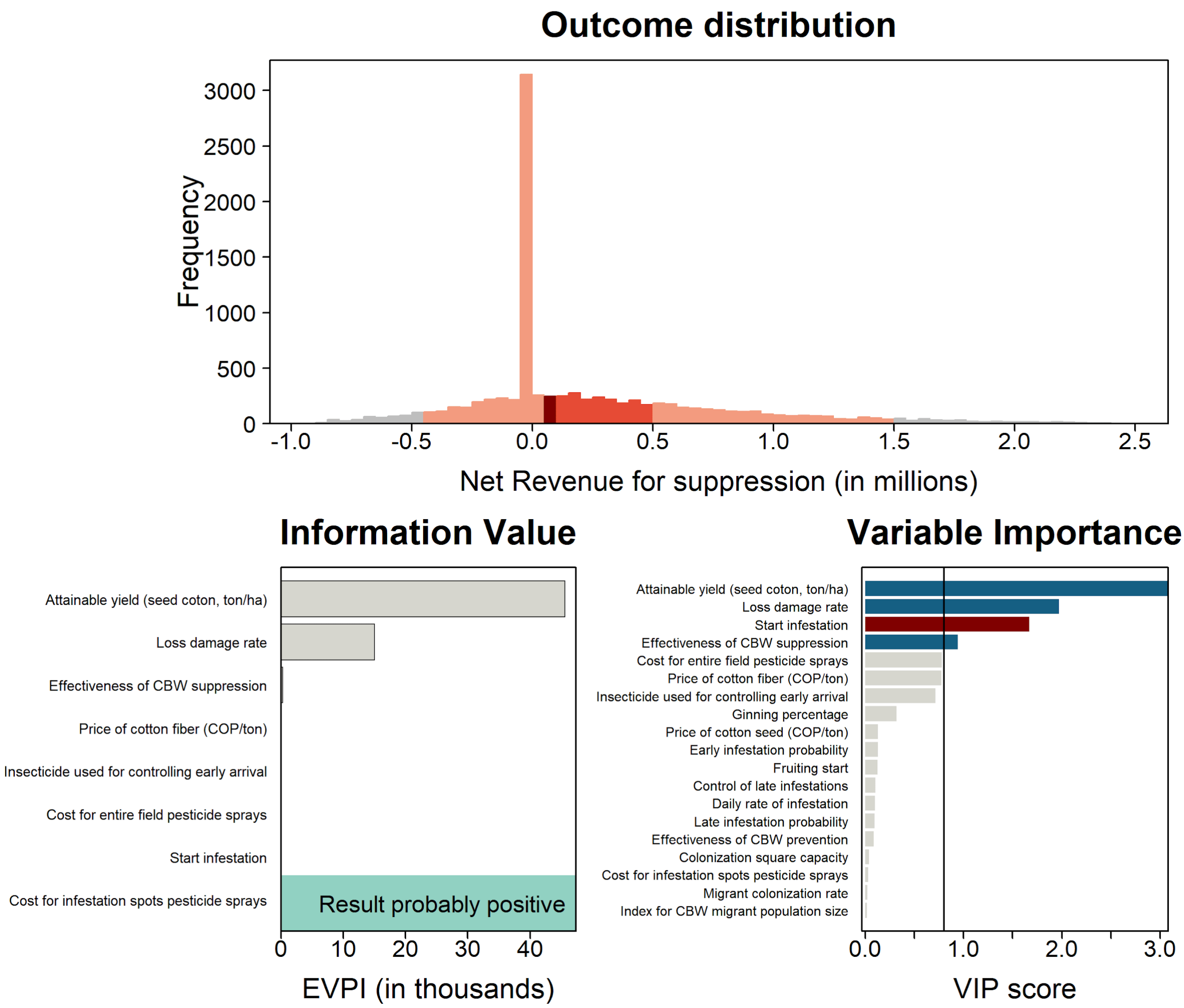
```
make_variables<-function(est,n=1)
{ x<-random(rho=est, n=n)
for(i in colnames(x)) assign(i, as.numeric(x[1,i]),envir=.GlobalEnv)}

make_variables(estimate_read_csv("PDF.csv"))
```

We gave the name `SYSTEM` the function that calculates the NPV for each individual control strategy against the boll weevil.

```
SYSTEM<-function(x, varnames)
{{

  Square_colonization <- Square_carrying_capacity/(1 + exp(-Colonization_rate*Trap_index)) # Based
on data presented by Rummel et al 1980 and field data from the Sinu Valley

  CBW_infestation_days <- ifelse((Boll_formation_DAS - Start_infestation_DAS)>0, (Boll_formation_DAS
- Start_infestation_DAS), 0)

  Square_infestation<- ifelse(CBW_infestation_days>0, (CBW_infestation_days*Infestation_daily_rate +
Square_colonization), 0)

  CBW_damage_loss<- Square_infestation*Loss_damage_rate/100

  ####### Yields estimation #######

  CBW_reduced_YIELD_SDC<-Attainable_yield*(1 - CBW_damage_loss) #SDC describes seed cotton yields /
Reduced yield
  Prevention_YIELD_SDC <- Attainable_yield*(1 - CBW_damage_loss*(1 - Prevention_effectiveness))#
Actual yield for the prevention strategy
  Suppression_YIELD_SDC <- Attainable_yield*(1 - CBW_damage_loss*(1 - Suppression_effectiveness))#
Actual yield for the suppression strategy

  #### Control Costs ########

  Prevention_sprays_number<- 1 +
Late_infestation_sprays*chance_event(Late_infestation_probability,1,0) #General field sprays
  Suppression_sprays_number<- Square_infestation*Spray_infestation_rate

  Prevention_cost<- Prevention_sprays_number*GRL_spray_cost
  Suppression_cost<- Suppression_sprays_number*GRL_spray_cost +
FOC_spray_cost*(ifelse(Suppression_sprays_number>1, 1, 0))

  No_action_cost <- 0

  ####### Revenues for all production situations: CBW control or no-action #########

  Revenue_CBW_reduced_YIELD_SDC<- CBW_reduced_YIELD_SDC*
```

```r
    (Ginning_fraction*Fiber_price_ton + (1-Ginning_fraction)*Seed_price_ton) -
    No_action_cost

  Revenue_Prevention_YIELD_SDC <- Prevention_YIELD_SDC*
    (Ginning_fraction*Fiber_price_ton + (1-Ginning_fraction)*Seed_price_ton) -
    Prevention_cost

  Revenue_Suppression_YIELD_SDC <- Suppression_YIELD_SDC*
    (Ginning_fraction*Fiber_price_ton + (1-Ginning_fraction)*Seed_price_ton) -
    Suppression_cost

  ##### Assessment of the decisions to intervene the system:##########
  ##### Cost and return analysis for the control actions #########

  Prevention_Net_Revenue <- Revenue_Prevention_YIELD_SDC - Revenue_CBW_reduced_YIELD_SDC
  Suppression_Net_Revenue <- Revenue_Suppression_YIELD_SDC - Revenue_CBW_reduced_YIELD_SDC
  }

  return(list(midSYSTEM_Prevention_cost=Prevention_cost,
              midSYSTEM_Suppression_cost=Suppression_cost,
              midSYSTEM_Revenue_CBW_reduced_YIELD_SDC=Revenue_CBW_reduced_YIELD_SDC,
              midSYSTEM_Revenue_Prevention_YIELD_SDC=Revenue_Prevention_YIELD_SDC,
              midSYSTEM_Revenue_Suppression_YIELD_SDC=Revenue_Suppression_YIELD_SDC,
              midSYSTEM_CBW_reduced_YIELD_SDC=CBW_reduced_YIELD_SDC,
              midSYSTEM_Prevention_YIELD_SDC=Prevention_YIELD_SDC,
              midSYSTEM_Suppression_YIELD_SDC=Suppression_YIELD_SDC,
              PRFSYSTEM_Prevention_Net_Revenue=Prevention_Net_Revenue,
              PRFSYSTEM_Suppression_Net_Revenue=Suppression_Net_Revenue))
}

### Running of the model
######################################################################################

decisionSupport("PDF.csv",
                outputPath='results',
                welfareFunction=SYSTEM,
                numberOfModelRuns=10000, randomMethod = "calculate",
                functionSyntax = "plainNames", relativeTolerance = 0.05,
                write_table = TRUE, plsrVipAnalysis = TRUE,
                individualEvpiNames = NULL, sortEvpiAlong = if (individualEvpiNames)
                  individualEvpiNames[[1]] else NULL, oldInputStandard = FALSE,
                verbosity = 1)

mc<-read.csv("results/mcSimulationResults.csv")
legend_table<-read.csv("PDF_legend.csv")
mc_EVPI<-mc[,-grep("midSYSTEM",colnames(mc))]
dir.create("Figures")

multi_EVPI(mc_EVPI,"PRFSYSTEM_Prevention_Net_Revenue",write_table=TRUE,outfolder="Figures")

for (variable_name in c("PRFSYSTEM_Prevention_Net_Revenue", "PRFSYSTEM_Suppression_Net_Revenue")) #
DAutilities
  compound_figure(variable_name=variable_name,
                  MC_table=mc,
                  PLS_table=read.csv(paste("results/",variable_name,"_pls_results.csv",sep="")),
                  EVPI_table=read.csv(paste("Figures/","EVPI_table_",variable_name,".csv",sep="")),
                  nbreaks=100,scaler="auto",percentile_remove=c(.01,.99),
                  plsthreshold=0.8,colorscheme="Chicago",MCcolor="mango",fonttype='sans',
                  borderlines=FALSE,lwd=2,
                  fileformat="png",filename=paste("Figures/","Combined_",variable_name,sep=""),
                  legend_table=read.csv("PDF_legend.csv"))
```


Outcome distribution
Frequency
1200
1000
800
600
400
200
0
0
1
2
3
Net Revenue for prevention (in millions)
Information Value
Start infestation
Attainable yield (seed coton, ton/ha)
Loss damage rate
Result probably positive
0
10
20
30
40
EVPI (in thousands)
Variable Importance
Start infestation
Attainable yield (seed coton, ton/ha)
Loss damage rate
Effectiveness of CBW prevention
Price of cotton fiber (COP/ton)
Control of late infestations
Fruiting start
Ginning percentage
Colonization square capacity
Daily rate of infestation
Cost for entire field pesticide sprays
Early infestation probability
Price of cotton seed (COP/ton)
Late infestation probability
Index for CBW migrant population size
Migrant colonization rate
Effectiveness of CBW suppression
Cost for infestation spots pesticide sprays
Insecticide used for controlling early arrival
0.0
1.0
2.0
3.0
VIP score



Outcome distribution
Frequency
3000
2500
2000
1500
1000
500
0
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
Net Revenue for suppression (in millions)
Information Value
Attainable yield (seed coton, ton/ha)
Loss damage rate
Effectiveness of CBW suppression
Price of cotton fiber (COP/ton)
Insecticide used for controlling early arrival
Cost for entire field pesticide sprays
Start infestation
Cost for infestation spots pesticide sprays
Result probably positive
0
10
20
30
40
EVPI (in thousands)
Variable Importance
Attainable yield (seed coton, ton/ha)
Loss damage rate
Start infestation
Effectiveness of CBW suppression
Cost for entire field pesticide sprays
Price of cotton fiber (COP/ton)
Insecticide used for controlling early arrival
Ginning percentage
Price of cotton seed (COP/ton)
Early infestation probability
Fruiting start
Control of late infestations
Daily rate of infestation
Late infestation probability
Effectiveness of CBW prevention
Colonization square capacity
Cost for infestation spots pesticide sprays
Migrant colonization rate
Index for CBW migrant population size
0.0
1.0
2.0
3.0
VIP score

Supplementary file S9. R-script describing the whole-farm system model

We employed the decisionSupportR package (Luedeling et al., 2020) (Luedeling, Goehring, and Schiffers 2019) and its functions to develop the model and to perform probabilistic simulations.

We defined sample values for all variables by generating a make_variables function to select randomly from each variable in the file describing their probability distribution functions (`"PDF.csv"`).

The `make_variables` function is used to generate one random value for each variable in the `"PDF.csv"` file. These values are not used in the simulation, but they are used for testing of the model code and troubleshooting purposes.

```
make_variables<-function(est,n=1)
{ x<-random(rho=est, n=n)
for(i in colnames(x)) assign(i, as.numeric(x[1,i]),envir=.GlobalEnv)}

make_variables(estimate_read_csv("PDF.csv"))
```

We gave the name `Whole_farm_system` the function that calculates the NPV for each individual crop option in an irrigated farm.

```
setwd("C:/Users/Oscar/Documents/BIOMONTERIA/R/MS44R Whole-farm model/MS44R.1")# Your local filepath

Whole_farm_system <-function(x, varnames)
{{
  # Year horizon for whole farm planning

  Initial_investment <- c(1,0,0,0,0)

  System_Cost<- Initial_investment*(Irrigation_System_cost/PU_size) +
    ((Irrigation_maintenance)/PU_size + (Land_lease + Irrigation_district_payment))

  # Cost of irrigation for one hectare of crop based on the number of used combustible
  Irrigation_cost <- (oilQ_price/N_irrigations_oilQ_ha +  combustibleG_price/N_irrigations_combustibleG_ha)

  ##########################################################
  # Eggplant crop
  ##########################################################

  ## Yield estimation

  EP_pest_loss <-chance_event(xEP_pest_frequency, (1-xEP_pest_loss*(1-xEP_pest_control)),1, n_years)

  EP_disease_loss <- chance_event(xEP_disease_frequency, (1-xEP_disease_loss*(1-xEP_disease_control)),1,
n_years)*
    chance_event(yEP_disease_frequency, (1-yEP_disease_loss*(1-yEP_disease_control)),1, n_years)

  EP_yield <- EP_Potential_yield*EP_pest_loss*EP_disease_loss

  ## Production Costs, revenues and profit per hectare

  EP_mean_price<- EP_seasonal_allocation*vv(EP_upper_price, EP_CV_price, n_years) +
    (1-EP_seasonal_allocation)*vv(EP_lower_price, EP_CV_price, n_years)

  EP_gross_revenue<- EP_mean_price*EP_yield

  EP_Yearly_land_occupation <- EP_total_growing_period/12

  EP_plot_revenue <- EP_gross_revenue - EP_cost - Irrigation_cost

  # Costs and benefits
```

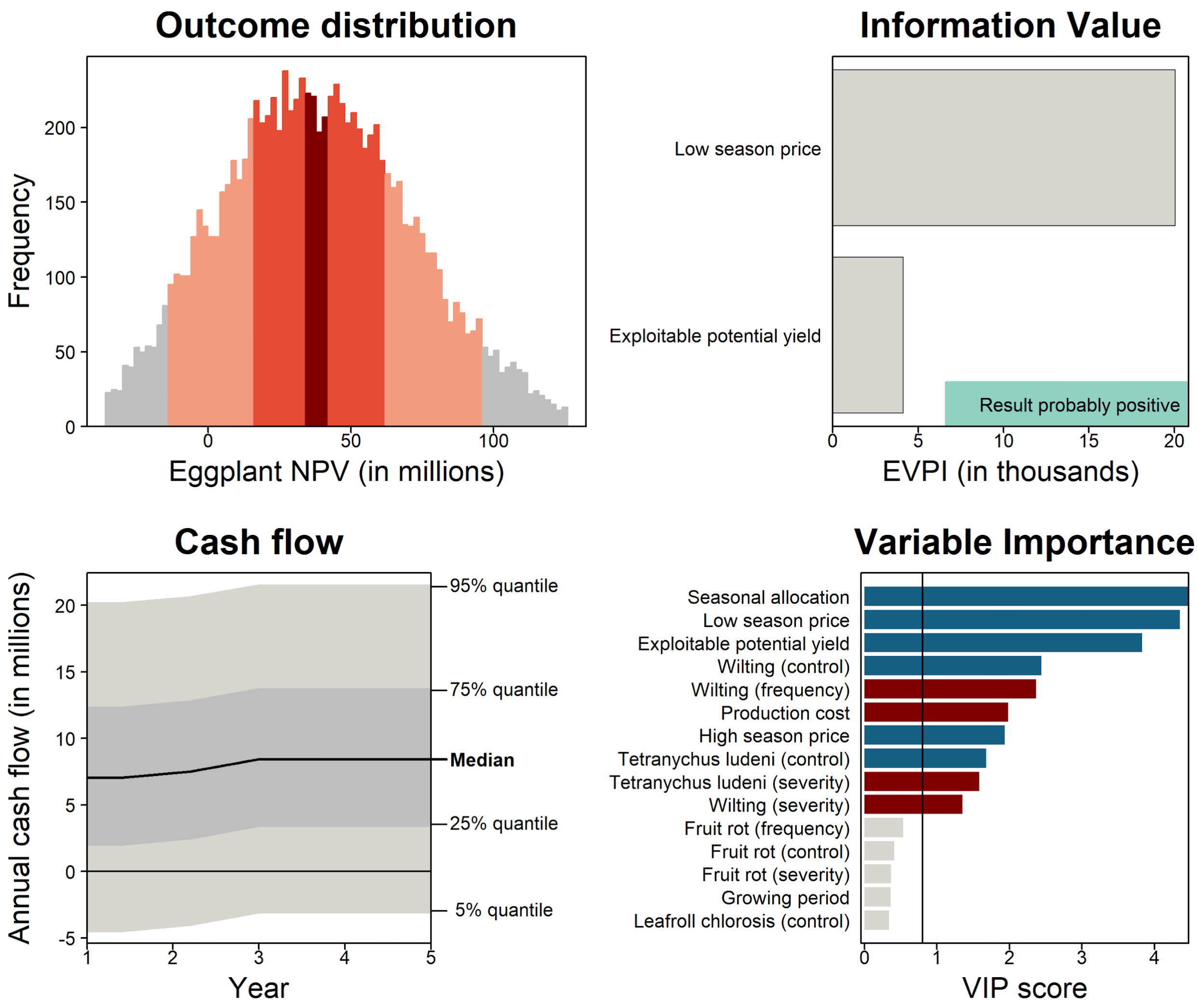
```
  EP_Production_Costs<- EP_cost + Irrigation_cost*EP_irrigation +
    EP_Yearly_land_occupation*(Initial_investment*(EP_irrigation_system) + System_Cost)

  EP_profit <- (EP_gross_revenue - EP_Production_Costs)*EP_area

  NPV_EP_profit<-discount(EP_profit,discount_rate, calculate_NPV = TRUE)

  Discounted_EP_Production_Costs <-discount(EP_Production_Costs,discount_rate, calculate_NPV = TRUE)

  Discounted_EP_revenue <-discount(EP_gross_revenue,discount_rate, calculate_NPV = TRUE)

  EP_MFP <- Discounted_EP_revenue/Discounted_EP_Production_Costs

  ##############################################################
  # Sweet pepper crop
  ##############################################################

  ### Yield estimation

  SP_pest_loss <- chance_event(xSP_pest_frequency,(1-xSP_pest_loss*(1-xSP_pest_control)),1, n_years)

  SP_disease_loss <- chance_event(xSP_disease_frequency,(1-xSP_disease_loss*(1-xSP_disease_control)),1,
n_years)*
    chance_event(ySP_disease_frequency,(1-ySP_disease_loss*(1-ySP_disease_control)),1, n_years)

  SP_yield <- SP_Potential_yield*SP_pest_loss*SP_disease_loss

  ### Production Costs, revenues and profit per hectare

  SP_mean_price<- SP_seasonal_allocation*vv(SP_upper_price, SP_CV_price, n_years) +
    (1-SP_seasonal_allocation)*vv(SP_lower_price, SP_CV_price, n_years)

  SP_gross_revenue <- SP_mean_price*SP_yield

  SP_Yearly_land_occupation <- SP_total_growing_period/12

  SP_plot_revenue <- SP_gross_revenue - SP_cost - Irrigation_cost# Revenue per hectare

  ### Cost and benefits

  SP_Production_Costs<- SP_cost + Irrigation_cost*SP_irrigation +
    SP_Yearly_land_occupation*(Initial_investment*(SP_irrigation_system) + System_Cost)

  SP_profit <- (SP_gross_revenue - SP_Production_Costs)*SP_area

  NPV_SP_profit<-discount(SP_profit,discount_rate, calculate_NPV = TRUE)

  Discounted_SP_Production_Costs <-discount(SP_Production_Costs,discount_rate, calculate_NPV = TRUE)

  Discounted_SP_revenue <-discount(SP_gross_revenue,discount_rate, calculate_NPV = TRUE)

  SP_MFP <- Discounted_SP_revenue/Discounted_SP_Production_Costs

  ##############################################################
  # Yardlong beans crop
  ##############################################################

  ### Yield estimation

  GB_pest_loss <-chance_event(xGB_pest_frequency,(1-xGB_pest_loss*(1-xGB_pest_control)), 1, n_years) *
    chance_event(yGB_pest_frequency,(1-yGB_pest_loss*(1-yGB_pest_control)), 1, n_years)

  GB_disease_loss <-chance_event(xGB_disease_frequency,(1-xGB_disease_loss*(1-xGB_disease_control)), 1,
n_years) *
    chance_event(yGB_disease_frequency,(1-yGB_disease_loss*(1-yGB_disease_control)), 1, n_years)

  GB_yield <- GB_Potential_yield*GB_pest_loss*GB_disease_loss

  ### Production Costs, revenues and profit per hectare

  GB_mean_price<- GB_seasonal_allocation*GB_upper_price + (1-GB_seasonal_allocation)*GB_lower_price
```

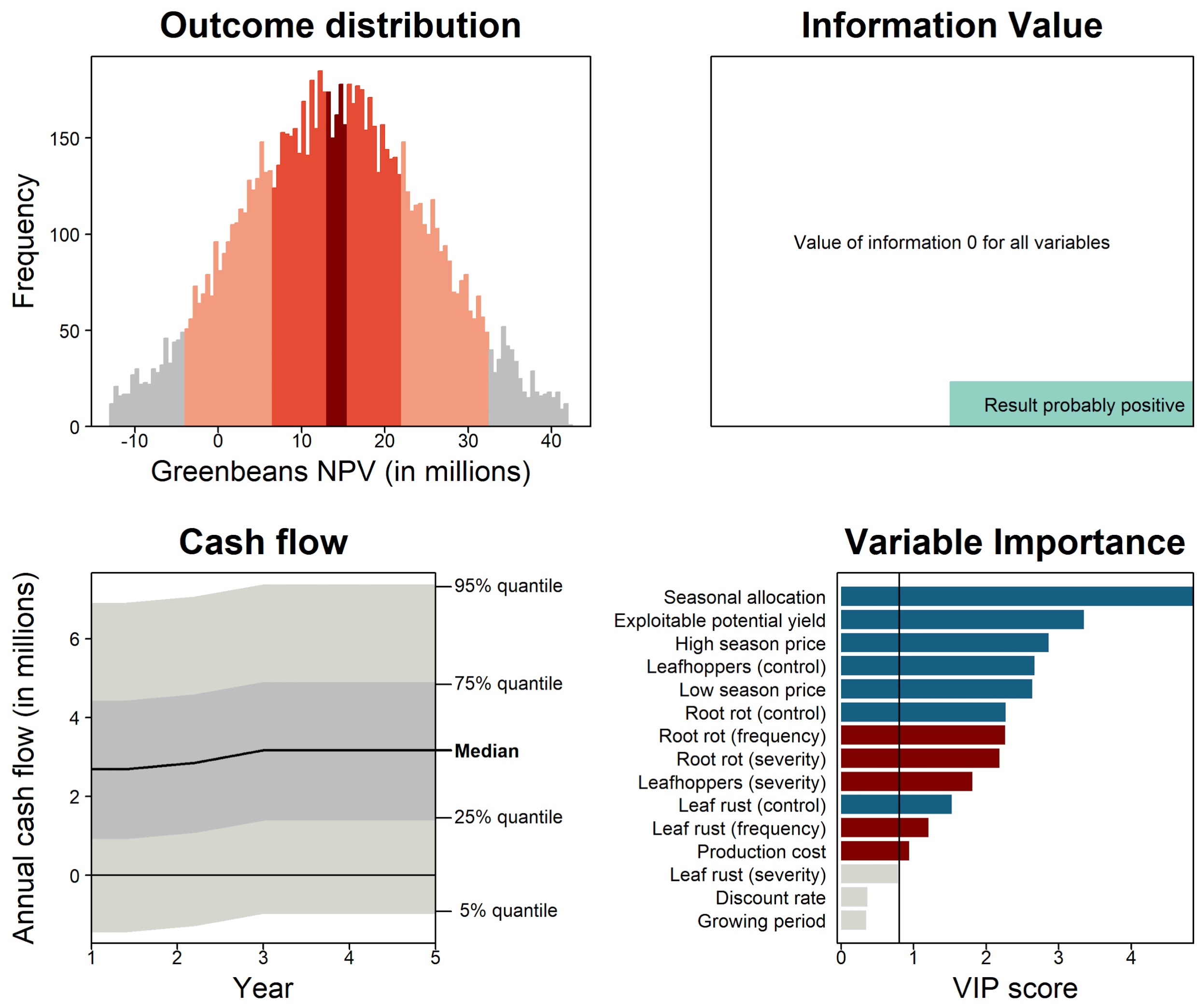
```
  GB_gross_revenue<- GB_mean_price*GB_yield

  GB_Yearly_land_occupation <- GB_total_growing_period/12

  GB_plot_revenue <- GB_gross_revenue - GB_cost - Irrigation_cost

  ### Costs and benefits

  GB_Production_Costs<- GB_cost + Irrigation_cost*GB_irrigation +
    GB_Yearly_land_occupation*(Initial_investment*(GB_irrigation_system) + System_Cost)

  GB_profit <- (GB_gross_revenue - GB_Production_Costs)*GB_area

  NPV_GB_profit<-discount(GB_profit,discount_rate, calculate_NPV = TRUE)

  Discounted_GB_Production_Costs <-discount(GB_Production_Costs,discount_rate, calculate_NPV = TRUE)

  Discounted_GB_revenue <-discount(GB_gross_revenue,discount_rate, calculate_NPV = TRUE)

  GB_MFP <- Discounted_GB_revenue/Discounted_GB_Production_Costs

  ##############################################################
  # Papaya crop
  ##############################################################

  ### Yield estimation

  PY_Planting_dates<- c(1, 1, 1, 1, 1)

  Year_cost_allocation<-c(relative_annual_yield, 1, 1, 1,(1-relative_annual_yield)) # Variable costs

  PY_pest_loss <- chance_event(xPY_pest_frequency,(1-xPY_pest_loss*(1-xPY_pest_control)),1, n_years)

  PY_disease_loss <- chance_event(xPY_disease_frequency,(1-xPY_disease_loss*(1-xPY_disease_control)),1,
n_years)*
    chance_event(yPY_disease_frequency,(1-yPY_disease_loss*(1-yPY_disease_control)),1, n_years)

  PY_yield <- PY_Potential_yield*PY_pest_loss*PY_disease_loss*Year_cost_allocation

  ### Production Costs, revenues and profit per hectare

  PY_mean_price<- PY_seasonal_allocation*vv(PY_upper_price, PY_CV_price, n_years) +
    (1- PY_seasonal_allocation)*vv(PY_lower_price, PY_CV_price, n_years)

  PY_gross_revenue<- PY_mean_price*PY_yield

  Overlapping_growing_seasons <- 1 + (PY_total_growing_period-12)/12

  PY_Yearly_land_occupation <- c(1, Overlapping_growing_seasons, Overlapping_growing_seasons,
                                Overlapping_growing_seasons,(PY_total_growing_period-12)/12)

  PY_plot_revenue <- PY_gross_revenue - PY_cost - Irrigation_cost

  ### Costs and benefits

  PY_Production_Costs<- PY_Planting_Cost*PY_Planting_dates +
    Year_cost_allocation*(PY_cost + Irrigation_cost*PY_irrigation) +
    PY_Yearly_land_occupation*(Initial_investment*(PY_irrigation_system) + System_Cost)

  PY_profit <-(PY_gross_revenue - PY_Production_Costs)*PY_area

  NPV_PY_profit<-discount(PY_profit,discount_rate, calculate_NPV = TRUE)

  Discounted_PY_Production_Costs <-discount(PY_Production_Costs,discount_rate, calculate_NPV = TRUE)

  Discounted_PY_revenue <-discount(PY_gross_revenue,discount_rate, calculate_NPV = TRUE)

  PY_MFP <- Discounted_PY_revenue/Discounted_PY_Production_Costs
}

  return(list(NPV_EP_profit=NPV_EP_profit,
```

```r
               VAR_cashflow_NPV_EP_profit=EP_profit,
               NPV_SP_profit=NPV_SP_profit,
               VAR_cashflow_NPV_SP_profit=SP_profit,
               NPV_GB_profit=NPV_GB_profit,
               VAR_cashflow_NPV_GB_profit=GB_profit,
               NPV_PY_profit=NPV_PY_profit,
               VAR_cashflow_NPV_PY_profit=PY_profit
               ))
}

##################################################################
# Running the model
##################################################################

decisionSupport("PDF.csv",
                outputPath='results',
                welfareFunction=Whole_farm_system,
                numberOfModelRuns=100, randomMethod = "calculate",
                functionSyntax = "plainNames", relativeTolerance = 0.05,
                write_table = TRUE, plsrVipAnalysis = TRUE,
                individualEvpiNames = NULL, sortEvpiAlong = if (individualEvpiNames)
                  individualEvpiNames[[1]] else NULL, oldInputStandard = FALSE,
                 verbosity = 1)
```

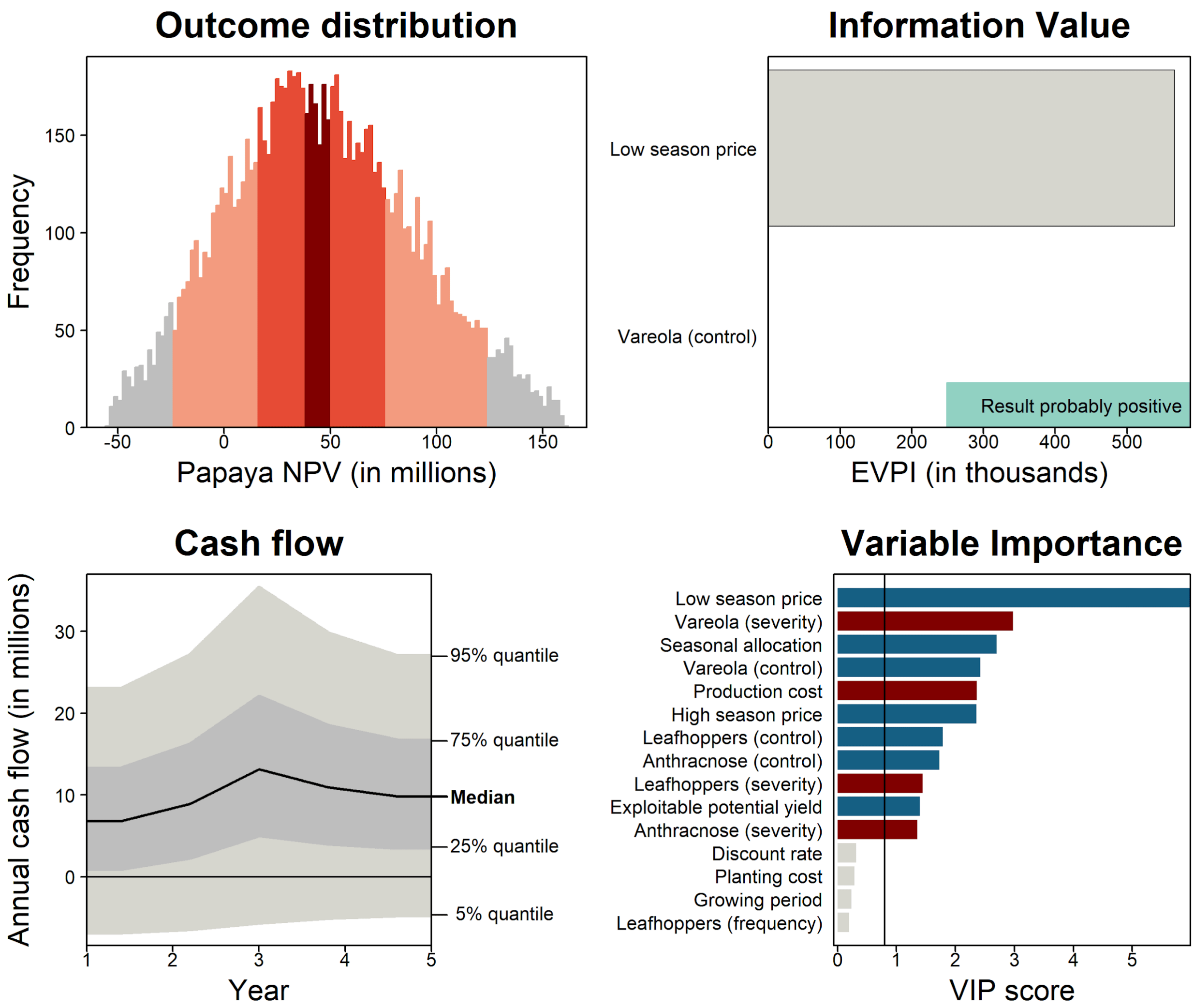
A graphical output for simulation results `("results/mcSimulationResults.csv")` of each crop option can be obtained with the following script:

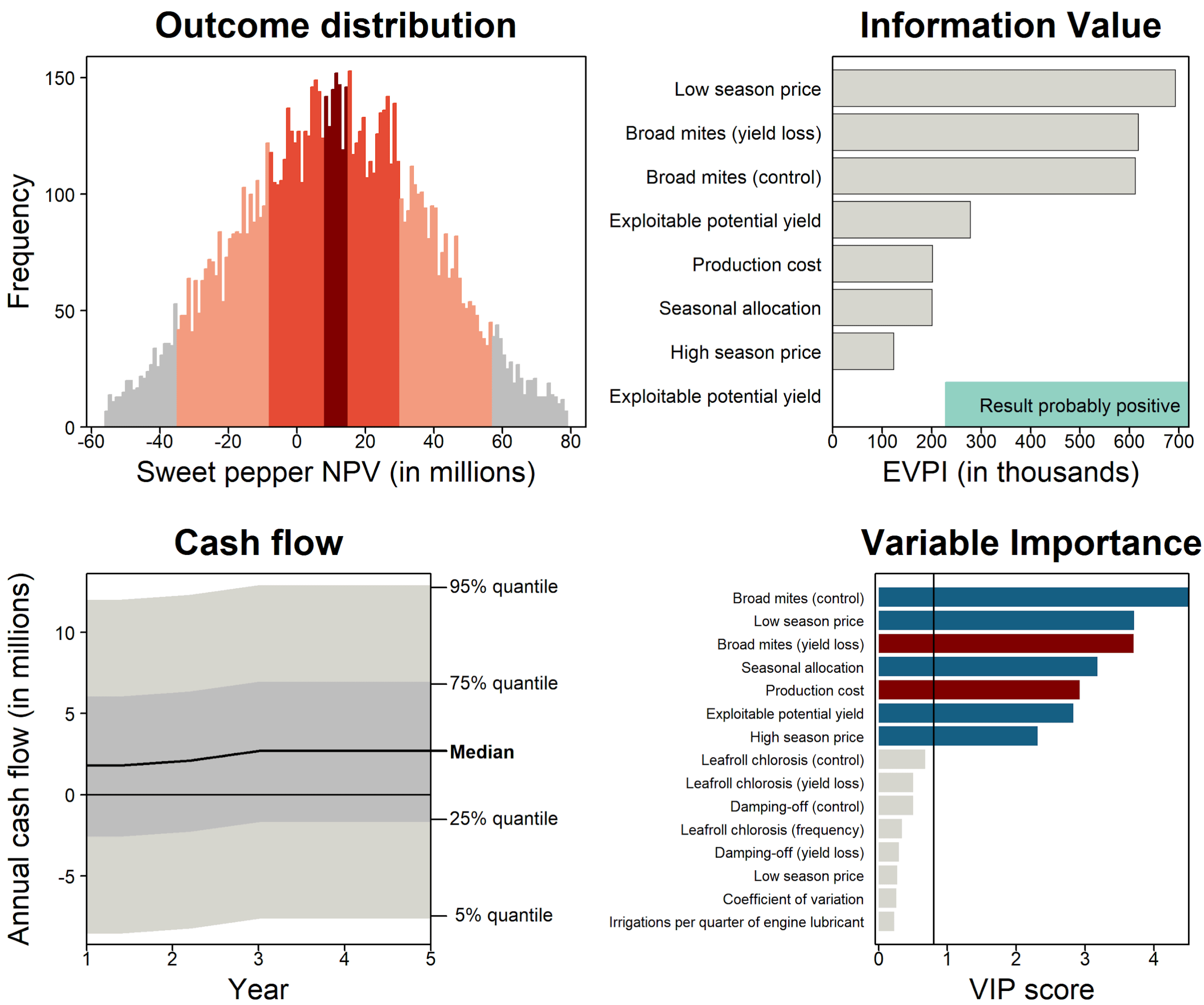
```r
# Graphical output

mc<-read.csv("results/mcSimulationResults.csv")

legend_table<-read.csv("PDF_legend.csv")

mc_EVPI<-mc[,-grep("VAR_",colnames(mc))]
dir.create("Figures")

multi_EVPI(mc_EVPI,"NPV_EP_profit",write_table=TRUE,outfolder="Figures")

for (variable_name in c("NPV_EP_profit", "NPV_SP_profit", "NPV_GB_profit", "NPV_PY_profit"))
  compound_figure(variable_name=variable_name,
                  MC_table=mc,
                  PLS_table=read.csv(paste("results/",variable_name,"_pls_results.csv",sep="")),
                  EVPI_table=read.csv(paste("Figures/","EVPI_table_",variable_name,".csv",sep="")),
                  cash_flow_vars=paste("VAR_cashflow_",variable_name,sep=""),
                  nbreaks=100,scaler="auto",percentile_remove=c(.01,.99),
                  npls=15,plsthreshold=0.8,colorscheme="Chicago",MCcolor="mango",fonttype='sans',
                  borderlines=FALSE,lwd=2,
                  fileformat="png",filename=paste("Figures/","Combined_",variable_name,sep=""),
                  legend_table=read.csv("PDF_legend.csv"))
```


Outcome distribution
Frequency
Eggplant NPV (in millions)
Information Value
Low season price
Exploitable potential yield
Result probably positive
EVPI (in thousands)
Cash flow
Annual cash flow (in millions)
95% quantile
75% quantile
Median
25% quantile
5% quantile
Year
Variable Importance
Seasonal allocation
Low season price
Exploitable potential yield
Wilting (control)
Wilting (frequency)
Production cost
High season price
Tetranychus ludeni (control)
Tetranychus ludeni (severity)
Wilting (severity)
Fruit rot (frequency)
Fruit rot (control)
Fruit rot (severity)
Growing period
Leafroll chlorosis (control)
VIP score



Outcome distribution
Frequency
Greenbeans NPV (in millions)
Information Value
Value of information 0 for all variables
Result probably positive
Cash flow
Annual cash flow (in millions)
95% quantile
75% quantile
Median
25% quantile
5% quantile
Year
Variable Importance
Seasonal allocation
Exploitable potential yield
High season price
Leafhoppers (control)
Low season price
Root rot (control)
Root rot (frequency)
Root rot (severity)
Leafhoppers (severity)
Leaf rust (control)
Leaf rust (frequency)
Production cost
Leaf rust (severity)
Discount rate
Growing period
VIP score


Outcome distribution
Frequency
Papaya NPV (in millions)
Information Value
Low season price
Vareola (control)
Result probably positive
EVPI (in thousands)
Cash flow
Annual cash flow (in millions)
95% quantile
75% quantile
Median
25% quantile
5% quantile
Year
Variable Importance
Low season price
Vareola (severity)
Seasonal allocation
Vareola (control)
Production cost
High season price
Leafhoppers (control)
Anthracnose (control)
Leafhoppers (severity)
Exploitable potential yield
Anthracnose (severity)
Discount rate
Planting cost
Growing period
Leafhoppers (frequency)
VIP score



Outcome distribution
Frequency
Sweet pepper NPV (in millions)
Information Value
Low season price
Broad mites (yield loss)
Broad mites (control)
Exploitable potential yield
Production cost
Seasonal allocation
High season price
Exploitable potential yield
Result probably positive
EVPI (in thousands)
Cash flow
Annual cash flow (in millions)
95% quantile
75% quantile
Median
25% quantile
5% quantile
Year
Variable Importance
Broad mites (control)
Low season price
Broad mites (yield loss)
Seasonal allocation
Production cost
Exploitable potential yield
High season price
Leafroll chlorosis (control)
Leafroll chlorosis (yield loss)
Damping-off (control)
Leafroll chlorosis (frequency)
Damping-off (yield loss)
Low season price
Coefficient of variation
Irrigations per quarter of engine lubricant
VIP score

Supplementary file S10. R-script for visualizing CDFs for NPV and multifactor productivity

We obtained cumulative distribution plots using the `ggplot2` (Wickham, 2011), `reshape` (Wickham and Wickham, 2015; Wickham, 2018) and `RColorBrewer` (Neuwirth, 2020, 2015) packages.

```r
library(ggplot2)
library(reshape)
library(RColorBrewer)

#############################################################
# NPV
############################################################

PY<- mc$NPV_PY_profit/1000000
GB<- mc$NPV_GB_profit/1000000
SP<- mc$NPV_SP_profit/1000000
EP<- mc$NPV_EP_profit/1000000
Run <- as.vector(t(mc[1]))
RunIndex <-as.Date(RUN, origin = "0000-00-00")

CROPINDEX <-data.frame("Papaya" = PY,"Yardlong-beans"= GB, "Sweet-pepper"= SP, "Eggplant"= EP, row.names =
RunIndex)

combine <- melt(CROPINDEX)
summary(combineNPV)

## Cumulative distribution function plot

Cumulative<-ggplot(data = combineNPV, aes(x=value, color=variable,shape=variable)) +
  stat_ecdf(size=0.5) + xlim(-75,200) + theme_bw(10) +
  scale_color_manual(values=c("darkorange2","darkgreen", "red", "purple")) +
  theme(legend.position = c(0.8, 0.3),
        legend.direction = "vertical",
        axis.title.y = element_text(margin = margin(t = 0, r = 10, b = 0, l = 0)))

print(Cumulative + labs(y="Cumulative Distribution", x = "NPV (million COP/ha)", colour="Crops"))

#############################################################
# Multi-factor Productivity
############################################################

PYmfp<- mc$VAR_PY_MFP
GBmfp<- mc$VAR_GB_MFP
SPmfp<- mc$VAR_SP_MFP
EPmfp<- mc$VAR_EP_MFP

combineMFP = melt(data.frame("Papaya" = PYmfp,"Yardlong-beans"= GBmfp, "Sweet-pepper"= SPmfp, "Eggplant"=
EPmfp))

## Cumulative distribution function plot

Cumulative<-ggplot(data = combineMPF, aes(x=value, color=variable,shape=variable)) +
  stat_ecdf(size=0.5) +
  xlim(0,3.5) +
  theme_bw(10) +
  scale_color_manual(values=c("darkorange2","darkgreen", "red", "purple")) +
  theme(legend.position = c(0.8, 0.3),
        legend.direction = "vertical",
        axis.title.y = element_text(margin = margin(t = 0, r = 10, b = 0, l = 0)))

print(Cumulative + labs(y="Cumulative Distribution", x = "Multifactor Productivity (MFP)",
colour="Crops"))
```

Supplementary file S11. R-script for building portfolio diversification strategies

We built diversification strategies for the irrigated horticultural production systems using the `(PortfolioAnalytics)` package (Bennett, 2018; Peterson et al., 2015)

```
library(PortfolioAnalytics)

data <-CROPINDEX[,1:4]

colnames(data) <- c("EP", "GB", "PY","SP")
port_spec <- portfolio.spec(colnames(data))
port_spec

port_spec <- add.constraint(portfolio = port_spec, type= "full_investment")

# constraint 2: long only:
port_spec <- add.constraint(portfolio = port_spec, type= "long_only")
port_spec
######################################################
# PortfolioAnalytics Portfolio Specification
######################################################

# objective 1: Maximizing pf return
port_spec <- add.objective(portfolio = port_spec,
                           type = "return",
                           name = "mean")
# objective 2: minimizing pf risk
port_spec <- add.objective(portfolio = port_spec,
                           type = "risk",
                           name = "StdDev")
print(port_spec)

# Run optimization and chat results in risk-reward space
opt <- optimize.portfolio(data, portfolio = port_spec,
                          optimize_method = "random",
                          trace=TRUE)

chart.RiskReward(opt, risk.col = "StdDev", return.col = "mean",
                 chart.assets = TRUE, xlim = (c(1,15)))

chart.Concentration(opt, return.col = "mean", risk.col = "StdDev",
                    chart.assets = TRUE, conc.type = c("weights", "pct_contrib"),
                    col = heat.colors(20), element.color = "lightgray", cex.axis = 0.8,
                    xlim =c(0.00, 15), ylim = NULL)

plot(opt, main="", risk.col="StdDev", neighbors=200, chart.assets = TRUE,
     cex.axis = 0.8, xlim=(1:15))

extractWeights(opt)
```

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