Learning from biophysical heterogeneity:

inductive use of case studies for maize cropping systems

in Central America

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STELLINGEN

1. Er zijn geen theoretische redenen voor het mijden van dynamische simulatiemodellen bij toepassingen op regionale schaal. Er zijn slechts praktische redenen.
   dit proefschrift

2. Gebrek aan geschikte bodemgegevens vormt de grootste beperking voor regionale analyse van teelt- en gewasrotatiesystemen.
   dit proefschrift

3. Visualisatie van de regionale mogelijkheden voor teeltsystemen bevordert multidisciplinaire discussie over en begrip van de opties voor agrarische ontwikkeling.
   dit proefschrift

4. Biofysische doelgerichtheid - zoals in dit proefschrift gedefinieerd - is een middel voor ruimtelijke en tijdgebonden prioriteitstelling door belanghebbenden bij planning van landgebruik.

5. Dat een mens ook maar een dier is, had bij de consequenties van de in de jaren '50 reeds ontdekt Kuru ziekte op Papua Nieuw-Guinea kunnen leiden tot inzicht waarmee de BSE crisis in koeien had kunnen worden voorkomen.

6. Dat het leven niet gemakkelijk hoeft te zijn, maar wel de moeite waard, zou ons moeten stimuleren om het hoofd vaker boven het maaiveld uit te steken. Heterogeniteit in de samenleving is een aanwinst.

7. De perspectieven voor vrouwelijke wetenschappers in ontwikkelingslanden kunnen worden vergroot door meer mannen aan te nemen op niet-wetenschappelijke posities.

8. Bij het signaleren van leemtes in kennis, zijn zwarte gaten erger dan witte vlekken.

Stellingen behorende bij het proefschrift van A.D. Hartkamp:
Learning from biophysical heterogeneity: inductive use of case studies for maize cropping systems in Central America
Wageningen, 3 juni 2002.

PROPOSITIONS

1. There are no theoretical reasons for avoiding dynamic process-based simulation models in applications at the regional scale. There are merely practical reasons.
   this thesis

2. Lack of appropriate soil data is the major limitation to regional cropping system analysis.
   this thesis

3. Visualization of the regional possibilities for cropping systems facilitates multi-disciplinary discussion and understanding of options for agricultural development.
   this thesis

4. Biophysical targeting - as described in this thesis - is a means for spatial and temporal priority setting by stakeholders in landuse planning.

5. If the consequences of the Kuru disease of Papua New Guinea, discovered in the 50's, had been studied more carefully, the concept that humans are also animals would have led to an insight that could have prevented BSE in cows.

6. The advancement of women in science in developing countries can be facilitated by increased recruitment of male personnel in non-scientific positions.

7. Life isn't supposed to be easy, it's supposed to be worth it; therefore we should not hesitate to stick our head out above the *Dutch* mowing field. After all, heterogeneity is a valuable asset to society.

8. When signaling knowledge gaps, black holes are worse than white spots.

Propositions belonging to the thesis by A.D. Hartkamp:
Learning from biophysical heterogeneity: inductive use of case studies for maize cropping systems in Central America
Wageningen, June 3, 2002.

ABSTRACT[1]

Global society has become conscious that efforts towards securing food production will only be successful if agricultural production increases are obtained through mechanisms that ensure active regeneration of the natural resource base. Production options should be targeted in the sense of that their suitability to improve agricultural production and maintain natural resources is evaluated prior to their introduction. Biophysical targeting evaluates production options as a function of the spatial and temporal variability of climate conditions, in interaction with soil, crop characteristics and agronomic management strategies. This thesis contributes to the development of a system-based methodology for biophysical targeting. Cropping system simulation and weather generator tools are interfaced to geographical information systems. Inductive use of two case studies – a green manure cover crop and reduced tillage with residue management – helped to develop the methodology. Insight is gained into the regional potential for and the soil and climate conditions under which successful introduction of these production options may be achieved. The resulting information supports regional stakeholders involved in agriculture in their analysis and discussion, negotiation and decision-making concerning where to implement production systems. This process can improve the supply of appropriate agricultural production practices that enhance production and conserve soil and water resources.

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[1] *Hartkamp, A.D., 2002. Learning from biophysical heterogeneity: inductive use of case studies for maize cropping systems in Central America. Ph.D. thesis. Wageningen University, The Netherlands, 256 pp.*

voor Sal…die vroeger uren in die ribben bibliotheek zat!

TABLE OF CONTENTS

1.
INTRODUCTION

This chapter introduces the reader to the focus, aim, objectives and approach of the study.

Designing and redesigning agricultural production systems

Agriculture is both the cause and victim of worldwide environmental degradation (Dover and Talbot, 1987).

Numerous quotes such as the above indicate that our global society has become conscious that efforts towards securing food production will only be successful if agricultural production increases are obtained through mechanisms that ensure active regeneration of the natural resource base. Degradation of resources for production has reached the stage that it seriously limits the productive capacity of some environments and undermines advances in others (Napier, 1994; Erenstein, 1999). The focus of agricultural research and development has been widened to include natural resource management. Equally evident is that production increases should largely come from the better use of land that is already in production (Shaxon et al., 1989). Despite the growing liberalization of global markets, the bulk of food will need to be produced in the places where it is needed, mainly due to socio economic and political constraints (Rabbinge, 1999). The design and redesign of agricultural production systems must therefore focus on the efficient use of the resources for production and on the location where it can be produced.

Key questions related to the design of these production systems are:

- What are untapped opportunities for production increases?
- Which production systems or practices can slow or reverse resource degradation?
- Which biophysical and social processes are affected by production systems and how do these processes increase the efficiency of the use of the resource base?
- Within which time frame do these processes take effect?
- Where is the introduction of these systems and practices most appropriate?
- Which trade-offs and decisions are to be made?

To respond to these potentially complex questions and issues, a problem-solving approach is fundamental. From the complex reality of societal demand for agricultural production and other products such as environment, landscape and health,

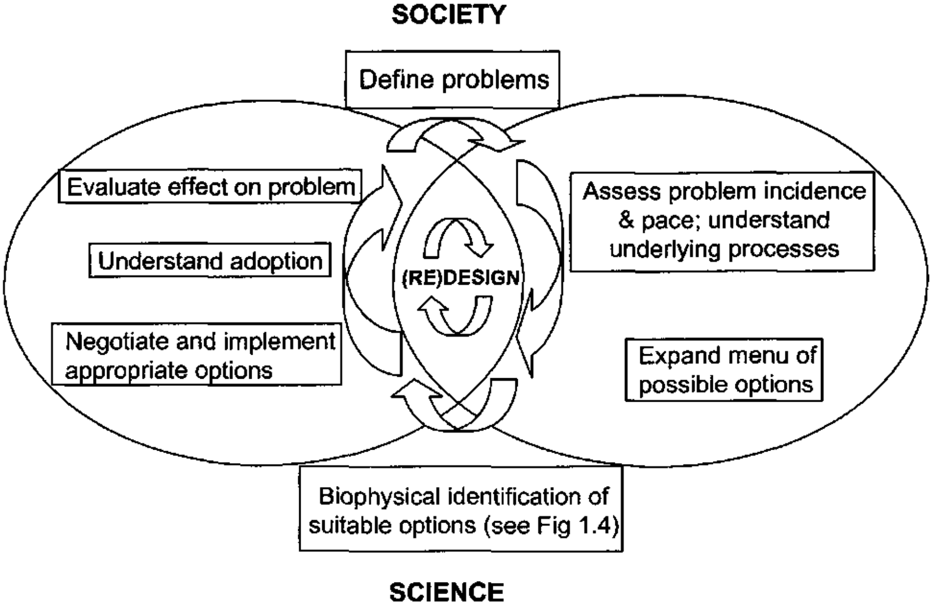

Figure 1.1 Design and redesign within a problem-solving approach.

problems or issues must be identified and defined for science to be able to contribute (Fig. 1.1). In this phase of definition of problems or issues it is highly desirable that stakeholders and scientists interact. Driven from smaller identifiable problems, the design of production options asks for innovation. This innovation may come from science, including on farm research by producers or from society. The introduction and implementation of production options should be targeted for their suitability to improve agricultural production and maintain natural resources. Suitability has several dimensions: environmental, economical and social. The feasibility of production options can be analysed through a hierarchy where climate and soil conditions are viewed as first order determinants. Subsequently, probability of success is revised based on biotic constraints (e.g., diseases and pests), economic viability and social acceptability. Promising options are tested and revised on experiment stations or in farmers' fields. To extrapolate the suitability from test sites to a wider region, we need to understand the 'which, where, when and why' of suitability of agricultural production options. The implementation of appropriate production options is a complex and often piecemeal engineering process. Scientists and stakeholders interact and negotiate further on the appropriate options within the societal settings. Adaptation or redesign of options may take place at this regional negotiation level or locally, on site. Often, several iterations are needed before a specific question or issue is 'resolved'.

This study focuses on a key component of the design and implementation process, namely the biophysical targeting of agricultural production options. This dimension of targeting aims to provide insight in the expected performance of production options given the spatial and temporal variability of climate conditions in interaction with soil, crop characteristics and agronomic management strategies. Through interactions with stakeholders, insights are further developed and used for decision-making. Further learning on socio-economic settings and possible negotiation on priorities – given normative, value driven objectives and specification of the target groups – determines the ultimate *targeting* of production options.

Biophysical targeting is important because it can:

- Prioritize areas for technology introduction and implementation.
- Reduce inappropriate wide scale introduction and implementation.
- Identify gaps in the options and in the knowledge needed for the (re)design.

Agricultural research and extension can seldom cover all areas and subjects dedicated to agriculture. Priority setting concerning substance as well as area is necessary. Biophysical targeting can support decision-making by indicating where, when and why production options are suitable taking into account the climate and soil conditions. Trade-off's and trade-on's are quantified to guide appropriate choices. Consequently, socio-economic research on technology development and adaptation can be targeted more systematically, augmenting the overall efficiency. Through this process, technological-knowledge gaps can be identified, triggering systematic design or redesign of production options. As a spin-off, geographical gaps also can be identified. The visualization and identification of these areas where the option is inappropriate can facilitate the design of alternative options. The ultimate goal of this process is to accelerate and improve the implementation of options for agricultural production.

Traditionally, a top-down supply-oriented linear 'knowledge' model for research and technology transfer has dominated agricultural development. Fundamental research fed one-way into strategic and applied research. Possibilities for end-user adaptation were minimal. Agricultural research and development followed a 'technology-push' pathway. Currently, we are aware that the pathway needs to be of a more 'technology-pull' nature. Besides this focus on the need for technology development and innovation, agricultural research contributes to a learning process that improves decision-making. A more interactive and iterative knowledge model is needed to improve the efficiency of answering societal demand for agricultural production options.

Methodologies for targeting

Large-scale promotion of single agricultural production options has led to sub-optimal and occasionally inappropriate introduction of these options. As a consequence, dis-adoption or abandonment occurs. Such negative experiences imply inefficient use of research and development resources and can lead to loss of faith in future suitability of production systems and options (Bunch, 1995). Methodologies to scale up from site- and term[1] specific research experiences to larger regional introduction are scarce and seldom robust. These methodologies are needed to *biophysically* target the technology, to identify where, when and why it is *biophysically* suitable.

Previously, targeting of production systems or technologies emphasized stratification of farmer groups in 'recommendation domains'. A recommendation domain is a group of roughly homogeneous farmers (in the sense of similar socio-economic resources) for whom we can make similar recommendations (Byerlee and Collinson, 1980; Harrington and Tripp, 1984; Shaner, 1984). Although heterogeneity among farmers (resources and objectives) is recognized in general terms, the latter is considered subordinate in the targeting process. This ignores the fact that success from technologies is spatially *variable* and that soil and climate conditions on site are first order determinants. In other words, technologies are not fixed packages that result in the same output if a standard input of management practices is applied. Therefore, it can be argued that recommendation domains fail to guide technology introduction in defining where, when and how certain agricultural production options work.

More biophysical approaches to targeting are those that classify environments into homogeneous ecological units, or agro-ecological zones frequently based on potential production level for single crops (Aggarwal, 1993; Wood and Pardey, 1993). Agro-ecological zones have proven useful in identifying large zones of similar production potential. However, the spatial variability within a zone can be high, and the method is unresponsive to crop characteristics or agronomic management (Garrity et al., 1989). For the targeting and implementation of specific cropping systems and management strategies, a method that is responsive to the heterogeneity of soil and climate is desired. Other methods include various forms of adaptation or suitability mapping such as land evaluation, crop geography, clustering aggregations and site similarity studies. Land evaluation is a physical suitability assessment method in which land properties are compared with requirements of a specific land use (FAO, 1976; Dent and Young, 1981). The land use requirements can represent the demands by a crop for 'unhindered' production. Crop geography uses crop requirements to map crop suitability. Site similarity studies indicate how similar climate and soil are spatially to a certain reference point where a production option has shown success (Corbett and O'Brien, 1997; Hodson et al., 1999). These methods evaluate the adaptation of one

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[1] *Term specific* refers to a specific fixed time frame for which the research or result is valid.

particular crop to climate and soil conditions often on an annual basis, seldom on a growing season basis. Additionally, individual crops are evaluated instead of *cropping sequences*. Climate and soil criteria are evaluated as additive criteria. However, plant responses to soil and climate are not additive or linear over a growing season and show complex variation on a daily or hourly basis (Milthorpe and Moorby, 1979; Goudriaan and Van Laar, 1994). Moreover, crop requirement criteria usually are assumed fixed or constant, and are not able to describe adaptability dynamically. For example, a minimal crop rainfall requirement for a sorghum crop is set at 350 mm, from which areas suitable for sorghum are identified. However, crop water requirements for sorghum may change with crop improvement or management strategies. Also the soil and water status are assumed stable or in equilibrium. However, this is seldom the case, soil properties and microclimate can be strongly influenced by alternating crops and management strategies that over time are constantly subject to change. The equilibrium in agriculture is never reached.

A schematic overview of the use of a few of the abovementioned methods is illustrated in Fig. 1.2. For instance, in box 1a, recommendation domains guide introduction of the technology. The dots or sites where introduction is targeted are either groups of 'similar' farmers or sites near to a well-known (farm or experimental) site. Or as in box 1b, the site is designated 'representative' for a whole area. If the technology proves successfully at the location it is subsequently introduced into the entire zone for which the site has been designated 'representative'. The geographic coverage of this method is often incomplete, resulting in areas where the effect of introduction is unknown. In box 2, classification, stratification and zoning of individual factors of soil, climate and topography that affect technology performance takes place before the targeting process. This yields zones in which technology introduction may be suitable at a potential, often qualitative, level (shaded areas). In areas where introduction is unsuitable (white areas) the understanding of the (interacting) factors that limit introduction is low, leaving little suggestive knowledge on how to (re)design alternatives. The methodology in this study follows the procedures in box 3. The suitability for introducing agricultural production systems is evaluated by explicitly accounting for spatial and temporal variability in climate in interaction with soil, crop characteristics and agronomic management strategies. This results in a quantitative evaluation of a technology, not only in the sense of production but also though a change of the determining factors. This output can indicate how (re)design of the technology can be (re)directed. This is an iterative process open to stakeholders who are thus involved in a learning experience on the system's behaviour. To develop the methodology, inductive use was made of two cases studies for maize based cropping options in Central America. The need for identifying where, when, why, and how maize-based cropping options enhance production and potentially conserve soil and water resources, becomes evident below.

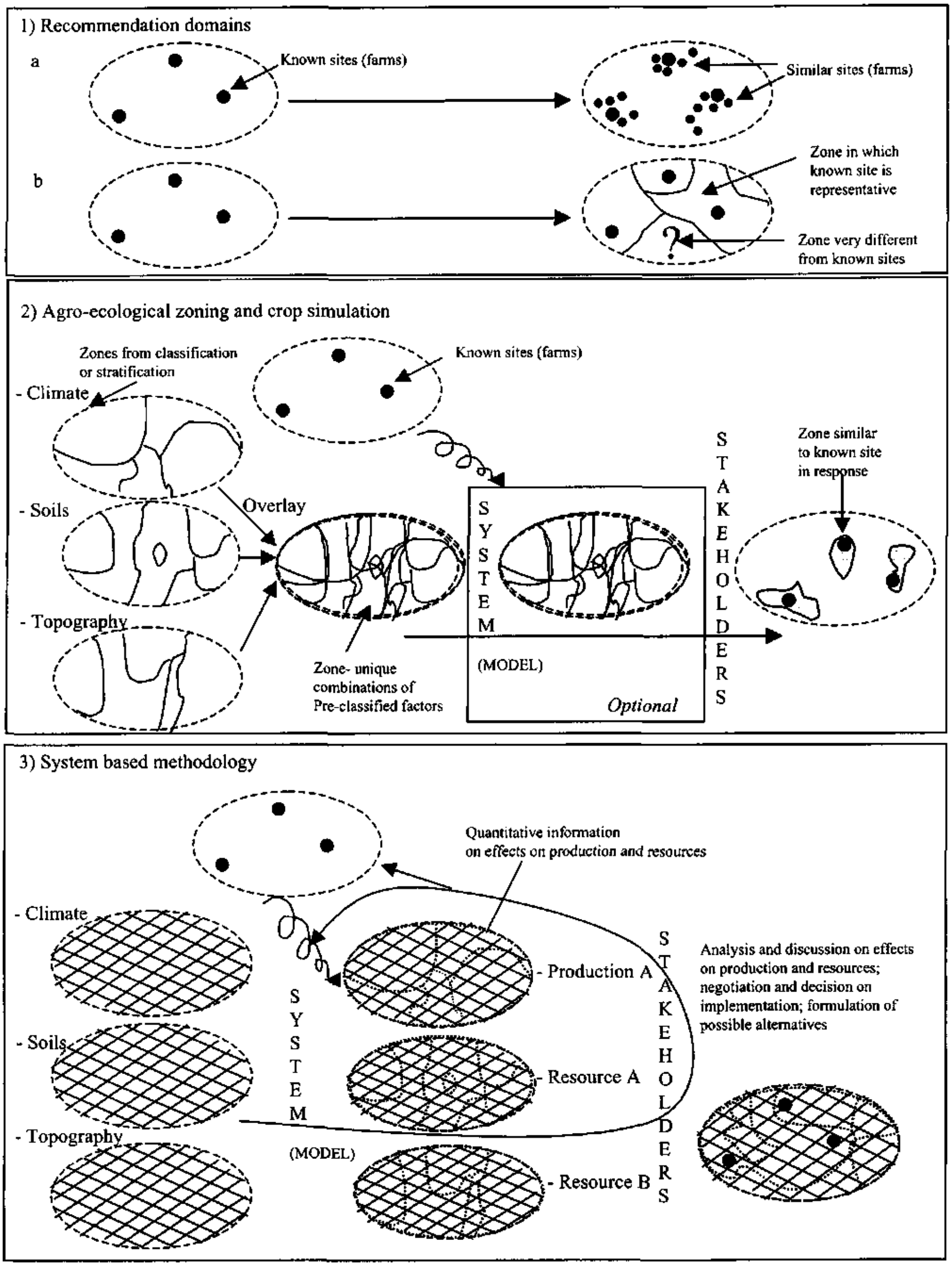

Figure 1.2 Methodologies for guiding technology introduction, adaptation and implementation (targeting).

The case of maize production systems and the need for targeting

Maize production systems in Central America are an important source of income and employment for resource poor farmers and are key to the food security of consumers, particularly of low-income urban population. Smallholders in the region commit more land, throughout a diverse range of ecologies, to maize than to all other food crops combined (see Smoock and Silva, 1989; Barreto and Hartkamp, 1999). The productivity of these systems, however, is being undermined by degradation of the soil and water resource base (Hawkins, 1984; Lopez et al., 1994; Bolaños, 1997).

Productivity-enhancing resource-conserving practices[2] for maize production systems have been developed in the region by NARS (e.g., INIFAP, IICA, DICTA), networks (e.g., PRM – Regional Maize Program for Central America), and NGOs (e.g., CIDICCO, Rockefeller Foundation, Proyecto Sierra Santa Marta in Veracruz Mexico), and international research institutes (e.g., CIMMYT, CIAT). Two main groups of practices have been identified, green manure cover crops (e.g., *Mucuna* spp., *Canavalia ensiformis*) and variations of reduced or zero tillage with residue retention. These practices have the potential to improve productivity while conserving soil and water resources (Erenstein, 1999; Sain, 1997; Sain and Barreto, 1996; Buckles and Perales, 1995).

The main strength of green manure cover crops and residue retention systems is that the soil remains covered. This cover has beneficial impact on several soil properties (physical, chemical, biological and hydrological) through the effects on soil and water processes. The major processes that are affected are infiltration and consequently, *runoff*. Soil erosion is reduced and soil fertility is conserved (Fig. 1.3). Cover reduces the impact of rainfall, and therefore *erosivity*. Moisture is conserved as soil surface *evaporation* is reduced. The cover, when left on the soil to decompose, contributes to *organic matter*. Organic matter improves soil physical properties, such as aggregate stability and porosity. It also encourages growth and activity of soil organisms and can improve nutrient availability by adding macro- and micronutrients extracted from deeper soil layers. GMCC, being living covers, have additional benefits, such as the ability to improve the soil nitrogen status through N-fixation and to suppress weeds.

Experimental evidence for benefits of green manure cover crops and residue retention systems has been found on-station and on-farm throughout Central America (Triomphe, 1996; Scopel et al., 1998; Eilittä, 1998; Arreola-Tostada, 2000). In maize production systems, green manure cover crops[3] can control erosion, suppress weeds, and contribute up to 200 kg nitrogen ha^{-1} (Van Eijk-Bos, 1987; Lopez, 1993; Buckles and Perales, 1995; Triomphe, 1996). The success of conservation tillage with residue

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[2] Production practice and production options are considered synonyms in this thesis.

[3] Of all Green Manure Cover Crops in Central America, velvet bean or Mucuna (*Mucuna pruriens*) is one of the most important.

retention in the tropics has been most pronounced in Brazil (e.g., Busscher et al., 1996), but positive experiences are also reported from Costa Rica, El Salvador, Guatemala, Mexico, and Panama (Shenk et al., 1983; Sosa and Bolaños, 1993; Sain and Barreto, 1996; Scopel, 1997; Pereira de Herrera and Sain, 1999). In semi-arid areas of the state of Jalisco, Mexico, crop residue retention can double maize grain yields in low rainfall areas even when only small amounts of mulch (2 ton ha^{-1}) are used, covering the soil surface only 25% at the start of the maize growing cycle (Scopel et al., 1998). Runoff erosion can be diminished by 80%, while over the total crop cycle the amount of available water is increased up to 40% (Scopel and Chavez-Guerra, 1999).

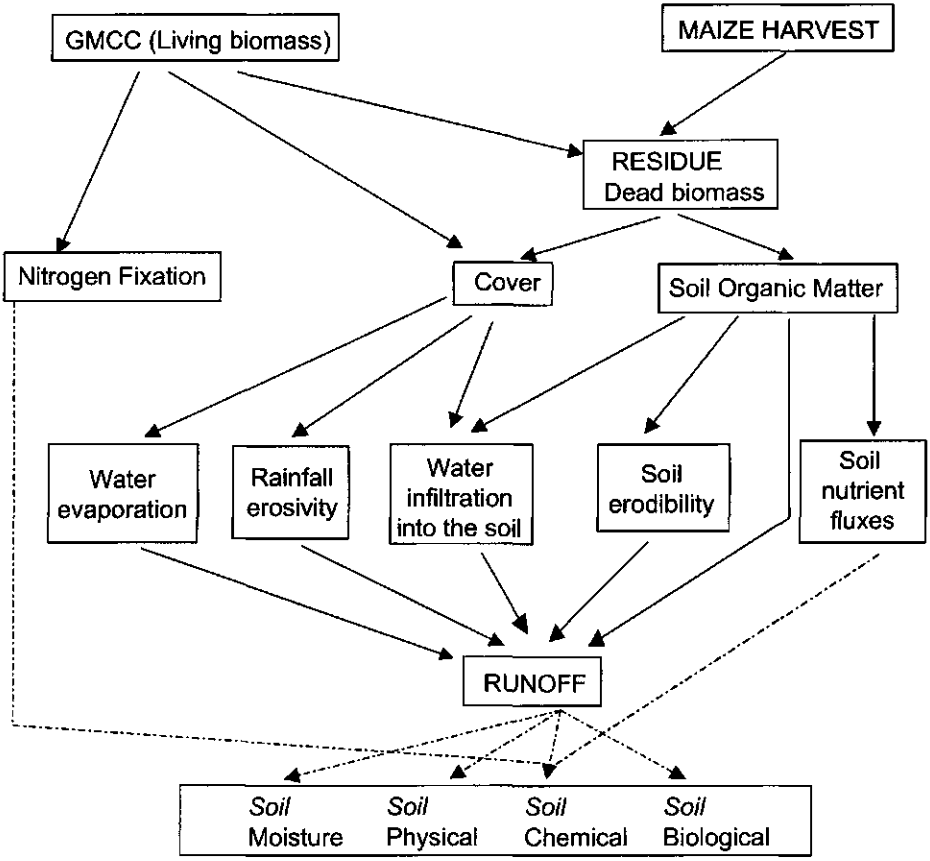

Figure 1.3 Schematic representation of the main soil and water processes influenced by green manures and residue retention.

However, many of these successes are site specific and have not been replicated over wider regions. Experiences from Jalisco show that within an area of 20 km^2, the variability in precipitation and soils is such that benefits from CTCRR can vary from nil to over a 100% yield increase (Scopel, 1997). Similarly in the Mexican states of Veracruz and Tabasco, early adoption of green manure practices by farmers was followed by abandonment due *in part* to insufficient growth of the legume in certain areas (Eilittä, 1998; J. Haggar, per. communication, 1997).

Besides biophysical aspects of site-specific success, economic viability and social acceptability are subject to spatial and temporal variability. Furthermore, there is diversity among stakeholders themselves as to individual perceptions on how to manage resources (see Röling, 1994, 1999). Although this larger context is recognized, this thesis focuses on learning from the biophysical heterogeneity in the evaluation of agricultural production options.

Objectives and approach

The objectives of this study are to:

- Develop a methodology to evaluate the biophysical suitability of agricultural production options that can enhance productivity and conserve soil and water resources.
- Explicitly account for the spatial and temporal variability of climate conditions in interaction with soil, crop characteristics and agronomic management strategies in this methodology.
- Operationalize the methodology through inductive use of two case studies of maize based production systems: green manure cover crop and reduced tillage with residue management.

The resulting information can support stakeholders involved in agricultural development and 'technology transfer' such as national agricultural R&D institutes and their extension services (e.g. INIFAP, CENAPROS, IICA) and NGO's (e.g. Rockefeller Foundation, World Neighbors, CIDICCO). An interaction with regional stakeholders to discuss and evaluate the results of the study was conducted.

The two case study practices and regions were chosen primarily because of their importance for maize production in Latin American. Secondarily, the contrasting nature of the different production environments was considered ideal for testing the methodology. Under the generally wetter conditions of Honduras, fallow season cropping is an option, while in semi-arid Jalisco, options are sought to improve fallow management through crop residue retention. Availability of agronomic and spatial data influenced selection of the regions. General information on the case study areas and practices is summarized in Appendix 1.1.

A methodology for biophysical targeting is developed based on systems simulation of agricultural production options within the larger approach to (re)design (Fig. 1.4). Part 1 of Fig. 1.4 is the focus of this thesis. Climate and soil conditions delimit the plausible range of agro-technical options. Using on-station or on-farm experimental experience, researchers and stakeholders select a smaller set of either newly designed production options or redesigned (adapted) production options. Agronomic management information for these production options is translated into input conditions for crop simulation models. Spatial climate data and daily weather sequences are created and soil data are defined as input to the model. Different crop management strategies, e.g., planting dates, plant densities and nitrogen levels, were separate input factors. A relatively short-term simulation horizon is applied (12 years). The outputs of the simulation model are evaluated through production and soil and water resource driven quantifiable variables, resulting in a spatial evaluation. In an interaction with regional stakeholders the results are presented, analysed and discussed. Additionally an evaluation of the methodology itself is carried out. Stakeholders and researchers can interact on the results and their own experiences, negotiate on collective objectives and prioritize options that should be promoted for introduction[4]. This feeds back into the iterative learning process and can initiate further innovation (design) or adaptation (redesign).

Outline of the thesis

The following chapters deal with the development and application of a methodology to evaluate potential productivity-enhancing resource-conserving maize-based cropping systems. The first part of the thesis (Chapters 2 - 6) provides a technical basis and evaluates the tools used in the proposed framework. The second part (Chapters 7 - 8) of the thesis describes the application of the methodology to case studies for Honduras and Jalisco.

Chapter 2 reviews strategies for interfacing agronomic simulation models to geographical information systems. It considers the terminology in use, programming approaches, issues of data and scale, and presents existing interfaces and applications. It summarizes the major challenges to future applications. Chapter 3 and 4 describe different approaches for obtaining spatial input for crop simulation. Interpolation techniques are used to arrive at spatial climate information on a monthly basis. Weather generators create daily weather data from monthly climate profiles. In both chapters, current tools are evaluated using data from Jalisco. Subsequently, the impact of different weather generators on the simulation of maize and bean systems is assessed in Chapter 4.

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[4] The adoption *per se* depends on the farmers' own perspective, objectives, management orientation and the resources available to him/her individually.

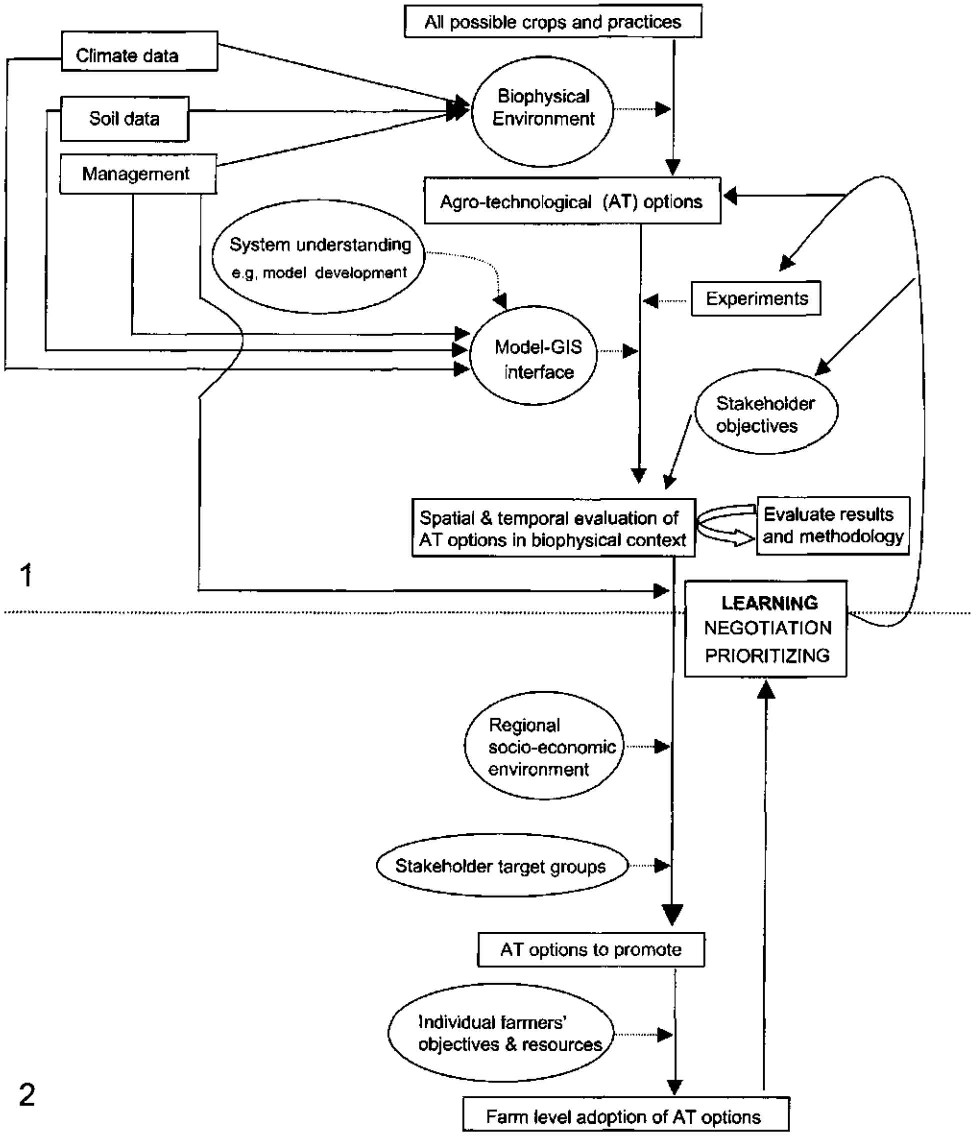

Figure 1.4 Proposed approach for identifying suitable agricultural production practices or agro-technological (AT) options. Circles and dotted lines show an influence or 'filter' function, rectangular boxes and solid lines resulting information (flow). Part 1 of the approach is the focus of this thesis.

Chapters 5 and 6 describe the development and evaluation of a generic green manure cover crop model for velvet bean (*Mucuna pruriens*). CROPGRO – Soybean was adapted to simulate growth and development of velvet bean at three sites in Mexico. Model performance was evaluated for phenology, growth, senescence and nitrogen accumulation at multiple locations around the world. The model was modified to track accumulation of litter.

The application of the methodology to the case study of velvet bean cropping systems for Honduras is described in Chapter 7, and for crop residue retention systems in Jalisco, Mexico in Chapter 8. Regional results on maize production and resources are presented. Analysis of the underlying water and nitrogen processes at individual site locations are used to understand the variation in system behaviour at the regional scale.

Chapter 9 documents on two separate interactions with stakeholders from the case study regions. A preliminary evaluation of the results from the case studies and methodology *per se* by the stakeholders is presented.

Chapter 10 provides a concluding discussion that integrates the main findings from the previous chapters. Recommendations for future research are provided.

Since the chapters of this thesis have been published or submitted as separate journal articles repetition of introductory information on the study occurs, allowing for the independent reading of the chapters.

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2.
INTERFACING GEOGRAPHIC INFORMATION SYSTEMS WITH AGRONOMIC MODELLING: A REVIEW

Abstract

Agronomic models are traditionally used for point or site-specific applications due to limitations in data availability as well as computer technologies. Interfacing geographic information systems (GIS) with agronomic models is attractive because it permits the simultaneous examination of spatial and temporal phenomena. The objective of this review is to examine strategies for interfacing GIS with agronomic models. It considers the diverse terminology in use, programming approaches, issues of data and scale, and existing applications. Linking is defined as merely passing input and outputs between a GIS and a model, combining is defined as automatic data exchange and GIS tool functions, and integrating is defined as embedding a model in a GIS or vice versa. Due to differences in research objectives, spatial and temporal scales, data sources or formats, and the natural processes being modelled, there is no universal approach for interfacing. Because of the detailed input requirements for agronomic models, expanding the models from a point-based application to a spatial application can greatly increase the volume of input data. Moreover, these extensive data requirements must be satisfied, while also ensuring data quality control. This review suggests that a major challenge in interfacing GIS to models lies in developing systems that handle spatial processes by implying interactions among spatial units.

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Introduction

Geographical information systems (GIS) facilitate the storage, manipulation, analysis, and visualization of spatial data. Most process-based agronomic models have examined temporal variation using point data from specific sites, and model outputs thus are site-specific. Agriculture is a spatial activity, however, and there is growing interest in placing site-specific information in a spatial and long-term perspective. Precision agriculture requires models that calculate spatial variation in crop growth at a scale of meters and with a time scale appropriate for management decisions, often hours or days (NRC, 1997). Efficient targeting of germplasm or production practices requires models that calculate germplasm × environment interactions on a regional scale (e.g., 1 to 5 km), usually through modelling at daily time scales (e.g., Chapman and Barreto, 1996). Climate change research calculates global effects with models that are often run on scales of 50 to 100 km, on the basis of multi-century time scales (NSTC, 1998). Furthermore, there is increasing interest in understanding how processes with a spatial component, such as runoff and lateral flow of solutes, affect system behavior. The interaction of both spatial and temporal issues seems best handled through interfacing agronomic models with GIS.

Geographical information systems have existed for almost three decades, but only in the last 10 years have applications been widely used in agriculture and natural resource management (Burrough, 1986). In the 1980s, the number of applications grew as a result of vendor-driven efforts to show the capabilities of GIS (Kam, 1993), and vendors' perceptions of the market guided the development of these applications (Dangermond, 1991). During the 1990s, as access to powerful computer technology became less costly, the number of GIS applications specific for research and development has increased. Consequently, a new generation of problems and issues have surfaced that are more pertinent to researchers and particular research objectives than to GIS developers *per se* (Kam, 1993).

An example of such a new issue is the adding of time as a fourth dimension to GIS capabilities. The time dimension can be included in GIS analyses in two ways. In the first approach, time-series of historic data from surveys or remote sensing can be examined as a series of overlays (Marble, 1984). These static spatial snapshots may be analysed with the help of statistical procedures (Croft and Kessler, 1996), such as Markov chains (Tomlinson Associates, 1987; Stoorvogel, 1995). Such analyses can document past trends, but their predictive power is weak, especially for new production practices or conditions. The second approach, that avoids this shortcoming by using process-based models to represent variation with time, is emphasized in this paper. The resulting model outputs may be viewed as a time series in GIS.

Use of the words 'model' and 'modelling' in relation to GIS can cause confusion.

Firstly, the focus of this paper is on simulation modelling, as opposed to spatial and environmental modelling. Spatial modelling often refers to techniques such as reclassification, overlay, and interpretation (Yakuup, 1993). Environmental modelling refers to techniques ranging from interpolating climate data to the use of data models and remote sensing. These techniques do not relate to simulation modelling per se, although environmental modelling in the narrow sense also exists (e.g., simulations of groundwater flow and the fate of contaminants) (Maslia et al., 1994). Nonetheless, spatial modelling can be used to facilitate interfaces between GIS and modelling. Secondly, this paper focuses on process-based models concerned with agricultural issues (e.g., crop production, soil erosion, or water pollution), as opposed to rule-based (logical) and empirical (regression) models.

The main attraction of interfacing models and GIS is to facilitate simultaneous analysis of spatial and temporal variation in processes. Our understanding and interpretation of the simulation results can not only significantly improve by spatially visualizing the results of models (Engel et al., 1997) but, more importantly, improve by advanced spatial analyses of model results (Campbell et al., 1989; Stoorvogel, 1995). Relevant methods include multivariate analysis, spatial autocorrelation, cluster analysis to define homogeneous zones prior to modelling, point pattern analysis, and error analyses.

Despite the growing number of computer-based applications, little attention has been paid to developing conceptual frameworks for the simultaneous use of GIS and modelling. The objective of this review is to examine strategies for interfacing GIS with agronomic models. We consider the diverse terminology in use, concepts of interfacing, and issues of data, scale, and error. Examples of applications in agronomy and natural resource management are discussed, including extraneous major challenges to effective interfacing.

Strategies for interfacing

Models have been interfaced with GIS since the mid-1980s, but early efforts did not emphasize process-based models (Nyerges, 1991). Nyerges (1991) noted that GIS vendors have had few incentives to develop such complex models, because of their limited market potential. In the past, therefore, GIS-model interfaces were developed within the various research disciplines in an *ad hoc* manner by researchers who were not professional GIS programmers (Stoorvogel, 1995). Because of these circumstances, a conceptual framework with standards for terminology, formats, and procedures for interfacing models with GIS does not exist.

Terms frequently used in describing systems that interface GIS and models, and their definition (Longman, 1984), include the following:

Interface:	The place at which diverse (independent) systems meet and act on or communicate with each other.
Link:	To connect.
Couple:	To link together; the act of bringing together.
Combine:	To unite, to merge.
Integrate:	To unite, combine, or incorporate into a larger unit; to end segregation.

We suggest that *interface* and *interfacing* be used as umbrella words for the simultaneous use of GIS and modelling tools, since they do not imply a specific level of interaction between them.

We consider *linking*, *combining*, and *integrating* to be suitable terminology for degrees of interfacing. Burrough (1996) and Tim (1996) refer to 'loose coupling', 'tight coupling', and 'embedded coupling', which correspond to linking, combining, and integrating, respectively. Fedra (1993) uses 'deep coupling', which corresponds to integrating. Distinguishing between linking and combining can be difficult, while integration is more easily distinguished (Tim, 1996). The terms 'linking', 'combining', and 'integrating' relate to the physical extent to which the GIS and models are interfaced.

Linking

Simple linkage strategies use GIS for spatially displaying model outputs. This approach often involves interpolation of model outputs (e.g., White and Hoogenboom, 1995). More sophisticated linkage strategies use GIS functions such as interpolation, overlay, and slope calculation to produce a database containing inputs for the model. Model outputs can be exported to the same or a separate database. Communication between the software systems is achieved through grid cell or polygon identifiers that link input and output to field locations. Simple transfer of files in ASCII format or a common binary file format is usually sufficient in this strategy. The concept of linking GIS and models is presented in Fig. 2.1a. Limitations of this strategy often include (i) the system's dependence on either the GIS or model output format; (ii) failure to take full advantage of the functional capabilities of the GIS (e.g., spatial analysis tools); and (iii) the incompatibility of operating environments and hardware (Tim, 1996). Lam et al. (1996) and Fedra (1991) have emphasized that users cannot exploit the full potential of the systems through linking. Examples of linking are GLEAMS to ArcInfo (Stallings et al., 1992), USLE to MAP GIS (Hession and Shanholz, 1988), and WOFOST to ArcInfo (Van Laanen et al., 1992) (Table 2.1).

Combining

Combining also involves processing data in a GIS and displaying model results; however, the model is configured with interactive tools of the GIS and the data are

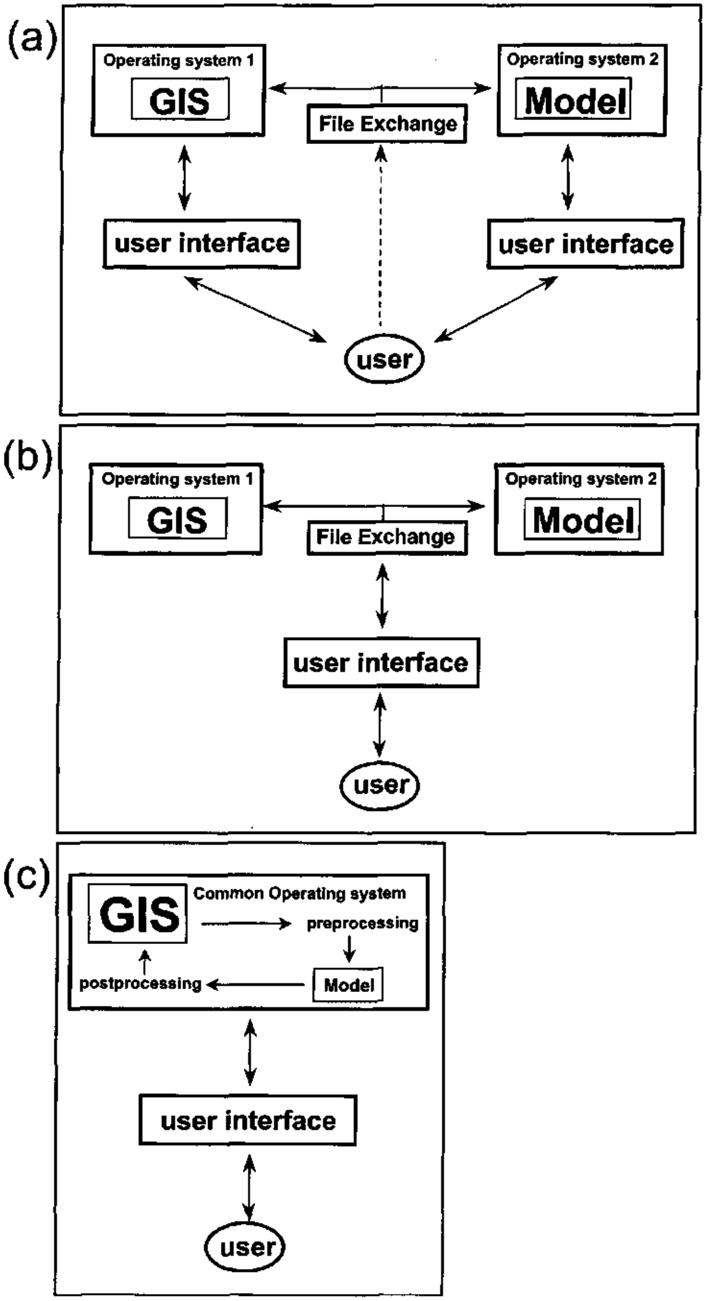

Figure 2.1 Organizational structure for (a) linking, (b) combining, and (c) integrating geographical information systems (GIS) and models. Adapted from Tim (1996) and Tim and Jolly (1996).

exchanged automatically (Burrough, 1996). Extensive use is made of mechanisms that are offered by GIS packages: macro languages, interface programs written in standard program languages, and libraries of user-callable routines (Tim, 1996). This approach usually requires more complex programming and data management than do simple linkages. The concept of combining GIS with models is presented in Fig. 2.1b. Examples of combining are AEGIS with ArcView (Engel et al., 1997), (GIDM) Gleams with ArcInfo (Fraisse et al., 1994), and WEPP with ArcView (Cochrane et al., 1997) (Table 2.1).

Integrating

Integration implies incorporating one system into the other. Either a model is embedded in a GIS, or a simple GIS system is included in a modelling system. Aside from making use of GIS and modelling tools, integration usually involves automatic use of relational databases, expert systems, and statistical packages. Full integration implies systems developed within the same or similar data structures. File transfer and format conversions are avoided or automated and thus are invisible to the user. The development of such systems may mean starting from scratch with data organization, among other tasks. A considerable programming effort is needed to develop these software systems, not to mention a considerable mutual understanding between the GIS specialist and modeller, and so only limited attempts have been made to integrate process-based models with GIS. More often integrated systems make use of simplified models (Tim, 1996). The concept of integrating GIS with models is presented in Fig. 2.1c. Examples of integrating are RAISON (Lam and Swayne, 1991; Lam et al., 1996) and the interface described by Stuart and Stocks (1993) (Table 2.1).

Additional examples of interfaces that have been linked, combined, and integrated are presented in Table 2.1. Abbreviations of the model names and interface tools are listed alphabetically in Table 2.2. In summary, limitations of the different strategies are related to problems of incompatibility of database structures, software, and hardware (Stoorvogel, 1995; Tim, 1996; Burrough, 1996). Linking strategies usually underuse the functional capabilities of GIS to achieve interactivity between the GIS and models. Point models are run only for a series of locations, and there is no attempt to consider interaction between neighboring locations, such as runoff or runon in adjacent plots. In combining and integrating, interactivity can be more readily achieved. Almost all interfacing activities require considerable effort from the developers and users (Engel et al., 1997). The ease of use, efficiency, development and maintenance costs, and necessary human resource training are important considerations for system design (Fedra, 1991; Nyerges, 1991). The amount of effort needed to develop integrated systems is large, and probably for this reason most efforts at interfacing have evolved through linking models with GIS. Stoorvogel (1995) noted that a modular approach should contribute to the transparency and flexibility of structure and procedures.

The choice of the interfacing strategy should depend on the research problem, the application objectives, and the investment the user is able to make. This sounds easy, but it is not. The research problem often has different relevance at different spatial and temporal scales (Fresco and Kroonenberg, 1992). The choice of the scale at which the problem is addressed may be subjective. It is often difficult to determine an approach that will provide valid research results at the farm level as well as the regional level. Procedures for up-scaling and down-scaling exist, but methods for calculating the effects of these procedures on resulting model calculations are still scarce. Few investigators have studied the effect of up- and down-scaling (e.g., Izaurralde et al., 1996; Wagenet and Hutson, 1996; Hijmans and Bowen, 1997). Hijmans and Bowen (1997) described aggregation of data in time (weather data) and space (soil data) when models were interfaced with GIS. They found that the effect of the aggregation or disaggregation on resulting calculations depends on a combination of environmental variability and model sensitivity. In heterogeneous regions and for models that are sensitive to changes, this may lead to errors in the resulting GIS-model calculations. Others have recognized the constraint (e.g., to aggregation to regional levels; Rosenberg, 1992) and explained that this is caused by a lack of efficient means to incorporate spatial variability in input variables (Carbone et al., 1996).

Structural issues affecting the interface strategy

The physical extent to which modelling and GIS capabilities are interfaced can be viewed as a programming issue. However, there are structural issues that affect the interface strategy. These are related to the research problem or the purpose of the application and include the scale, type (linear, non-linear), and complexity of the processes modelled and of the data sources, the format and structure of the available data, and the dynamic relations between model runs and the spatial units.

Scale and complexity

The spatial scale of the research problem may range from the plot to the field, farm, watershed, region (intranational), nation, region (international), continent, and/or global level. The temporal scale can vary from seconds to several years or more. Related scales in interfacing include the data measurement scale, original map and GIS scale, modelling scale, data manipulation scale, natural scale of the phenomenon, and scale of application (Burrough, 1996).

Issues of scale for the GIS component of an interfaced system are straightforward. The map scale is often predefined. For instance, map scales between 1 : 100,000 and 1 : 250,000 are often recommended for regional studies, whereas scales of 1 : 1000 and 1 : 2500 are more appropriate for farm-level applications (Garrity and Singh, 1991). Unfortunately, use of detailed map scales is frequently precluded by practical constraints, such as poor data availability or inadequate computer resources. Wilson et

Table 2.1 Examples of GIS-model interfaces, organized by interface type, main data format (polygon or raster) and reference.

Tool/Model	GIS system[1]	Focus	Interface type[2]	DF[3]	Reference
AGNPS	VirGIS	Cropland management and pollution	L	P	Hession et al. (1989)
GRAGRO	ArcInfo	Ley production potential	L	P	Magnusson and Söderström (1994)
PLANTGRO	ArcInfo	Forest production planning	L	P	Pawitan (1996)
GLEAMS	ArcInfo	Hydrology, groundwater	L	P	Stallings et al. (1992)
PESTRAS	ArcInfo	Pesticide fate	L	P	Tiktak et al. (1996)
USLE	-	Regional Soil erosion	L	P	Ventura et al. (1988)
CMLS	ArcInfo	Hydrology	L	P	Zhang et al. (1990)
CMLS	ArcInfo	Solute transport, input data resolution effect	L	P/R	Wilson et al. (1996)
GOA	ArcInfo	Land suitability evaluation	L	R	Brisson et al. (1992)
ANSWERS	-	Erosion	L	R	De Roo et al., (1989)
(R)USLE	IDRISI	Erosion and deposition	L	R	Desmet and Govers (1995); Desmet and Govers (1996)
USLE	MAP	Regional Sediment Load	L	R	Hession and Shanholtz (1988)
MODFLOW	ArcInfo	Groundwater flow	L	R	Hinaman (1993)
ANSWERS	GRASS	Watershed erosion/deposition	L	R	Rewerts and Engel (1991); Srinivasan and Engel (1991)
SPUR	ERDAS	Watershed hydrology	L	R	Sasowsky and Gardner (1991)
AGNPS	Arc/Info	Hydrology/pollution	L	R	SathyaKumar and Farell-Poe (1995)
NLEAP	GRASS	N leaching	L	R	Shaffer et al. (1996)
WOFOST	ArcInfo	Crop production potential/land use planning	L	R	Van Laanen et al. (1992)
LINTUL	-	Agro-ecological zoning	L	R/P	Van Keulen and Stol (1995)
CROPSYST	ArcView	Cropping systems/rotations	L/C	P	Donatelli et al. (1997)
CMLS	ArcInfo	Pesticide fate	L/C	P	Foussereau et al. (1993)
FLOWCONC	ArcInfo	Pesticide/herbicide fate	L/C	P	Lücke et al. (1995)
WEPP	ArcView	Watershed erosion	C	P	Cochrane et al. (1997)
AEGISWIN(DSSAT)	ArcView	Precision farming	C	P	Engel et al. (1997)
GIDM (GLEAMS)	ArcInfo	Dairy waste management/water quality	C	P	Fraisse et al. (1994)
IAEGIS (DSSAT)	ArcInfo	Crop management modelling	C	P	Hoogenboom et al. (1993)
AEGIS+ (DSSAT)	ArcInfo	Crop management modelling	C	P	Luijten and Jones (1997)
AGNPS	ArcInfo	Water quality/pollution	C	P	Tim and Jolly (1994)
CMLS	ArcInfo	Herbicide fate	C	P	Wilson et al. (1993)
SWAT	ArcView	Watershed hydrology, water quality	C	P/R	Stallings, pers.comm. (1996)
AGNPS	GRASS	Watershed erosion/nutrient movement	C	R	Engel et al. (1993)

Table 2.1 Continued.

Tool/Model	GIS system[1]	Focus	Interface type[2]	DF[3]	Reference
GISMO (EPIC)	GRASS	Erosion; climate variability/sensitivity	C	R	Martin and Neiman (1996); Goddard et al. (1996)
AGNPS	ERDAS	Hydrology/pollution	C	R	Olivieri et al. (1991)
AGNPS	GRASS	Hydrology/pollution	C	R	Park et al. (1995)
WEPP	GRASS	Watershed erosion	C	R	Savabi et al. (1997)
SWAT	GRASS	Watershed hydrology, water quality	C	R	Srinivasan and Arnold (1994)
USTED (CLUE)	IDRISI	Land use planning	C	R	Stoorvogel (1995)
SMoRMOD	GRASS	Rainfall-runoff	C	R	Zollweg et al. (1996)
DSSAT	IDRISI[4]	Crop management modelling	C	R	Thornton et al. (1997)
MICRO-FEM	ILWIS	Hydrology, Groundwater flow	C	R/P	Biesheuvel and Hemker (1993)
TOPMODEL	ILWIS	Hydrology	C	R/P	Romanowicz et al. (1993)
EGIS (MODFLOW)	swGIS	Hydrology/pollution	C/I	R	Deckers (1993)
RUSLE	MAPS	Erosion	I	R	Blaszczynki (1992)
-	GINIS Terrasoft	Nitrate leaching	I	R	Jordan et al. (1994)
RAISON	-	Environmental modelling, fish richness	I	P	Lam and Swayne (1991); Lam (1993)
HYDRUS[5]	ArcInfo	Water flow and solute transport	I	P	Mohanty and Van Genuchten (1996)
TOPMODEL	SPANS	Hydrology	I	P	Stuart and Stocks (1993)

[1] GIS Systems:
ArcInfo, ESRI GIS software; ArcView, ESRI GIS software; ERDAS, GIS software; GEOPACK, Geostatistical Software Package; GRASS, Graphical Resources Analysis Support System; IDRISI, GIS Software from Clark University, USA; ILWIS, Integrated Land and Water Information System; MAPS, Montana Agricultural Potential system, GIS software; MAP, Map Analysis Package, GIS software; MAPS, Map Analysis and Processing System, GIS software; SPANS, Spatial Analysis System (GIS software).

[2] Interface type: L = linking; C = combining; I = integrating.

[3] DF = data format; P = polygon, R = raster.

[4] IDRISI-based, but handles Surfer and ArcInfo grid files in ASCII format.

[5] Integrated with soil databases (UNSODA; STATSGO) and geostatisctical package (GEOPACK).

Table 2.2 Abbreviations and Acronyms of models and interface tools.

Short name	Expanded name
AEGIS	Agricultural and Environmental Geographic Information Systems
AGNPS	Agricultural NonPoint Source
ANSWERS	Areal Nonpoint Source Watershed Environmental Response Simulation
CMLS	Chemical Movement through Layered Soils
CROPSYST	CROPping SYSTems
DSSAT	Decision Support System for Agrotechnology Transfer
EPIC	Erosion Productivity Impact Calculator
EGIS	Evaluation of Groundwater resources Information System
FLOWCONC	Unknown acronym for pesticide/herbicide fate model
GIDM	Generic Interactive Dairy Model
GISMO	GIS and Modelling
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
GOA	Grignon-Orleans-Avignon (Labs participating in Model Development)
GRAGRO	Grass Grow Model
HYDRUS	HYDRo(water) UnSaturated
LINTUL	*Light INTerception and UtiLization Simulator*
MODFLOW	MODular Three Dimensional Finite-Difference Groundwater FLOW Model
MICRO-FEM	Finite Element groundwater Model
NLEAP	Nitrate Leaching and Economic Analysis Package
PESTRAS	PESticide TRAnSport Assessment
PLANTGRO	Plant Grow Model
RAISON	Regional Analysis by Intelligent Systems ON a microcomputer
RUSLE	Revised Universal Soil Loss Equation
SMoRMOD	Soil Moisture based Runoff MOdel
SPUR	Simulating Production and Utilization of Range Land
STATSGO	State Soil Geographical Database
SWAT	Soil and Water Assessment Tool
TOPMODEL	Topographic Model
USTED	Uso Sostenible de Tierras en El Desarollo
UNSODA	UNsaturated SOil Hydraulic DAtabase
USLE	Universal Soil Loss Equations
WEPP	Water Erosion Prediction Project
WOFOST	WOrld FOod STudies

al. (1996), Inskeep et al. (1996), and Wagenet and Hutson (1996) found that the impact of input map (data) resolution on final model calculation depends on the processes accounted for by the model.

The scale of a model is more problematic and involves three closely linked dimensions: space, time, and complexity (Penning de Vries, 1996). Model scale is often equated with the complexity of the processes that are modelled. However, this is incorrect. For example, a model of global climate patterns may simulate complex atmospheric processes but operate at a spatial resolution of 50 km or larger. Simple models of physiological processes may run on a time scale of minutes. Traditional point-based agronomic models lack an explicit *spatial scale*, although it is often suggested that they are valid at the plot or field scale. However, when such a model is interfaced to spatial data in a GIS, the spatial scale is usually predetermined by the scale of the spatial data or application. The *temporal scale* of a model may be influenced by the time span of the types of processes being modelled, data availability, computational constraints or scale of the application.

Model complexity is largely determined by the type (e.g., linear or non-linear) and detail of the processes represented. However, it can also be influenced by data availability, computational constraints, and interests in making underlying assumptions readily understandable.

The choice of an appropriate model scale is often difficult and is a topic of active debate. Clearly, the answer to the scale and/or complexity issue should lie in the research problem or application objective itself (Boote et al., 1996). Passioura (1996) made the valuable distinction between scientific models, which are intended to improve the understanding of processes, and engineering models, which are intended to provide sound calculations for decision makers. Monteith (1996) noted that the ease of software development afforded by modern personal computers may have led some researchers to develop excessively complex models. However, this view may be contrasted with that of Leenhardt et al. (1995), who argued that, for modelling effects of spatial soil and water variability at a regional scale, simplification of models to facilitate modelling across large regions or long time scales is unjustified on theoretical grounds. Given equal experimental effort, simple approaches allow a greater spatial sampling density than more mechanistic ones, but simplifying processes can reduce the sphere of validity of the outputs. Furthermore, integrated parameters are often difficult to relate to specific measurable parameters, such as soil texture or leaf area index. Burrough (1989) related the choice of model complexity and sampling density to an economic consideration of investment. Stoorvogel (1995) noted that complex models are often avoided because of limited availability of data.

Model complexity relates not only to the processes modelled and data requirements, but also to computational requirements of the model. A simple model, such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), can be embedded more easily in a GIS than a model with complex computational requirements, such as parallel processing, that are not provided by GIS software and hardware (Burrough, 1996).

Model complexity also affects functionality for end-users (Moore et al., 1993). The tendency to develop complex, physically based models that are difficult for users to understand is liable to grow unless common concepts and terminology are developed. Generic system-integration tools developed under a common conceptual theory have been proposed as a means to reduce the gap between theoretical GIS practitioners and discipline-oriented applications specialists (Stoorvogel, 1995).

Spatial distribution and type of data

The spatial distribution of the available data can influence the strategy for interfacing. Weather stations and soil samples can have an irregular, sparse distribution. Their values can show large variation in space. Before these weather and soil data can be useful for input into a model they may need to be interpolated. Interpolation methods include kriging and cokriging (Krige, 1951; Journel and Huijbregts, 1978), splining (Hutchinson, 1991), and spatial domain methods based on state–space models (Shumway et al., 1989; Wendroth et al., 1992). The choice of spatial interpolators depends on type and distribution of the data and research objective (e.g., DeBrule, 1983).

The type of data, continuous or discontinuous, can also influence the strategy for interfacing. For example, it can be problematic to relate discontinuous point measurements, such as soil taxonomic units, to a final polygon or raster structure. If a variable is discontinuous, point data lose their connection to the polygon or raster unless borders are exactly delineated by measurement. In this case, Monte Carlo simulations can be used to capture the variance, as in the work of Foussereau et al. (1993) on soil variables within discontinuous soil taxonomy units. Also, fuzzy logic can be used to estimate the spatial distribution of soil types and to derive soil properties (e.g., Zhu et al., 1997).

Spatial data format

The appropriate spatial data format depends on the type of data or data source. Quantitative data such as climate or soil traits are often provided as interpolated surfaces in raster (gridded) format. Soil taxonomy maps and land-use data are more commonly recorded in vector (polygon) formats. The choice of raster or vector depends on the importance of spatial interactions in the process being studied and how these are handled in the model (Fraisse et al., 1994). Relative advantages and disadvantages of the two different formats are reviewed in basic texts on GIS (e.g., Burrough, 1986). Fortunately, enhancements in recent software have reduced this format incompatibility, and some interfaces can use both formats (e.g., Wilson et al., 1996). The spatial data format has consequences for subsequent analysis, particularly where spatial scales are varied. Raster data (grid cells) can be easily overlaid and can be aggregated (lumped to bigger grid cell sizes) more easily than polygon structures, which have irregular shapes. Furthermore, with polygon structures small 'splinter' areas are often formed, which are hard to interpret.

Model simulations in relation to type and size of spatial unit

A model can be run for all spatial units (i.e., grid cells or polygons) in a study area or, to decrease the number of runs, for a subset of the spatial units. The type (interacting or non-interacting) and size of spatial units influence the selection of spatial units for the simulations.

Non-interacting spatial units Non-interacting spatial units are units (grid cells or polygons) whose value does not affect the value of the neighboring unit. If the total study area is small relative to the spatial unit size, simulations may be run on all possible spatial units, and the spatial database may be used as model input without alteration. However, if the study area is large and the spatial units are small (with few classes), simulations may be run for only specific classes of units. Class values that are not farming areas, such as cities or water bodies, can be masked out. Values can be sorted and classified in an intermediate database structure, using multivariate analyses. Studying maize (*Zea mays* L.) yield potential of East Africa, Collis and Corbett (1997) created what they called effective environments – climate zones that were defined through cluster analysis. Model simulations were conducted for each environment only.

For large databases or small spatial units, a random subset of units can be evaluated (the Monte Carlo method). In a modified Monte Carlo, units are pre-stratified. For example, variable numbers of simulations are executed for different regions according to their relative importance as production areas or for specific soil types. More simulations may be executed for border cells to reduce edge effects.

Interacting spatial units Spatial units are considered to interact when values of one unit affect the values of neighboring units. For interacting units, a model may have to be run for all spatial units, or else sub-sampling has to be carefully managed. Furthermore, the order of the simulation runs must be determined prior to running the simulation. In the case of surface runoff, the sequence of the simulations is determined by identifying the flow path over the terrain, as is done in ANSWERS (Rewerts and

Engel, 1991) and ZOO (Ioannidis et al., 1997). Given that traditional agronomic models are one-dimensional and essentially ignore horizontal flow when interfaced to a GIS, this potentially important interaction is usually ignored. These applications will remain less useful in areas of variable terrain or topography.

Managing input and output To analyse different scenarios, many simulations may have to be conducted for a single spatial unit. A data and programming issue that arises is how to manage long-term modelling of different inputs for one spatial unit structure. For example, if three irrigation levels and three fertilizer levels are applied to five crops for 20 years of variable soil and weather data, a single spatial unit would have 900 values for each output variable. Fortunately, advances in imaging allow outputs to be viewed as a series of images, either displayed together or as a dynamic view (animation). For example, yearly images could present differences in yield due to treatments, with summary statistics used as aids. Further development of viewing and analysis tools in this area is anticipated.

Applications

In agronomy and natural resource management research, applications of interfaces of GIS and modelling have grown from primarily hydrological applications in the mid-1980s to the current wide range of applications. Ordered roughly by increasing detail of spatial scale, examples can be categorized into groups such as the following.

1. Atmospheric modelling (Lee et al., 1993).
2. Climate change, sensitivity and/or variability studies (Rosenzweig, 1990; Wei et al., 1994; Beinroth et al., 1998).
3. Agroecological characterization and zonation (Bouman et al., 1994; Aggarwal, 1995).
4. Regional risk analysis (Bouman, 1993).
5. Scenario modelling and impact assessment, ex ante and also ex post (WRR, 1992; De Koning et al., 1993; Lam, 1993; Stoorvogel, 1995; Stockle, 1996).
6. Hydrology, water quality, water pollution (Warwick and Haness, 1992; Holloway, 1992; Kovar and Nachtnebel, 1993; Maidment, 1993; Corwin and Loague, 1996; Mamillapalli et al., 1996).
7. Spatial yield calculation – regional, global (Haskett et al., 1995; Van Keulen and Stol, 1995; Karthikeyan et al., 1996).
8. Precision farming (spatial yield calculation) (Hoogenboom et al., 1993; Booltink and Verhagen, 1997a; Engel et al., 1997).

However, strict borders between the application groups do not exist. For instance, nutrient management, particularly minimizing nitrate leaching, is a cross-cutting theme, especially in Groups 5, 6, and 8. Climate change and variability may be seen as a scenario, but *scenario modelling*, as defined here, includes scenarios derived from policy goals (e.g., WRR, 1992). Examples of linking the DSSAT family of crop models to GIS at different spatial scales (field to regional) are presented in Table 2.3.

By interfacing with GIS, models are often run for areas where they have not been validated. In this case, the interfacing of GIS to models serves as a sensitivity analysis of the model. White and Hoogenboom (1995) simulated dry bean (*Phaseolus vulgaris* L.) yields over the eastern United States and Canada, varying only weather conditions, and found that the simulated crop growth roughly matched expectations based on known crop distributions. These exercises could be extended by varying parameters such as soil depth and moisture retention. However, caution must be taken to ensure that potential users understand the difference between sensitivity analysis and calculation, and consider the limitations of spatial scale.

Table 2.3 Applications of DSSAT models at different scales.

Driving factor	Application	Scale	Reference
Soil	Crop management minimizing nitrogen leaching in barley in The Netherlands	Farm/field	Booltink and Verhagen (1997a)
Soil	Spatial variability of dry bean yield in Puerto Rico	Farm/field	Calixte et al. (1992)
Soil	Spatial variability of dry bean yield in Guatemala	Farm/field	Hoogenboom and Thornton (1990)
Soil	Spatial variability of yields of various crops at Georgia Experimental Station	Farm/field	Hoogenboom et al. (1993)
Soil	Regional productivity analysis	Regional	Carbone et al. (1996)
Soil	Regional productivity analysis in Puerto Rico	Regional	Lal et al. (1993)
Soil	Regional productivity analysis	Regional	Papajorgji et al. (1993)
Soil	Regional productivity analysis of sorghum for semiarid India	Regional	Singh et al. (1993)
Soil	Regional productivity analysis of maize in Malawi	Regional	Thornton et al. (1995)
Climate	Impact of climate change and climate variability on crop production	Farm/field	Wei et al. (1994)
Climate	Climate change effect on watershed irrigation demand in Colombia	Watershed	Beinroth et al. (1998)
Climate	Climate change effect on soybeans in Georgia and tomato in Puerto Rico	Regional	Beinroth et al. (1998)
Climate	Impact of climate change and climate variability in southeastern USA	Regional	Papajorgji et al. (1994)
Climate	Crop response to the impact of climate change and variability in southern Great Plains	Regional	Rosenzweig (1990)
Climate/Soil	Regional productivity analysis	Regional	Georgiev et al. (1998)

Additionally, care must be taken not to assume that the model application remains the same when it is interfaced to GIS. The model name or acronym may remain unchanged as the application evolves. EPIC (Erosion Productivity Impact Calculator) was first developed to examine relations among crop management practices, productivity, and soil erosion. More recently the GIS-interfaced version of the model has been used in climate sensitivity, hydrology, and water quality assessment applications. Consequently, the original acronym has acquired a new meaning, Environmental Policy Integrated Climate (Ramanarayanan, pers. communication, 1997). In some cases, the confusion is reduced by giving the GIS-model interface a new name, such as AEGIS (Agricultural and Environmental Geographic Information Systems), which developed within the DSSAT (Decision Support System for Agrotechnology Transfer) framework.

Challenges for successful applications

The large number of software systems in which models and GIS have already been interfaced (Table 2.1) suggests that, while interfacing *per se* is not a trivial exercise, it is a relatively tractable software engineering problem. In this review, other challenges are apparent. These include developing interfaced systems that achieve interactivity and satisfying data requirements while ensuring data quality control by developing methods for error analysis.

Interactivity

As mentioned above in the section on strategies for interfacing, linking interfaces often does not achieve interactivity, because spatial output is created merely by interpolating point-based simulations. The points themselves are considered independent of their neighbors when the simulations are run. A challenge to interfacing applications is to make the simulations interactive, and so truly achieve spatial modelling. This interactivity between spatial units can be achieved more easily by combining and integrating efforts.

Data availability and information sharing

Because of the detailed input requirements for agronomic models, expanding the models from a point-based application to a spatial application necessarily expands the need for data. Although it is not stated in the interfacing studies, data availability must be enhanced to fully realize the potential of interfacing GIS to models.

Improved data availability may be achieved through use of additional sources, encouraging data format standards, and improving information sharing management systems. Remote sensing is thought to be a potentially important additional source of data in precision agriculture (NRC, 1997) and in county-level yield mapping (Carbone et al., 1996). It has been used to help estimate parameters for model input, such as leaf area index, soil moisture, and surface soil water evaporation (Reiniger and Seguin, 1986; Bouman, 1995; Moran et al., 1995), and to evaluate and validate results of GIS-modelling efforts (Maas, 1993; Bouman, 1995; Booltink and Verhagen, 1997b).

Data availability can also be improved by reducing data incompatibility due to physical storage (format), syntactic organization (conversion, repackaging needs), quality and accuracy, or semantic interpretation. The first two problems can be resolved by standards (Evans, 1994). Efforts to standardize input formats have been promoted for crop modelling by the International Consortium for Agricultural Systems Application (ICASA) (Hunt et al., 1994; Ritchie, 1995; Tsuji et al., 1998). These standards facilitate interchange of data, thereby increasing data availability. Differences in accuracy and semantics are harder to solve and may still inhibit information sharing (Evans, 1994).

Besides technical issues, data availability and information exchange are often affected by organizational, legal, cultural, and bureaucratic factors. There is considerable discussion on whether governments should encourage data distribution on a free or subsidized basis, as opposed to charging the full costs of data collection and distribution. Economic analyses (Porter and Callahan, 1994) suggest that data contributors should receive more benefit than they currently do. Information management policies that increase the credit to the collector and ensure the responsibility of quality and documentation are necessary. However, the benefits of open data access in agricultural systems might include long-term effects on regional economies or on the natural resource base that are difficult to quantify. Porter and Callahan (1994) provided a broad review of other issues related to the organizational, legal, and bureaucratic aspects of data sharing for environmental research.

Error analysis

Spatial data have errors due to measurement, digitization, or interpolation. Similarly, models, being simplified representations of reality, produce output with error. How these errors interact when systems are interfaced is poorly understood, and so error analysis will become increasingly important as more models are interfaced with GIS. Users become concerned about the reliability and quality of the model outputs (Loague et al., 1998). Error analysis is also useful for assessing optimal combinations of sampling density and model complexity (Leenhardt et al., 1995). Uncertainty analysis is related to error analysis. Quantifying the effects of the uncertainty of variables on modelling can provide an indication of the reliability of the resulting calculations (Bouman, 1993; Corwin and Loague, 1996).

Conventional error propagation theory can be used to assess the quality of modelling results only if they are influenced by random errors. For data or variables stored in a

GIS or used as model input, sources of error are usually functions of observations, measurements, and entry. These are random errors. However, some techniques used in GIS, such as logic models (e.g., suitability classes) contain a systematic error of unknown magnitude that error propagation theory cannot address effectively (Drummond, 1987). Burrough (1986) recognized this problem and developed propagation rules for several GIS procedures.

Other attempts at error analysis for GIS have used probability modelling. This approach is problematic, because of the variety of possible spatial data processing procedures and the rigorous requirements of probabilistic data gathering. In a GIS, two major classes of error or uncertainty can be defined, those dealing with positional error (digitizing, georeferencing) and those addressing thematic uncertainty and error. For questions of spatial variability, fuzzy surfaces are used for uncertainty analysis and Monte Carlo methods for error analysis (Davis and Keller, 1996).

In simulation modelling validation (Neelamkavil, 1987), sensitivity analysis and Monte Carlo analyses can help determine error (Bouman, 1993). Bouman (1995) also suggested using remote sensing to reduce uncertainty in modelling efforts.

Methods for analysing error propagation in GIS and model interfaces are still lacking. Hill et al. (1996) estimated error using an iterative Monte Carlo process for a range of model parameters, grid resolutions, and value estimates where the rules of Burrough (1986) were not applicable. Data resolution and model organization are often changed to interface GIS and models. Error can increase because of the aggregation. De Roo et al. (1989) found that simulations with the GIS-interfaced version of a model calculated 46% more runoff and 36% more erosion than with the original model. Stallings (pers. communication, 1997) found that aggregated soil data led to a 100% error in model outputs. These results suggest that there is still a poor understanding of how up- and down-scaling influence error propagation, when models are interfaced to GIS.

Discussion and conclusions

In reviewing existing GIS-model interfaces, this study identified 'linking', 'combining', and 'integrating' as suitable terminology for characterizing basic strategies for interfacing agronomic models with GIS. Structural issues such as scale of models and the type, distribution, and scale of data were discussed.

Although there is an increased availability of user interfaces for linking GIS to simulation modelling, there is no guarantee that this improves science. On the contrary, in working with complex interfaces, users have fewer incentives to learn basic concepts, procedures, and the limitations of the underlying systems. Questions on the contribution of complex systems to our problem-solving capacity have been raised in crop modelling research (Passioura, 1996; Sinclair and Seligman, 1996). Both GIS and simulation models have been developed with their own conventions, procedures and limitations. However, linking them at a technical level does not guarantee improved understanding nor useful prediction (Burrough, 1996). There is a danger that calibration, validation, and error analysis will be neglected if GIS-modelling interfaces become too easy to use (Burrough, 1996).

Major challenges lie in achieving full interactivity of a GIS and a model, and in satisfying spatial data requirements while ensuring data quality control through error analysis. Qualitative and subjective procedures are often used for spatial analysis in GIS, and the resulting information loses much of its relevance and statistical validity (Stoorvogel, 1995). More quantitative quality indicators, together with spatial statistics and error analysis, are needed to improve the value of GIS-modelling interfaces.

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3.
INTERPOLATION TECHNIQUES FOR CLIMATE VARIABLES

Abstract

Understanding spatial variation in climatic conditions is key to many agricultural and natural resource management activities. However, the most common source of climatic data is meteorological stations, which provide data only for single locations. This paper examines statistical approaches for interpolating climatic data over large regions, providing a brief introduction to interpolation techniques for climate variables of use in agricultural research, as well as general recommendations for future research to assess interpolation techniques. Three approaches: (1) inverse distance weighted averaging (IDWA), (2) thin plate smoothing splines and (3) co-kriging – were evaluated for a 20,000 km^2 square area covering the state of Jalisco, Mexico. Validation of the surfaces using two independent sets of test data showed no difference among the three techniques for predicting precipitation. For maximum temperature, splining performed best. Taking into account valued error prediction, data assumptions, and computational simplicity; we recommend use of thin-plate smoothing splines for interpolating climate variables.

Frequently used acronyms and terminology

CIMMYT	International Maize and Wheat Improvement Center
DEM	Digital elevation model; a digital description of a terrain in the shape of data and algorithms
ERIC	Extractor Rápido de Información Climatológica
GCV	Generalized cross validation. A measure of the predictive error of the fitted surface which is calculated by removing each data point, one by one, and calculating the square of the difference between each removed data point from a surface fitted to all the other points
IDWA	Inverse distance weighted averaging
IMTA	Instituto Mexicano de Tecnología del Agua
INIFAP	Mexican National Institute of Forestry, Agriculture, and Livestock Research (Instituto Nacional de Investigaciones Forestales y Agropecuarias)
Interpolation	The procedure of estimating the value of properties at unsampled sites within an area covered by sampled points, using the values of properties from those points

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Introduction

Geographic information systems (GIS) and modelling are becoming powerful tools in agricultural research and natural resource management. Spatially distributed estimates of environmental variables are increasingly required for use in GIS and models (Collins and Bolstad, 1996). This usually implies that the quality of agricultural research depends more and more on methods to deal with crop and soil variability, weather generators (computer applications that produce simulated weather data using climate profiles), and spatial interpolation – the estimation of the value of properties at unsampled sites within an area covered by sampled points, using the data from those points (Bouman et al., 1996). Especially in developing countries, there is a need for accurate and inexpensive quantitative approaches to spatial data acquisition and interpolation (Mallawaarachchi et al., 1996).

Most data for environmental variables (soil properties, weather) are collected from point sources. The spatial array of these data may enable a more precise estimation of the value of properties at unsampled sites than simple averaging between sampled points. The value of a property between data points can be interpolated by fitting a suitable model to account for the expected variation. A key issue is the choice of interpolation approach for a given set of input data (Burrough and McDonnell, 1998). This is especially true for areas such as mountainous regions, where data collection is sparse and measurements for given variables may differ significantly even at relatively reduced spatial scales (Collins and Bolstad, 1996). Burrough and McDonnell (1998) state that when data are abundant most interpolation techniques give similar results. When data are sparse, the underlying assumptions about the variation among sampled points may differ and the choice of interpolation technique and parameters may become critical. With the increasing number of applications for environmental data, there is a growing concern about accuracy and precision. Results of spatial interpolation contain a certain degree of error, and this error is sometimes measurable. Understanding the accuracy of spatial interpolation techniques is a first step toward identifying sources of error and qualifying results based on sound statistical judgments.

Interpolation techniques

One of the most simple techniques is interpolation by drawing boundaries – for example Thiessen (or Dirichlet) polygons – which are drawn according to the distribution of the sampled data points, with one polygon per data point and the data point located in the center of the polygon (Fig. 3.1). This technique, also referred to as the 'nearest neighbour' technique, predicts the attributes of unsampled points based on those of the nearest sampled point and is best for qualitative (nominal) data, where other interpolation techniques are not applicable. Another example is the use of nearest available weather station data, in absence of other local data (Burrough and

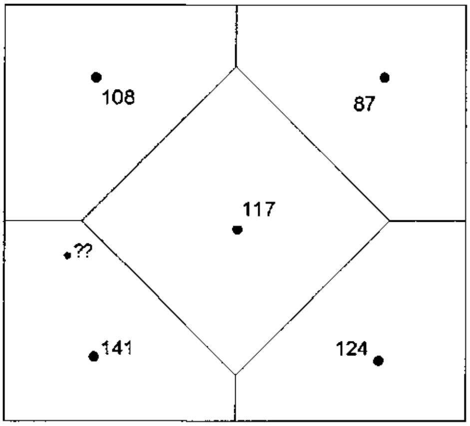
McDonnell, 1998). In contrast to this discrete technique, all other techniques embody a model of continuous spatial change of data, which can be described by a smooth, mathematically delineated surface.

Techniques that produce smooth surfaces include various approaches that may combine regression analyses and distance-based weighted averages. As explained in more detail below, a key difference among these approaches is the criteria used to weight values in relation to distance. Criteria may include simple distance relations (e.g., inverse distance techniques), minimization of variance (e.g., kriging and co-kriging), minimization of curvature, and enforcement of smoothness criteria (splining). On the basis of how weights are chosen, techniques are 'deterministic' or 'stochastic'. Stochastic techniques use statistical criteria to determine weight factors.

Examples of each include:

- Deterministic techniques: Thiessen polygons, inverse distance weighted averaging.
- Stochastic techniques: Polynomial regression, trend surface analysis, and (co)kriging.

Interpolation techniques can be 'exact' or 'inexact'. The former term is used in the case of an interpolation technique that, for an attribute at a given, unsampled point, assigns a value identical to a measured value from a sampled point. All other



Thiessen polygons : ?? is closest to 141 , therefore ??=141
Inverse distance weighted averaging: The value for ?? is calculated by weighting the values of all 5 points by the inverse of their distance squared to point ?? After interpolation, ?? = 126
The number of neighbours taken into account is a choice in this interpolation procedure.

Figure 3.1 An example of interpolation using Thiessen polygons and inverse distance weighted averaging to predict precipitation.

Table 3.1 A comparison of interpolation techniques (Burrough and McDonnell, 1998).

Method	Deterministic/ Stochastic	Local/ Global	Transitions abrupt/ gradual	Exact Interpolator	Limitations of the procedure	Best for	Computing Load	Output data structure	Assumptions of Interpolation model
Classification	Deterministic 'soft' information	Global	Abrupt if used alone	No	Delineation of areas and classes may be subjective. Error assessment limited to within-class standard derivations.	Quick assessments when data are sparse. Removing systematic differences before continuous interpolation from data points.	Small	Classified polygons	Homogeneity within boundaries
Trend surfaces	Essentially deterministic (empirical)	Global	Gradual	No	Physical Meaning of trend may be unclear. Outliers and edge effects may distort surface. Error assessment limited to goodness of fit.	Quick assessment and removal of spatial trends.	Small	Continuous gridded surface	Phenomenological explanation of trend, normally distributed data
Regression models	Essentially deterministic (empirical-statistical)	Global with local refinements	Gradual if inputs have gradual variation	No	Results depends on the fit of the regression model and the quality and detail of the input data surfaces. Error assessment possible if input errors are known.	Simple numerical modelling of expensive data when better methods are not available or budgets are limited.	Small	Polygons or continuous, gridded surface	Phenomenological explanation of regression model
Thiessen polygons (proximal mapping)	Deterministic	Local	Abrupt	Yes	No errors assessment, only one data point per polygon. Tessellation pattern depends on distribution of data.	Nominal data from point observations.	Small	Polygons or gridded surface	Best local predictor is nearest data point
Pycnophylatic interpolation	Deterministic	Local	Gradual	No, but conserves volumes	Data inputs are counts or densities.	Transforming step-wise patterns of population counts to continuous surfaces.	Small-moderate	Gridded surface or contours	Continuous, smooth variation is better than ad hoc areas
Linear Interpolation	Deterministic	Local	Gradual	Yes	No error assessments. Results depend on size of search window and choice of weighting parameter. Poor choice of window can give artifacts when used with high data densities such as digitized contours.	Interpolating from point data when data densities are high as in converting gridded data from one project to another.	Small	Gridded surface	Data densities are so large that linear approximation is no problem

Table 3.1 Continued.

Method	Deter-ministic/ Stochastic	Local/ Global	Transitions abrupt/ gradual	Exact Inter-polator	Limitations of the procedure	Best for	Comp-uting Load	Output data structure	Assumptions of Interpolation model
Moving averages and inverse distance weighting	Deterministic	Local	Gradual	Not with regular smoothing window, but can be forced	No error assessments. Results depend on size of search window and choice of weighting parameter. Poor choice of window can give artifacts when used with high data densities such as digitized contours.	Quick interpolation from sparse data on regular grid or irregularly spaced samples.	Small	Gridded surface	Underlying surface is smooth
Thin plate splines	Deterministic with local stochastic component	Local	Gradual	Yes, within smoothing limits	Goodness of fit possible, but within the assumption that the fitted surface is perfectly smooth.	Quick interpolation (univariate or multivariate) of digital elevation data and related attributes to create DEMs from moderately detailed data.	Small	Gridded surface contour lines	Underlying surface is smooth everywhere
Kriging	Stochastic	Local with global variograms. Local with local variograms when stratified. Local with global trends	Gradual	Yes	Error assessment depends on variogram and distribution of data points and size of interpolated blocks. Requires care when modelling spatial correlation structures.	When data are sufficient to compute variograms, kriging provides a good interpolator for sparse data. Binary and nominal data can be interpolated with indicator kriging. Soft information can also be incorporated as trends or stratification. Multivariate data can be interpolated with co-kriging.	Mod-erate	Gridded surface	Interpolated surface is smooth. Statistical stationarity and the intrinsic hypothesis
Conditional simulation	Stochastic	Local with global variograms. Local with local variograms when stratified. Local with global trends	Irregular	No	Understanding of underlying stochastic process and models is necessary.	Provides an excellent estimate of the range of possible values of an attribute at unsampled locations that are necessary for Monte Carlo analysis of numerical models, also for error assessments that do not depend on distribution of the data but on local values.	Mod-erate/ Heavy	Gridded surface	Statistical stationarity and the intrinsic hypothesis

interpolation techniques are described as 'inexact'. Statistics for the differences between measured and predicted values at data points are often used to assess the performance of inexact interpolators. Interpolation techniques can also be described as 'global' or 'local'. Global techniques (e.g. inverse distance weighted averaging, IDWA) fit a model through the prediction variable over all points in the study area. Typically, global techniques do not accommodate local features well and are most often used for modelling long-range variations. Local techniques, such as splining, estimate values for an unsampled point from a specific number of neighbouring points. Consequently, local anomalies can be accommodated without affecting the value of interpolation at other points on the surface (Burrough, 1986). Splining, for example, can be described as deterministic with a local stochastic component (Burrough and McDonnell, 1998). For soil data, popular techniques include kriging, co-kriging, and trend surface analysis (McBratney and Webster, 1983; Yates and Warrick, 1987; Stein et al., 1988a, 1989a, 1989b). In climatology, IDWA, splining, polynomial regression, trend surface analysis, kriging, and co-kriging are common approaches (Tabios and Salas, 1985; Hutchinson, 1991; Phillips et al., 1992; Hutchinson and Corbett, 1995; Collins and Bolstad, 1996). For temperature interpolations, techniques often allow for an effect of the adiabatic lapse rate (decrease in temperature with elevation) (e.g. Jones, 1996). An overview and comparison of interpolation techniques, their assumptions, and their limitations is presented in Table 3.1. In the following section, three interpolation techniques commonly used in interpolating climate data – IDWA, splining and (co)kriging –, are described in more detail.

Inverse distance weighted averaging

IDWA is a deterministic estimation technique whereby values at unsampled points are determined by a linear combination of values at known sampled points. Weighting of nearby points is strictly a function of distance – no other criteria are considered. This approach combines ideas of proximity, such as Thiessen polygons, with a gradual change of the trend surface. The assumption is that values closer to the unsampled location are more representative of the value to be estimated than values from samples further away. Weights change according to the linear distance of the samples from the unsampled point; in other words, nearby observations have a heavier weight. The spatial arrangement of the samples does not affect the weights. This approach has been applied extensively in the mining industry, because of its ease of use (Collins and Bolstad, 1996). Distance based weighting techniques have also been used to interpolate climatic data (Legates and Willmont, 1990; Stallings et al., 1992). The choice of power parameter (exponential degree) in IDWA can significantly affect the interpolation results. At higher powers, IDWA approaches the nearest neighbour interpolation technique, in which the interpolated value simply takes on the value of the closest sample point. IDWA interpolators are of the form:

$$\hat{q}(x) = \Sigma \lambda_i y(x_i)$$

where:

λ_i = the weights for the individual locations (x_i).
$y(x_i)$ = the variables evaluated in the observation locations (x_i).

The sum of the weights is equal to 1. Weights are assigned proportional to the inverse of the distance between the sampled and prediction point. So the larger the distance between sampled point and prediction point, the smaller the weight given to the value at the sampled point.

Splining

This is a deterministic, locally stochastic interpolation technique that represents two-dimensional curves on three-dimensional surfaces (Eckstein, 1989; Hutchinson and Gessler, 1994). Splining may be thought of as the mathematical equivalent of fitting a long flexible ruler to a series of data points. Like its physical counterpart, the mathematical spline function is constrained at defined points. The polynomial functions fitted through the sampled points are of degree m or less. A term r denotes the constraints on the spline. Therefore:

- When $r = 0$, there are no constraints on the function.
- When $r = 1$, the only constraint is that the function is continuous.
- When $r = m+1$, constraints depend on the degree m.

For example, if $m = 1$ there are two constraints ($r = 2$):

- The function has to be continuous.
- The first derivative of the function has to be continuous at each point.

For $m = 2$, the second derivative must also be continuous at each point. And so on for $m = 3$ and more. Normally a spline with $m = 1$ is called a 'linear spline', a spline with $m = 2$ is called a 'quadratic spline', and a spline with $m = 3$ is called a 'cubic spline'. Rarely, the term 'bicubic' is used for the three-dimensional situation where surfaces instead of lines need to be interpolated (Burrough and McDonnell, 1998).

Thin plate smoothing splines Splining can be used for exact interpolation or for 'smoothing'. Smoothing splines attempt to recover a spatially coherent – i.e., consistent – signal and remove the noise (Hutchinson and Gessler, 1994). Thin plate smoothing splines, formerly known as 'laplacian smoothing splines', were developed principally by Wahba and Wendelberger (1980) and Wahba (1990). Applications in climatology have been implemented by Hutchinson (1991, 1995), and Hutchinson and Corbett (1995). Hutchinson (1991) presents a model q_i for partial thin plate smoothing splines with two independent spline variables:

$$q_i = f(x_i, y_i) + \sum_{j=1}^{p} \beta_j \psi_{ij} + \varepsilon_i \qquad (i = 1, \ldots\ldots, n)$$

where:

$f(x_i, y_i)$ = unknown smooth function
β_j = set of unknown parameters
x_i, y_i, ψ_{ij} = independent variables
ε_i = independent random errors with zero mean and variance $d_i\sigma^2$
d_i = known weights

The smoothing function *f* and the parameters β_j are estimated by minimizing:

$$\sum_{i=1}^{n} \left[\left(q_i - f(x_i, y_i) - \sum_{j=1}^{p} \beta_j \psi_{ij} \right) / d_i \right]^2 + \lambda J_m(f)$$

where:

$J_m(f)$ = a measure of the smoothness of *f* defined in terms of *m*th order derivates of *f*
λ = a positive number called the smoothing parameter

The solution to this partial thin plate spline becomes an ordinary thin plate spline, when there is no parametric sub-model (i.e., when p=0). The smoothing parameter λ is calculated by minimizing the generalized cross validation function (GCV). This technique is considered relatively robust, since the technique of minimizing of the GCV directly addresses the predictive accuracy and is less dependent on the veracity of the underlying statistical model (Hutchinson, 1995).

Co-kriging and fitting variogram models

Named after its first practitioner, the south-African mining engineer Krige (1951), kriging is a stochastic technique similar to IDWA, in that it uses a linear combination of weights at known points to estimate the value at an unknown point. The general formula for kriging was developed by Matheron (1970). The most commonly applied form of kriging uses a 'semi-variogram' – a measure of spatial correlation between pairs of points describing the variance over a distance or lag *h*. Weights change according to the spatial arrangement of the samples. The linear combination of weights are of the form:

$$\Sigma \lambda_i y_i$$

where:

y_i = the variables evaluated in the observation locations
λ_i = the kriging weights

Kriging also provides a measure of the error or uncertainty of the estimated surface.

The semi-variogram and model fitting The semi-variogram is an essential step for determining the spatial variation in the sampled variable. It provides useful information for interpolation, sampling density, determining spatial patterns, and spatial simulation. The semi-variogram is of the form:

$$\gamma(h) = \frac{1}{2} \quad E \times (y(x) - y(x+h))^2$$

where:

$\gamma(h)$ = semi-variogram, dependent on lag or distance h
$(x, x+h)$ = pair of points with distance vector h
$y(x)$ = regionalized variable y at point x
$y(x) - y(x+h)$ = difference of the variable at two points separated by h
E = mathematical expectation

Two assumptions need to be met to apply kriging: stationarity and isotropy. Stationarity for spatial correlation (necessary for kriging and co-kriging) is based on the assumption that the variables are stationary. When there is stationarity, $\gamma(h)$ does not depend on x, where x is the point location and h is the distance between the points. So the semi-variogram depends only on the distance between the measurements and not on the location of the measurements. Unfortunately, there are often problems of non-stationarity in real-world datasets (Collins and Bollstad, 1996; Burrough, 1986). Stein et al. (1991a) propose several equations to deal with this issue. In other cases the study area may be stratified into more homogeneous units before co-kriging (Goovaerts, 1997); e.g., using soil maps (Stein et al., 1988b).

When there is isotropy for spatial correlation, $\gamma(h)$ depends only on $|h|$. So the semi-variogram depends only on the magnitude of h and not on its direction. For example, it is highly likely that the amount of groundwater increases when approaching a river. In this case there is anisotropy, because the semi-variogram will depend on the direction of h. Usually, stationarity is also necessary for the expectation $E\ (y(x))$, to ensure that the expectation doesnot depend on x and is constant.

From the semi-variogram (Fig. 3.2), various properties of the data are determined: the sill (A), the range (r), the nugget (C_0), the sill/nugget ratio, and the ratio of the square sum of deviance to the total sum of squares (SSD/SST). The nugget is the intercept of the semi-variogram with the vertical axis. It is the non-spatial variability of the variable and is determined when h approaches 0. The nugget effect can be caused by variability at very short distances for which no pairs of observations are available, sampling inaccuracy, or inaccuracy in the instruments used for measurement. In an ideal case (e.g., where there is no measurement error), the nugget value is zero. The

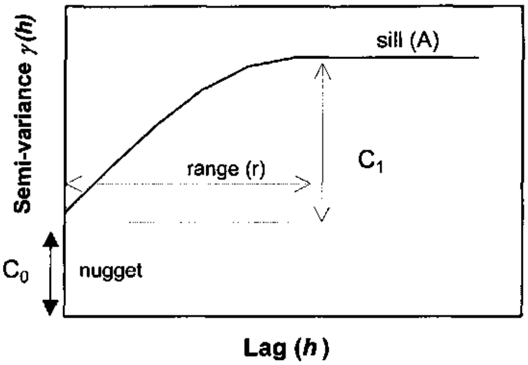


Figure 3.2 An example of a semi-variogram with range, nugget, and sill.

range of the semi-variogram is the distance *h* beyond which the variance no longer shows spatial dependence. At h, the sill value is reached. Observations separated by a distance larger than the range are spatially independent observations. To obtain an indication of the part of the semi-variogram that shows spatial dependence, the sill:nugget ratio can be determined. If this ratio is close to 1, then most of the variability is non-spatial. Normally a 'variogram' model is fitted through the empirical semi-variogram values for the distance classes or lag classes. The variogram properties – the sill, range and nugget – can provide insights on which model will fit best (Cressie, 1993; Burrough and McDonnell, 1998). The most common models are the linear model, the spherical model, the exponential model, and the Gaussian model (Fig. 3.3). When the nugget variance is important but not large and there is a clear range and sill, a curve known as the spherical model often fits the variogram well.

Spherical model:

$$\gamma(h) = C_0 + A \times \left(\frac{3}{2}\left(\frac{h}{\mathrm{r}}\right) - \frac{1}{2}\left(\frac{h}{\mathrm{r}}\right)^3 \right) \qquad \text{for } h \in (0,\mathrm{r}]$$

$$= C_0 + A \qquad \text{for } h > \mathrm{r}$$

(where = r is the range, *h* is lag or distance, and C_0+A is the sill

If there is a clear nugget and sill but only a gradual approach to the range, the exponential model is often preferred.

Exponential model:

$$\gamma(h) = C_0 + A \times \left(1 - e^{-\frac{h}{r}}\right) \text{ for } h > 0$$

If the variation is very smooth and the nugget variance is very small compared to the spatially random variation, then the variogram can often best be fitted by a curve having an inflection such as the

Gaussian model:

$$\gamma(h) = C_0 + A \times \left(1 - e^{-\left(\frac{h}{r}\right)^2}\right) \text{ for } h > 0$$

All these models are known as 'transitive' variograms, because the spatial correlation structure varies with the distance *h*. Non-transitive variograms have no sill range within the sampled area and may be represented by the linear model:

$$\gamma(h) = C_0 + b\,h \qquad b = \text{constant}$$

However, linear models with sill also exist and are in the form of:

$$\gamma(h) = A \times \frac{h}{\mathrm{r}} \text{ for } h \in (0, b]$$

The ratio of the square sum of deviance (SSD) to the total sum of squares (SST) indicates which model best fits the semi-variogram. If the model fits the semi-variogram well, the SSD/SST ratio is low; otherwise, SSD/SST will approach 1. To test for anisotropy, the semi-variogram needs to be determined in a different direction than *h*. To ensure isotropy, the semi-variogram model should be unaffected by the direction in which *h* is taken.

Co-kriging is a form of kriging that uses additional covariates, usually more intensely sampled than the prediction variable, to assist in prediction. Co-kriging is most effective when the covariate is highly correlated with the prediction variable. To apply co-kriging one needs to model the relationship between the prediction variable and a co-variable. This is done by fitting a model through the cross-variogram (the semi-variogram for co-variables). Estimation of the cross-variogram is carried out similarly to estimation of the semi-variogram:

$$\gamma_{1,2}(h) = \frac{1}{2} \quad E \quad \left((y_1(x) - y_1(x+h))(y_2(x) - y_2(x+h)) \right)$$

High cross-variogram values correspond to a low covariance between pairs of observations as a function of the distance *h*. When interpolating with co-kriging, the variogram models have to fit the 'linear model of co-regionalization' as described by Journel and Huijbregts (1978) and Goulard and Voltz (1992). (See Appendix 3.1 for a description of the model.) To have positive definiteness, the semi-variograms and the cross-variogram have to obey the following relationship:

$$\gamma_{1,2}(h) \le \sqrt{(\gamma_1(h)\gamma_2(h))}$$

This relationship should hold for all *h*. The actual fitting of a variogram model is an interactive process that requires considerable judgment and skill (Burrough and McDonnell, 1998).

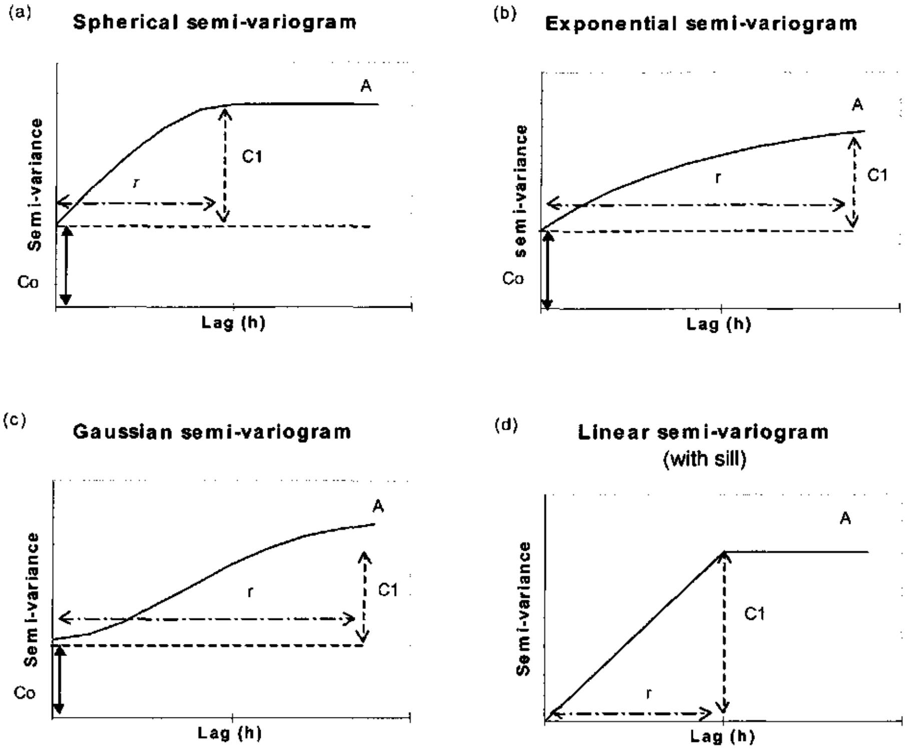


Figure 3.3 Examples of most commonly used variogram models (a) Spherical, (b) Exponential, (c) Gaussian, and (d) Linear.

Reviewing interpolation techniques

Early reviews of interpolation techniques (Lam, 1983; Ripley, 1981) often provided little information on their efficacy and did not evaluate them quantitatively. Recent studies, however, have focused on efficacy and quantitative criteria, through comparisons using datasets (Stein et al., 1989a, b; Hutchinson and Gessler, 1994; Laslett, 1994; Collins and Bolstad, 1996). Collins and Bolstad (1996) compared eight spatial interpolators across two regions for two temperature variables (maximum and minimum) at three temporal scales. They found that several variable characteristics (range, variance, correlation with other variables) can influence the choice of a spatial interpolation technique. Spatial scale and relative spatial density and distribution of sampling stations can also be determinant factors. MacEachren and Davidson (1987) concluded that data measurement accuracy, data density, data distribution and spatial variability have the greatest influence on the accuracy of interpolation. Burrough and McDonnell (1998) concluded that most interpolation techniques give similar results when data are abundant. For sparse data the underlying assumptions about the variation among sampled points differ and, therefore, the choice of interpolation technique and parameters becomes critical.

The most common debate regards the choice of kriging or co-kriging as opposed to splining (Dubrule, 1983; Hutchinson, 1989; Hutchinson, 1991; Stein and Corsten, 1991; Hutchinson and Gessler, 1994; Laslett, 1994). Kriging has the disadvantage of high computational requirements (Burrough and McDonnell, 1998). Modelling tools to overcome some of the problems include those developed by Pannatier (1996). However, the success of kriging depends upon the validity of assumptions about the statistical nature of variation. Several studies conclude that the best quantitative and accurate results are obtained by kriging (Dubrule, 1983; Burrough and McDonnell, 1998; Stein and Corsten, 1991; Laslett, 1994). Cristobal-Acevedo (1993) evaluated thin splines, inverse distance weighting, and kriging for soil parameters. His conclusion was that thin splines were the less exact of the three. Collins and Bolstad (1996) confirm what has been said before: splining has the disadvantage of providing no error estimates and of masking uncertainty. Also, it performs much better when dense, regularly-spaced data are available; it is not recommended for irregular spaced data. Martinez Cob and Faci Gonzalez (1994) compared co-kriging to kriging for evapotranspiration and rainfall. Predictions with co-kriging were not as good for evaporation but better for precipitation. However, prediction error was less with co-kriging in both cases. The debate does not end there. For example, Hutchinson and Gessler (1994) pointed out that most of the aforementioned comparisons of interpolation techniques did not examine high-order splines and that data smoothing in splining is achieved in a statistically rigorous fashion by minimizing the generalized cross validation (GCV). Thus, thin plate smooth splining does provide a measure of spatial accuracy (Wahba and Wendelberger, 1980; Hutchinson, 1995).

There appears to be no simple answer regarding choice of an appropriate spatial interpolator. The performance of the technique depends on the variable under study, the spatial configuration of the data, and the underlying assumptions of the techniques. Therefore a technique is 'best' only for specific situations (Isaaks and Srivastava, 1989).

A case study for Jalisco, Mexico

The GIS/Modelling Lab of the CIMMYT Natural Resources Group (NRG) is interfacing GIS and crop simulation models to address temporal and spatial issues simultaneously. A GIS is used to store the large volumes of spatial data that serve as inputs to the crop models. Interfacing crop models with a GIS requires detailed spatial climate information. Interpolated climate surfaces are used to create grid-cell-size climate files for use in crop modelling. Prior to the creation of climate surfaces, we evaluated different interpolation techniques – including inverse distance weighting averaging (IDWA), thin plate smoothing splines, and co-kriging – for climate variables for 20,000 km^2 roughly covering the state of Jalisco in northwest Mexico. While splining and co-kriging have been described as formally similar (Dubrule, 1983; Watson, 1984), this study aimed to evaluate practical use of related techniques and software.

Material and methods

Regarding software, the ArcView spatial analyst (ESRI, 1998) was used for inverse distance weighting interpolation. For thin plate smoothing splines, the ANUSPLIN 3.2 multi-module package (Hutchinson, 1997) was used. The first module or program is used to fit different partial thin plate smoothing spline functions for more independent variables. The first program either SPLINAA or SPLINA depends on the type of variable to be predicted. The SPLINAA program uses year to year monthly variances to weigh sampled points and is more suitable for precipitation, the SPLINA program uses month to month variance to weigh sampling points and is more suitable for temperature. Inputs to the module are a point data file and a covariate grid. The program yields several output files:

- A large residual file, which is used to check for data errors.
- An optimization parameter file containing parameters used to calculate the optimum smoothing parameter(s).
- A file containing the coefficients defining the fitted surfaces that are used to calculate values of the surfaces by LAPPNT and LAPGRD.
- A file that contains a list of data and fitted values with Bayesian standard error estimates (useful for detecting data errors).
- A file that contains an error covariance matrix of fitted surface coefficients. This is used by ERRPNT and ERRGRD to calculate standard error estimates for the fitted surfaces.

The program LAPGRD produces the prediction variable surface grid. It uses the surface coefficients file from the SPLINAA program and the co-variable grid, in this case the DEM. The program ERRGRD calculates the error grid, which depicts the standard predictive error.

For co-kriging, the packages SPATANAL and CROSS (Staritsky and Stein, 1993), WLSFIT (Heuvelink, 1992), and GSTAT (Pebesma, 1997) were used. The SPATANAL and CROSS programs were used to create semi-variograms and cross-variograms respectively from ASCII input data files. The WLSFIT program was used to get an initial model fit to the semi-variogram and cross-variogram. GSTAT was used to improve the model. GSTAT produces a prediction surface grid and a prediction variance grid. A grid of the prediction error can be produced from the prediction variance grid using the map calculation procedure in the ArcView Spatial analyst.

Data The following sources were consulted:

- Digital elevation model (DEM): 1 km^2 (USGS, 1997).
- Daily precipitation and temperature data from, 1940 to 1990, Instituto Mexicano de Tecnología del Agua (IMTA; 868 stations per 20,000 km^2).
- Monthly precipitation data from 1940 to 1996, Instituto Nacional de Investigaciones Forestales y Agropecuarias (INIFAP; 100 stations per 20,000 km^2). In this study, daily precipitation and temperature (maximum and minimum) data were extracted from the Extractor Rápido de Información Climatológica (ERIC, IMTA, 1996). We selected a square (106 °W; –101 °W; 18 °N; 23 °N) that covered the state of Jalisco, northwest Mexico, encompassing approximately 20,000 km^2 (Fig. 3.4). A subset of station data from 1965 to 1990 was 'cleaned up' using the Pascal program and the following criteria:
    - If more then 10 days were missing from a month, the month was discarded.
    - If more then 2 months were missing from a year, the year was discarded.
    - If fewer than 19 or 16 years were available for a station, the station was discarded.

Data for monthly precipitation from 180 stations were provided by INIFAP. There were 70 data points with station numbers identical to some in ERIC (IMTA, 1996). The coordinates from these station numbers were compared and, in a few cases, were different. INIFAP had verified the locations for Jalisco stations using a geographic positioning system, so the INIFAP coordinates were used instead of those from ERIC, wherever there were differences of more than 10 km (Table 3.2). For the other states in the selected area, we used ERIC data. In four cases stations had identical coordinates (Table 3.3), and the second station was removed from the dataset that was to be used for interpolation.

Table 3.2 Stations for which geographic co-ordinates were changed to INIFAP values.

Station NR.	Name	ERIC latitude	ERIC longitude	INIFAP latitude	INIFAP longitude
14089	La Vega, Teuchitlan	20.58	−103.75	20.595	−103.844
14073	Ixtlahuacan del Rio	20.87	−103.33	20.863	−103.241
14043	Ejutla, Ejutla	19.97	−104.03	19.900	−104.167
14006	Ajojucar, Teocaltiche	21.42	−102.40	21.568	−102.435

Table 3.3 Station numbers with identical geographic co-ordinates (stations in bold were kept for interpolation).

Station NR.	Latitude	Longitude
16164	**19.42**	**102.07**
16165	19.42	102.07
16072	**19.57**	**102.58**
16073	19.57	102.58
18002	**21.05**	**104.48**
18040	21.05	104.48

Daily data were used to calculate the monthly means per year and consequently the station means using SAS 6.12 (SAS Institute, 1997). The monthly means by station yielded the following files:

- Monthly precipitation based on 19 years or more for 194 stations.
- Monthly precipitation based on 16 years or more for 316 stations.
- Monthly mean maximum temperature based on 19 years for 140 stations.
- Monthly mean minimum temperature based on 19 years for 175 stations.

Validation sets To evaluate whether splining or co-kriging was best for interpolating climate variables for the selected area, we determined the precision of prediction of each using test sets. These sets contain randomly selected data points from the available observations. They are not used for prediction nor variogram estimation, so it is possible to compare predicted points with independent observations. In this study two test sets were used. First five smaller, almost equal sub-areas were defined (Fig. 3.4). For precipitation, 10 stations were randomly selected from each. These 50 points were divided into two sets. Each dataset had 25 validation points and 169 interpolation points. The benefit of working with.11 two datasets of 169 points each is that all 194 points are used for analysis and interpolation, but the validation stations are still independent of the dataset. The interpolation techniques were tested as well for maximum temperature. Because only 140 stations were available, only 6 validation points were randomly selected from each square. Therefore, interpolation for maximum temperature was executed using 125 points and 15 points were kept independent as a validation set.

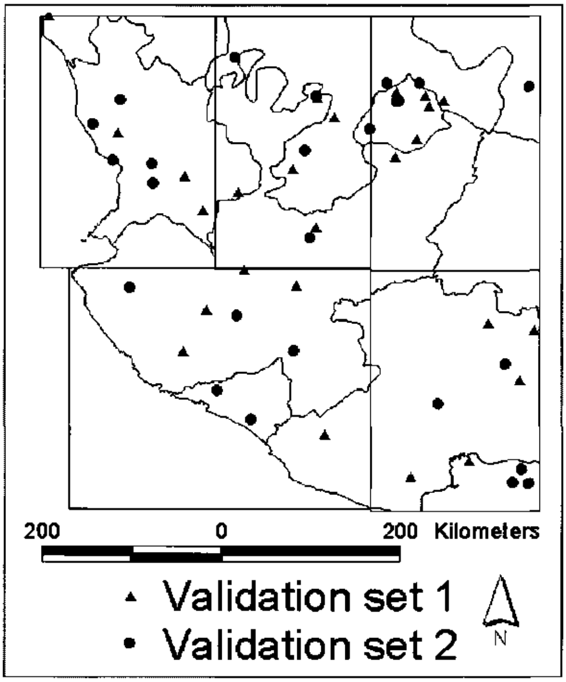


Figure 3.4 Validation selection areas and two validation sets of 25 points each for precipitation.

Exploratory data analysis and co-kriging requirements An exploratory data analysis was conducted prior to interpolation to consider the need for transformation of precipitation data, the characteristics of the dataset to be used, and the correlation coefficients between the prediction variable and the co-variable 'elevation'. Log transformation is commonly applied to give precipitation data a more normal distribution. However, back-transforming the precipitation values can be problematic because exponentiation tends to exaggerate any interpolation-related error (Goovaerts, 1997).

The two precipitation datasets were compared to see if the dataset from 194 stations (19 years or more) had greater precision than that from 320 stations (16 years or more). This was done by comparing the nugget effects of the variograms. As an indication of measurement accuracy, if the nugget of the large dataset is larger than the nugget of the small dataset, then the large dataset is probably less accurate. For each variogram, the number of lags and the lag distance were kept at 20 and 0.2 respectively. The model type fitted through the variogram was also the same for each dataset. This allowed a relatively unbiased comparison of the two nugget values, because the nugget difference is independent of model, number of lags, and lag distance. Variogram fitting was done with the WLSFIT program (Heuvelink, 1992). The nugget difference can be calculated as:

(Nugget of the 320 station dataset) – (Nugget of the 194 station dataset).

Thus, the relative nugget difference can be presented as:

$$\left(\frac{nugget320 - nugget194}{nugget320}\right)\times 100\%$$

Results

In the exploratory data analysis, precipitation data for all months showed an asymmetric distribution. The difference between the non-transformed surface and the transformed surface was high only in areas without stations. In most areas, the difference was smaller than the prediction error. We therefore decided not to transform the precipitation data for interpolation. The temperature data did not show an asymmetric distribution, so it was not necessary to test transformation (De Beurs, 1998). The relative nugget difference of the large precipitation dataset (320 stations, 16 years of data) was compared to that for the small dataset (194 stations, 19 years of data). For every month except July and November, the relative nugget difference was less then 30% (Appendix 3.2) and, in two cases, the nugget value was smaller for the small dataset. Because the difference in accuracy between the two datasets was not large, the small dataset of monthly means based on more than 19 years was used.

Co-kriging works best when there is a high absolute correlation between the co-variable and the prediction variable. In general, during the dry season precipitation shows a positive correlation with altitude, whereas during the wet season there is a negative correlation. The correlation between each variable to be interpolated (precipitation and maximum temperature) and the co-variable (elevation) were determined. For the selected area, April, May, August and September had acceptable correlation coefficients between precipitation and elevation (Table 3.4). May to October had the highest precipitation values. The lack of a correlation between precipitation and elevation for June may be because it rains everywhere, making co-kriging difficult for that month. There is little precipitation in the other months. Maximum temperature showed a greater absolute correlation with elevation, so the interpolation techniques were evaluated for the same months (April, May, August and September). April and May had the lowest and August and September the highest correlation coefficients.

Table 3.4 Correlation coefficients between prediction variables: precipitation (P), maximum temperature (Tmax), and the co-variable (elevation).

Month	Correlation P × Elevation	Correlation Tmax × Elevation
January	–0.26	–0.82
February	0.26	–0.80
March	0.20	–0.71
April	0.68	–0.63
May	0.59	–0.63
June	–0.02	–0.74
July	–0.36	–0.84
August	–0.52	–0.84
September	–0.59	–0.84
October	–0.39	–0.85
November	–0.37	–0.85
December	–0.39	–0.84

Semi-variogram fitting for the co-kriging technique

Variograms were made and models fitted to them. For months with a negative correlation, cross-variogram values were also negative. To fit a rough model with the WLSFIT program (Heuvelink, 1992), it was necessary to make the correlation values positive, because WLSFIT does not accept negative correlations. This first round of model fitting was used to obtain an initial impression. The final model was then fitted using GSTAT (Pebesma, 1997). Linear models of co-regionalization were determined only for the months April, May, August and September (Tables 3.5 and 3.6). A linear model of co-regionalization occurs when the variogram and the cross-variogram are given the same basic structures and the co-regionalization matrices are positive semi-definite (Appendix 3.1). For precipitation the other months had correlation coefficients that were too low for satisfactory co-kriging. The final ASCII surfaces interpolated at 30 arc seconds were created with GSTAT.

Surface characteristics and surface validation

Splining and co-kriging technique results were truncated to zero to avoid unrealistic, negative precipitation values. Interpolated monthly precipitation surfaces are displayed for April, May, August, and September in Appendix 3.3. Surfaces were also created with IDWA, splining, and co-kriging (not shown). The IDWA surfaces show clear 'bubbles' around the actual station points. Visually, the co-kriging surfaces follow the IDWA surfaces very well. The splined surfaces are similar to the DEM surface but appear more precise. Basic characteristics of the DEM, monthly precipitation, and temperature surfaces created through IDWA, co-kriging, and

Table 3.5 Variogram and cross-variogram values for the linear model of co-regionalization for precipitation.

		Semi-variogram				Cross-variogram			
Month	Variable	Model	Nugget	Sill	Range	Model	Nugget	Sill	Range
April	Precip.	Exponen.	3.20	46.3	2.10	Exponen.	17.8	3720	2.10
	Elevation	Exponen.	5050	565000	2.10				
May	Precip.	Exponen.	38.4	256	2.10	Exponen.	0	8680	2.10
	Elevation	Exponen.	5050	565000	2.10				
August	Precip.	Gaussian	1110	43400	5.65	Gaussian	2330	−198000	5.65
	Elevation	Gaussian	62300	2990000	5.65				
Sept.	Precip.	Gaussian	1260	64300	7.00	Gaussian	1560	−365000	7.00
	Elevation	Gaussian	63500	4400000	7.00				

Table 3.6 Variograms and cross-variograms for the linear model of co-regionalization for maximum temperature.

		Semi-variogram				Cross-variogram			
Month	Variable	Model	Nugget	Sill	Range	Model	Nugget	Sill	Range
April	Tmax	Exponen.	1.40	9.69	0.60	Exponen.	22.4	−1310	0.60
	Elevation	Exponen.	360	303000	0.60				
May	Tmax	Exponen.	1.10	9.81	0.60	Exponen.	20.3	−1280	0.60
	Elevation	Exponen.	380	303000	0.60				
August	Tmax	Spherical	0.926	10.7	1.50	Spherical	−11.2	−1640	1.50
	Elevation	Spherical	2810	309000	1.50				
Sept.	Tmax	Spherical	1.13	10.1	1.50	Spherical	−20.2	−1580	1.50
	Elevation	Spherical	2810	309000	1.50				

splining are presented in Appendix 3.4. Maximum elevation as reported in the stations is 2,361 m. Maximum elevation from the DEM was 4,019 m, much higher than the elevation of the highest station. Therefore precipitation and maximum temperature were estimated at elevations higher than elevations of the stations. It is not possible to validate these values because there are no measured values for such high elevations.

Table 3.7 Validation statistics for four monthly precipitation surfaces.

Precipitation	Mean absolute difference (mm)				Relative difference (%)			
	April	May	August	September	April	May	August	September
Validation 1								
IDWA	2.0	5.4	23.9	25.9	31	23	12	17
Splining	2.5	5.5	35.9	31.3	38	23	18	20
Co-kriging	2.0	5.5	33.6	32.5	31	23	17	21
Validation 2								
IDWA	1.9	6.6	41.2	41.7	41	31	20	24
Splining	2.2	6.1	55.1	47.3	46	28	26	27
Co-kriging	1.7	6.4	39.1	40.9	37	30	19	23

Table 3.8 Validation statistics for four maximum temperature surfaces.

Tmax	Mean absolute difference (°C)				Relative difference (%)			
	April	May	August	September	April	May	August	September
IDWA	2.7	2.5	2.0	1.9	8.6	7.6	7.0	6.7
Splining	1.6	1.4	1.2	1.1	5.0	4.5	4.2	3.9
Co-kriging	2.6	2.3	1.8	1.9	8.4	7.3	6.6	6.5

However, in the extreme values of the interpolated surfaces can be evaluated. For precipitation, it is difficult to know whether values at high elevations were reasonable estimates, because there is no generic association with elevation as occurs with temperature. The maximum value of the splined surfaces was smaller than the maximum measured value from the station. Measured precipitation data have a distribution that is skewed to the right. A frequency distribution of precipitation after interpolation (Fig. 3.5) provides another means of comparing the effects of interpolation techniques. The interpolated surfaces were clipped to the area of Jalisco to avoid side effects. Depending on the month, splining and co-kriging produced contrasting distributions. In May, splining indicated that 77% or more grid cells had less than 30 mm precipitation, whereas co-kriging allocated 70% of cells to this precipitation range. For September, co-kriging showed over 28% of the cells had from 138 to 161 mm precipitation, whereas splining assigned 24.5% of the cells to this precipitation class. In both cases co-kriging gave a wider precipitation range. The frequency of the co-variable 'elevation' within Jalisco is not normally distributed either (Fig. 3.6). Considering that there was a positive correlation between precipitation and altitude in May and a negative correlation in September, splining seemed to follow the distribution of elevation more than co-kriging. However, in the

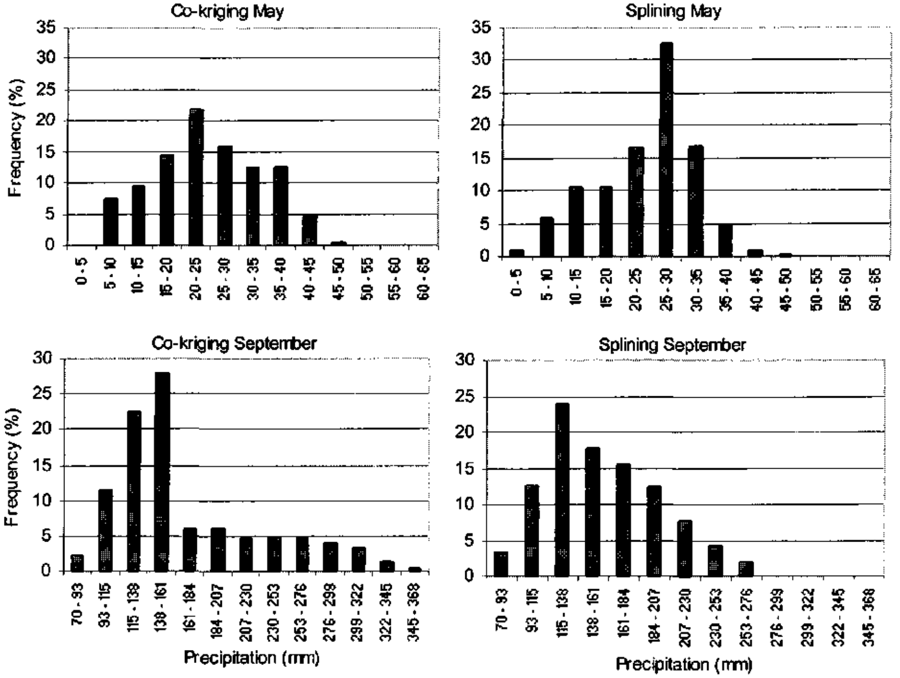


Figure 3.5 Frequency distribution of precipitation values after splining and co-kriging for two months, for Jalisco.

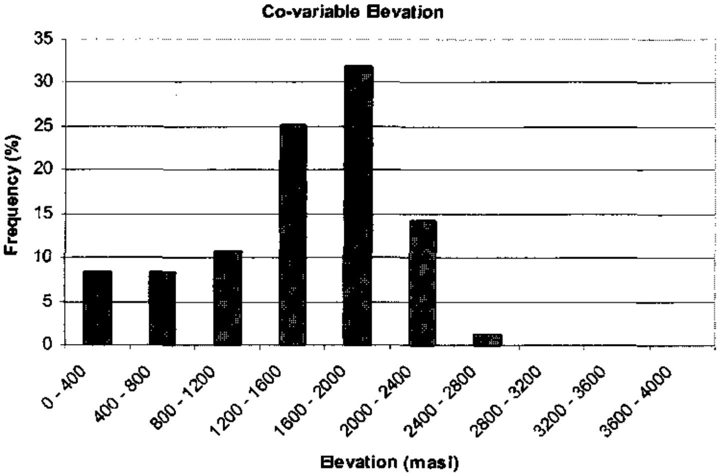


Figure 3.6 Frequency distribution of elevation, the co-variable for interpolation in this study, for Jalisco.

absence of more extensive validation data, it is not possible to state that one technique was superior to the other based on resulting frequency distributions. Usually, temperature decreases 5 to 6 °C per 1,000 m increase in elevation, depending on relative humidity and starting temperature (Monteith and Unsworth, 1990; see also Linacre and Hobbs, 1977). The difference between the maximum elevation of the stations and the maximum elevation in the DEM was 1,658 m. Thus, the estimated maximum temperature should be approximately 11 °C below values measured from the stations. This can be seen for the minimum value of the spline-interpolated values, which were about 9-10 °C below measured values (Appendix 3.4). The range of the co-krige and IDWA interpolated values was almost the same as that for the measured data. Therefore, at higher elevations splining appeared to predict the maximum temperature better than co-kriging. The surfaces were validated using the two independent test sets. For precipitation, the IDWA appeared to perform better than the other techniques (Table 3.7), but the difference was not significant (statistical analysis not shown). There was little difference between splining and co-kriging, but we could apply the latter only for the four months when there was a high correlation with the co-variable. The predictions for August and September using the second interpolation set were less accurate than those obtained using the first set. Validation showed that splining performed better for all months for maximum temperature (Table 3.8). There was no difference between co-kriging and IDWA predictions (statistical analysis not shown).

Prediction uncertainty (GCV)

Prediction uncertainty or 'error' surfaces were produced with the splining and co-kriging techniques. Appendix 3.5 shows this for precipitation. The prediction error from splining was more constant across months. The co-kriging error surfaces showed greater variability spatially and between months.

Conclusions for the study area

IDWA gave the best results for precipitation, though its superiority was not significant over results obtained through the other techniques. There was no gain from using elevation as a co-variable to interpolate precipitation. Distance to sea was another co-variable checked. However, the correlation was local and not always present (De Beurs, 1998). Other co-variables were not readily available. For maximum temperature there was a higher correlation with elevation and interpolation improved when this co-variable was used. Interpolation of maximum temperature was better handled by splining than by co-kriging or IDWA.

Conclusions and recommendations for further work

Conclusions of this work apply to this case study only, but several general recommendations can be made for future case studies:

- Splining and co-kriging should be preferred over the IDWA technique, because the former provide prediction uncertainty or 'error' surfaces that describe the spatial quality of the prediction surfaces. Co-kriging was possible for only four months for precipitation in the study area, due to the data prerequisites for this technique. Spline interpolation was preferred over co-kriging because it is faster and easier to use, as also noted in other studies (e.g., Hutchinson and Gessler, 1994).
- For all techniques interpolation can be improved by using more stations.
- For splining and co-kriging, interpolation can be improved by using more independent co-variables that are strongly correlated with the prediction variable.
- Preferably, all surfaces for one environmental variable should be produced using only one technique.
- Interested readers might wish to evaluate kriging with external drift, where the trend is modelled as a linear function of smoothly varying secondary (external) variables, or regression kriging, which looks very much like co-kriging with more variables. In regression kriging there is no need to estimate the cross-variogram of each co-variable individually; all co-variables are incorporated into one factor.

Taking into account error prediction, data assumptions, and computational simplicity, we would recommend use of thin-plate smoothing splines for interpolating climate variables.

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4.
COMPARISON OF THREE WEATHER GENERATORS FOR CROP MODELLING: A CASE STUDY FOR SUBTROPICAL ENVIRONMENTS

Abstract

The use and application of decision support systems (DDS) that consider variation in climate and soil conditions has expanded in recent years. Most of these DSS are based on crop simulation models that require daily weather data, so access to weather data, at single sites as well as large amount of sites that may cover a region, becomes a critical issue. In many agricultural regions, especially in developing countries, the density of meteorological stations is low, and reliable long-term continuous data are scarce. Researchers can use interpolated surfaces of weekly or monthly climate variables and generate daily weather from these. Various software tools, called 'weather generators', are available to automate this data generation process. The main objective of this study was to compare the performance of three weather generators, MARKSIM, SIMMETEO and WGEN, to observed daily weather data for one of the major maize growing regions in Northwest Mexico. A second objective was to evaluate the impact of using different generators for creating daily weather data for the simulation of maize and bean growth at nine locations. No single generator was clearly superior. However, considering data requirements, the weather generator SIMMETEO is robust and can be recommended for (crop) modelling applications at single point locations as well as for applications that use interpolated summary weather data as input. The weather generator MARKSIM created a high inter-annual variability and long chains of wet days that are not found in observed data, but the generator has use for areas of poor distribution of weather stations or where monthly means are unavailable. The results from this study can be considered valid for the subtropical region from which the test locations were selected. For climates in different regions of the world, we suggest repeating the evaluation process following procedures similar to those used in this paper.

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Introduction

The use and application of decision support systems (DDS) that consider explicit variation in climate and soil conditions is growing in agricultural research (see Chapter 2). Applications include hydrology (Thornton et al., 1997), agro-ecology (Hutchinson, 1987; Jones, 1987; Aggarwal, 1995) and regional crop productivity modelling or forecasting (Calixte et al., 1992; Lal et al., 1993; Papajorgji et al., 1993; Singh et al., 1993; Haskett et al., 1995; Thornton et al., 1995; Van Keulen and Stol, 1995; Carbone et al., 1996; Georgiev et al., 1998). These applications frequently rely on point models that use daily weather data as inputs. An important methodological issue is whether to create spatial input before simulation or to create spatial output from simulation results at point locations. Interpolation procedures can create both spatial input data and spatial output data. Brisson et al. (1992) concluded that the choice of interpolating either input or output data depends upon the scale of the model that is being used for the simulation as well as the area is being considered. Brisson et al. (1992) preferred to interpolate model inputs. For moisture deficit, Stein et al. (1991) found that it was better to simulate first and then interpolate. Meinke and Hammer (1995) interpolated simulation results but recognized that interpolating arbitrarily spaced model outputs is unable to capture spatial variation as well as the interpolation of the driving input variables. Theoretically, the statistical or mathematical algorithms available for interpolating climate data are more robust than those that are used for interpolating simulation results. Practically, the benefit obtained through interpolation of inputs depends on the quality of the data being interpolated, and on the density of the points at which processes, e.g., crop growth, will be simulated.

The density of meteorological stations is often low, especially in developing countries, and reliable and complete long-term data are scarce (see e.g., NCDC, 1994). With a few exceptions from developed countries (see Thornton et al., 1997), daily-interpolated surfaces of meteorological variable rarely exist. More commonly, weather data used in applications that cover large geographic regions come from interpolated surfaces of weekly or monthly climate variables (e.g., Collis and Corbett, 1997; Jones and Thornton, 1999, 2000). From these interpolated surfaces, daily weather data for crop simulation models are then generated using statistical models that attempt to reproduce series of daily data with means and variability similar to what would be observed at a given location

Both the amount and distribution of precipitation are among the most important environmental variables that influence the soil water balance and crop growth. Precipitation is also strongly related to other weather variables such as solar radiation, temperature and humidity (Geng et al., 1986). Unfortunately, precipitation is the most difficult weather parameter to generate. The objective of this study was to compare the performance of the generic weather generators MARKSIM, SIMMETEO and WGEN, with emphasis on precipitation. The performances of the weather generators that were compared included both the generation of daily weather data *per se* as well as the impact on the simulation of maize growth and yield.

Weather generators typically calculate daily precipitation first and use this information to guide the generation of other weather variables, such as daily solar radiation, maximum and minimum temperature, and potential evapotranspiration (Richardson, 1981, 1985; Hutchinson, 1987; Thornton et al., 1997). Daily precipitation is usually generated by modelling the occurrence of wet days and the amount of rain on a wet day (Geng et al., 1986). First order Markov chains are often used to describe the occurrence of wet days (Geng et al., 1986), which were originally proposed by Gabriel and Neumann (1962). Weather generators that use second or higher order Markov chains have been recommended for sites that are not located in temperate regions (e.g., Jones, 1987; Jones and Thornton, 1993, 1997). However, parameters for higher order Markov chains are more difficult to obtain, usually less reliable and more sensitive to errors in estimating the occurrence of wet days (Hutchinson, 1987).

To generate the amount of precipitation on wet days, a two-parameter gamma distribution function is commonly used (Richardson, 1981, 1985; Geng et al., 1986; Hutchinson, 1987). The two parameters, α and β, are directly related to the average amount of precipitation per wet day (Geng et al., 1986). They can therefore be determined with the monthly means for the number of rainy days per month and the amount of precipitation per month, which are obtained either from compilations of climate normals or from interpolated surfaces.

Materials and methods

Description of weather generators

Three weather generators were evaluated in this study:

- WGEN (Richardson, 1984, 1985) is a first order Markov daily generator that requires long-term daily weather data for estimation of its parameters.
- SIMMETEO (Geng et al., 1986, 1988) is a first order Markov daily generator that estimates the parameters from monthly summary data instead of daily data. Monthly averages, calculated from 5 to 10 years daily weather data, are assumed to be sufficient to produce reliable parameters (Geng et al., 1986).
- MARKSIM (Jones and Thornton, 1998, 2000) is a third order Markov daily weather generator that obtains parameters from climate clusters of interpolated surfaces. This generator was specifically developed to generate precipitation data for tropical regions. The software allows three types of input to estimate parameters for the generator:

1) Latitude and longitude;
2) Latitude, longitude and elevation; or
3) Latitude, longitude, elevation and long-term monthly climate normals.

In this study, options 2 and 3 were used to generate weather data with MARKSIM, which are referred to MARKSIM-IP (Interpolated) and MARKSIM-CN (climate normal) respectively in the following sections. Because of their reduced data requirement and certain theoretical assumptions, the SIMMETEO and MARKSIM generators appeared especially suitable for application in developing countries.

Description of locations and data sources for the subtropical case study

Nine stations, located in the major maize growing region of northwest Mexico, were selected that had the longest available daily weather records (Table 4.1). To include a wide range of climatic conditions, these nine stations were selected over three elevations – or maximum temperature – by three precipitation strata, emphasizing the main growing season of maize, i.e., June to December. Daily weather records for the stations were obtained from the digital source Extractor Rápido de Información Climatológica or ERIC (IMTA, 1996). The records were checked for obvious errors such as temperatures > 50 °C and daily rainfall events > 600 mm. Daily solar radiation data were not available from this source. For northwest Mexico, monthly solar radiation data were not available at the station locations and therefore, these were extracted from interpolated surfaces of CLIMWAT solar radiation data (FAO, 1993; see Chapter 3).

Table 4.1 Location of stations used for evaluating weather generators.

Stratification by altitude[1] and precipitation[2]	Station name	Latitude (°)	Longitude (°)	Altitude (m)	Precipitation GS[2] (mm)	Number of years[3]
Lowland, limiting	El Vaso Infernillo	18.77	−101.87	277	420	21
Midland, limiting	Zocoalco	20.23	−103.58	1363	481	23
Highland, limiting	Mesillas	22.32	−102.20	1975	364	21
Lowland, sufficient	Tepames	19.10	−103.63	499	865	20
Midland, sufficient	Mascota	20.52	−104.82	1651	934	23
Highland, sufficient	El Tule Arandas	20.73	−102.40	2026	881	20
Lowland, wet	Paso de Arocho	21.83	−105.13	24	1641	25
Midland, wet	Coalman	18.77	−103.15	1030	1556	24
Highland, wet	San Gregorio	19.87	−103.35	1937	1220	21

[1] Altitude and maximum temperature during growing season (June-December): Lowland (< 1000 m): Tmax > 30 °C; Midlands (1000-1700 m): Tmax 25 - 30 °C; Highlands (> 1700 m): Tmax < 25 °C .

[2] Precipitation growing season (June-Dec.): Limiting 0-500 mm; Sufficient 500 - 1200 mm; Wet > 1200 mm.

[3] During the period 1965 - 1990.

Calculation of parameters and generation of weather data

Parameters for WGEN and SIMMETEO were calculated independently for each of the nine selected locations using twenty to twenty five years of observed daily weather data at the respective location and accessing the two generators through the Decision Support Systems for Agrotechnology Transfer (DSSAT) software package (Hansen et al., 1994; Tsuji et al., 1994). Weather data were generated for all the stations to match the number of years of observed data that were available. As described briefly above, MARSKIM can generate weather data using two different methods, referred to as MARKSIM-IP (Interpolated) and MARKSIM-CN (climate normal) in this paper. In the first method, the location coordinates and elevation of the station are used as input and climate parameters are estimated from interpolated surfaces incorporated in the MARKSIM software (Jones and Thornton, 1998). In the second, method long-term normals based on twenty to twenty five years of daily weather data of that station are added to the climate parameter database of MARKSIM. Procedures on how to determine these inputs are described in Jones and Thornton (1998, 2000). In all cases, data were generated for 'normal weather conditions', i.e., no climate change scenario was applied.

Statistical analysis of generated and observed weather data

Summary statistics for generated and observed weather data were calculated. Complete years of observed data were not included in the calculation of the mean annual precipitation if more than four days were missing for a given year. Daily generated and observed precipitation data were compared for the hypothesis that the mean difference between observed and simulated values was zero. Because precipitation amounts are seldom normally distributed, two tests were used to evaluate this hypothesis. The first used a student *t*-test, which is a parametric test. The second was the non-parametrical and distribution free, signed rank or Wilcoxon test (see Snedecor and Cochran, 1980). For both tests, a high probability value means that the hypothesis of similarity is accepted. The duration of chains of consecutive wet days was also compared, and frequency distributions of precipitation and maximum and minimum temperature were analysed. Statistical analyses were conducted using SAS (SAS Institute, 1997).

Simulation of a twenty-year seasonal maize – fallow rotation

Simulations using generated and observed weather data were run for a twenty-year maize-fallow rotation and for a twenty-year dry bean–fallow rotation using the seasonal analysis program within DSSAT (Thornton et al., 1994; Thornton and Hoogenboom, 1994). The seasonal analysis program runs the years as repetitions without a carry over of soil, water and nutrient status between seasons, so the effect of one year of weather does not affect the following year of simulation. Observed years of weather data and consequently, results from the simulations, were excluded from

Table 4.2 Comparison of observed and generated weather data for nine locations in Jalisco, Mexico.

Station	Source	Tmax (°C)			Tmin (°C)			Precipitation (mm)				
		Average	Min.	Max.	Average	Min.	Max.	Average	Stdev	Min.	Max.	No. years
El Vaso Infernillo	Observed	34.3	18.5	41.5	22.2	13.0	27.5	450	137	240	764	17
	MarksimIP	35.2	23.6	44.9	23.0	10.5	31.5	835	278	441	1459	20
	MarksimCN	34.2	22.0	43.5	22.2	10.2	30.4	567	183	244	912	20
	Simmeteo	34.2	21.8	43.7	22.1	10.0	30.9	462	106	284	666	20
	Wgen	34.4	18.6	44.6	22.2	14.1	28.2	436	93	231	585	20
Zocoalco	Observed	29.6	11.0	42.0	13.3	1.0	32.0	519	124	333	723	12
	MarksimIP	26.6	7.9	39.3	12.0	–6.4	26.5	789	172	579	1131	20
	MarksimCN	30.0	14.8	43.2	14.5	–2.3	27.3	844	293	428	1726	20
	Simmeteo	29.3	11.1	41.1	13.1	–3.3	26.5	522	151	278	723	20
	Wgen	30.2	15.5	43.1	14.6	–2.9	34.5	565	111	362	740	20
Mesillas	Observed	25.7	9.0	43.0	9.6	–6.0	19.0	416	127	185	683	18
	MarksimIP	24.3	7.8	36.3	9.1	–10.7	25.3	496	176	289	1008	20
	MarksimCN	25.7	11.6	38.3	9.6	–10.4	26.1	462	173	157	774	20
	Simmeteo	25.5	8.0	38.5	9.5	–10.0	24.0	446	102	258	677	20
	Wgen	25.7	7.5	43.8	9.6	–5.4	20.4	480	128	247	736	20
Tepames	Observed	35.4	13.0	46.0	16.3	1.0	28.5	952	216	412	1234	13
	MarksimIP	31.2	19.3	42.6	17.8	4.7	29.3	935	231	638	1459	20
	MarksimCN	35.2	22.8	44.0	16.1	3.1	27.2	1303	156	1015	1567	20
	Simmeteo	35.5	23.4	44.9	16.3	3.9	27.5	913	240	476	1339	20
	Wgen	35.6	11.2	47.1	16.4	2.5	28.8	908	222	617	1457	20
Mascota	Observed	29.3	13.0	38.0	13.4	0.0	22.0	1022	143	745	1345	18
	MarksimIP	25.9	12.6	38.5	11.6	–8.2	26.2	956	138	752	1366	23
	MarksimCN	29.2	17.4	40.8	13.9	–3.7	26.3	1040	246	672	1538	23
	Simmeteo	29.1	18.0	40.9	13.6	–2.9	26.7	998	160	722	1271	23
	Wgen	29.2	13.0	39.5	13.7	2.7	23.7	942	146	736	1192	23
El Tule Arandas	Observed	25.1	9.0	38.5	8.5	–6.0	17.0	982	161	706	1310	16
	MarksimIP	25.6	9.9	38.2	9.9	–8.9	24.3	919	198	564	1186	20
	MarksimCN	25.1	10.2	37.8	8.5	–9.9	22.5	888	202	433	1239	20
	Simmeteo	25.1	10.6	38.8	8.5	–10.7	24.8	983	171	715	1265	20
	Wgen	25.1	5.6	38.6	8.5	–3.8	20.2	935	186	637	1304	20
Paso de Arocha	Observed	31.9	20.0	41.5	18.4	6.5	26.0	1748	324	934	2264	18
	MarksimIP	33.1	20.6	43.4	18.5	4.0	29.8	1648	337	1049	2169	25
	MarksimCN	31.8	19.8	42.8	18.4	3.6	30.4	2280	424	1358	3101	25
	Simmeteo	31.8	21.1	41.9	18.5	4.2	29.7	1764	237	1195	2313	25
	Wgen	31.9	16.3	40.2	18.4	6.6	26.9	1724	224	1290	2154	25
Coalman	Observed	31.5	15.5	39.5	15.1	2.0	25.0	1399	425	854	2301	18
	MarksimIP	30.4	17.4	41.0	17.5	3.6	27.9	1277	282	838	1705	22
	MarksimCN	31.4	18.9	43.4	14.9	–1.7	27.7	1402	300	911	2015	22
	Simmeteo	31.5	18.9	43.1	15.0	–0.4	28.5	1329	201	979	1733	22
	Wgen	31.4	15.7	42.6	14.8	–0.5	26.5	1338	210	910	1708	22
San Gregorio	Observed	23.5	9.0	39.0	6.9	–8.5	17.5	1384	209	1036	1803	17
	MarksimIP	23.3	6.8	37.5	9.6	–9.7	23.2	961	214	453	1412	20
	MarksimCN	23.6	5.8	37.6	6.9	–12.8	25.9	1393	258	1043	2140	20
	Simmeteo	23.8	9.8	37.1	7.2	–12.8	22.6	1382	211	980	1849	20
	Wgen	23.6	9.9	32.9	6.8	–9.4	19.0	1294	152	978	1657	20

Data for temperature are based on long term daily records for maximum (Tmax) and minimum (Tmin) for twenty years, and data for precipitation are based on annual totals.

analysis if more than two days of weather data were missing during the growing season (June to December). For both the maize-fallow rotation and dry bean–fallow rotation systems, two management scenarios were chosen:

- No fertilizer application.
- Two fertilizer applications following regional agricultural recommendations. For maize nitrogen applications are reported as 50 kg ha^{-1} at planting and 100 kg ha^{-1} 40 days after planting (Glo and Martin, 1995; Jourdain, 1999) and for beans 45 kg ha^{-1} (Samuel Nunez, pers. communication).

The same initial soil water and nitrogen conditions were used for all simulation scenarios. Maize and dry bean biomass and grain yield were compared using the procedure 'MIXED' within an analysis of variance of the statistical analysis package SAS (SAS Institute, 1997). Maize grain yield probability distributions were also graphically displayed.

Results

Precipitation

SIMMETEO and WGEN generated mean total annual precipitation within 50 mm of observed values (Table 4.2), which generally was within 5% deviation from the observed. In the case of the station 'El Vaso Infernillo', precipitation data from MARKSIM-IP showed 85% deviation from the observed. This might be due to the weather station not being situated close to the reported location, but more likely was caused by an error in the climate cluster from interpolated weather surfaces.

SIMMETEO and WGEN data commonly showed equal or less inter-annual variability in precipitation than the observed data (Table 4.2). A higher inter-annual variability in precipitation as compared to the observed was found in seven out of nine cases for MARKSIM-IP and in eight of nine cases for MARKSIM-CN. Also, in six out of nine cases MARKSIM-CN showed a higher inter-annual variability than MARKSIM-IP. This was unexpected since MARKSIM-CN should be closer to the observed data than MARKSIM-IP. In the case of station 'Paso de Arocha', MARKSIM-CN data appeared to ignore the climate normal of 1710 mm provided as an input and generated an average annual precipitation of 2280 mm. The generation process was repeated four times with MARKSIM-CN to determine whether there was a bias in the data generation. Average annual precipitation values of 2443 mm, 2341 mm, 2309 mm and 2434 mm were the result, suggesting a bias from the climate normal and not a random variation about the normal. Since resampling provided no improvement in the generation of the average annual precipitation, subsequent analysis used the first data set created by MARKSIM-CN for this station.

In the comparison of daily precipitation data, results varied across locations and tests (Table 4.3). Nonetheless, the hypothesis that the difference between daily generated

Table 4.3 Comparison of generated and observed daily precipitation data.

Name	Comparison	Student *t*-test		Signed rank test	
		P	*t*	P	Rank sum
El Vaso Infernillo	observed-marksimip	0.00	−7.14	0.00	−11891
	observed-marksimcn	0.02	−2.28	0.00	−4351
	observed-simmeteo	0.75	0.32	0.76	384
	observed-wgen	0.25	1.14	0.30	1240
	marksimip-marksimcn	0.00	5.58	0.00	7244
	marksimip-simmeteo	0.00	7.31	0.00	11558
	marksimip-wgen	0.00	8.76	0.00	12320
	marksimcn-simmeteo	0.01	2.75	0.00	5261
	marksimcn-wgen	0.00	3.56	0.00	5309
	simmeteo-wgen	0.46	0.74	0.37	949
Zocoalco	observed-marksimip	0.00	−6.98	0.00	−12310
	observed-marksimcn	0.00	−4.17	0.52	−725
	observed-simmeteo	0.56	0.59	0.05	2253
	observed-wgen	0.50	−0.67	0.57	−665
	marksimip-marksimcn	0.45	−0.75	0.00	8150
	marksimip-simmeteo	0.00	7.50	0.00	14648
	marksimip-wgen	0.00	6.18	0.00	13138
	marksimcn-simmeteo	0.00	4.34	0.09	1857
	marksimcn-wgen	0.00	3.94	0.63	515
	simmeteo-wgen	0.24	−1.18	0.15	−1530
Mesillas	observed-marksimip	0.00	−2.92	0.01	−4974
	observed-marksimcn	0.10	−1.67	0.13	−2804
	observed-simmeteo	0.34	−0.95	0.65	791
	observed-wgen	0.03	−2.13	0.30	−1859
	marksimip-marksimcn	0.24	1.19	0.79	−493
	marksimip-simmeteo	0.13	1.51	0.01	4348
	marksimip-wgen	0.59	0.55	0.48	1256
	marksimcn-simmeteo	0.63	0.48	0.01	4493
	marksimcn-wgen	0.54	−0.61	0.93	166
	simmeteo-wgen	0.35	−0.94	0.05	−3492
Tepames	observed-marksimip	0.61	−0.51	0.61	−715
	observed-marksimcn	0.00	−4.01	0.07	−2485
	observed-simmeteo	0.93	−0.08	0.97	−52
	observed-wgen	0.99	0.02	0.85	233
	marksimip-marksimcn	0.00	−4.00	0.14	−2193
	marksimip-simmeteo	0.67	0.43	0.38	1310
	marksimip-wgen	0.63	0.48	0.05	2731
	marksimcn-simmeteo	0.00	4.25	0.01	3485
	marksimcn-wgen	0.00	4.29	0.00	3928
	simmeteo-wgen	0.92	0.10	0.21	1502
Mascota	observed-marksimip	0.15	1.44	0.32	1846
	observed-marksimcn	0.49	−0.69	0.95	−112
	observed-simmeteo	0.81	0.24	0.15	2335
	observed-wgen	0.08	1.73	0.01	4210
	marksimip-marksimcn	0.03	−2.14	0.28	−1912
	marksimip-simmeteo	0.33	−0.97	0.41	1475
	marksimip-wgen	0.73	0.35	0.10	2852
	marksimcn-simmeteo	0.41	0.83	0.33	1593
	marksimcn-wgen	0.03	2.15	0.13	2426
	simmeteo-wgen	0.20	1.28	0.19	1850

Table 4.3 Continued.

Name	Comparison	Student *t*-test		Signed rank test	
		P	*t*	P	Rank sum
El Tule Arandas	observed-marksimip	0.31	1.02	0.41	1320
	observed-marksimcn	0.06	1.92	0.45	1376
	observed-simmeteo	0.82	–0.22	0.20	2174
	observed-wgen	0.43	0.79	0.06	3280
	marksimip-marksimcn	0.44	0.77	0.17	–2305
	marksimip-simmeteo	0.27	–1.11	0.47	–1125
	marksimip-wgen	0.74	–0.33	0.75	–526
	marksimcn-simmeteo	0.07	–1.85	0.76	548
	marksimcn-wgen	0.28	–1.09	0.19	2345
	simmeteo-wgen	0.38	0.88	0.81	–415
Paso de Arocha	observed-marksimip	0.34	0.95	0.18	2257
	observed-marksimcn	0.00	–3.24	0.99	30
	observed-simmeteo	0.61	–0.52	0.64	–763
	observed-wgen	0.99	0.01	0.73	584
	marksimip-marksimcn	0.00	–4.47	0.09	–2654
	marksimip-simmeteo	0.15	–1.45	0.33	–1664
	marksimip-wgen	0.35	–0.94	0.19	–2144
	marksimcn-simmeteo	0.00	3.13	0.65	712
	marksimcn-wgen	0.00	3.72	0.18	2062
	simmeteo-wgen	0.61	0.51	0.80	392
Coalman	observed-marksimip	0.00	3.37	0.00	8105
	observed-marksimcn	0.94	–0.07	0.36	1663
	observed-simmeteo	0.87	–0.16	0.92	182
	observed-wgen	0.74	–0.33	0.73	623
	marksimip-marksimcn	0.15	–1.44	0.04	–3865
	marksimip-simmeteo	0.00	–3.29	0.00	–6936
	marksimip-wgen	0.00	–3.59	0.00	–6738
	marksimcn-simmeteo	0.30	1.04	0.57	982
	marksimcn-wgen	0.35	0.93	0.31	1722
	simmeteo-wgen	0.88	–0.15	0.92	171
San Gregorio	observed-marksimip	0.00	9.13	0.00	17318
	observed-marksimcn	0.78	–0.27	0.56	1135
	observed-simmeteo	0.91	–0.11	0.40	1655
	observed-wgen	0.08	1.77	0.04	3889
	marksimip-marksimcn	0.00	–7.35	0.00	–12175
	marksimip-simmeteo	0.00	–7.71	0.00	–12828
	marksimip-wgen	0.00	–7.16	0.00	–12498
	marksimcn-simmeteo	0.86	0.18	0.58	–1048
	marksimcn-wgen	0.07	1.83	0.45	1438
	simmeteo-wgen	0.07	1.79	0.22	2377

and observed precipitation data is zero was commonly rejected ($P < 0.05$, Table 4.3) for precipitation data generated with MARKSIM-IP. MARKSIM-CN data appear to follow the observed better than MARKSIM-IP. Although SIMMETEO was not found different to WGEN, for both the *t*-test as well as the signed rank test, SIMMETEO showed a higher probability than WGEN for similarity to the observed in seven cases. MARKSIM-CN gave a higher probability than SIMMETEO only once for the *t*-test and five times for the signed rank; however it was not found significant.

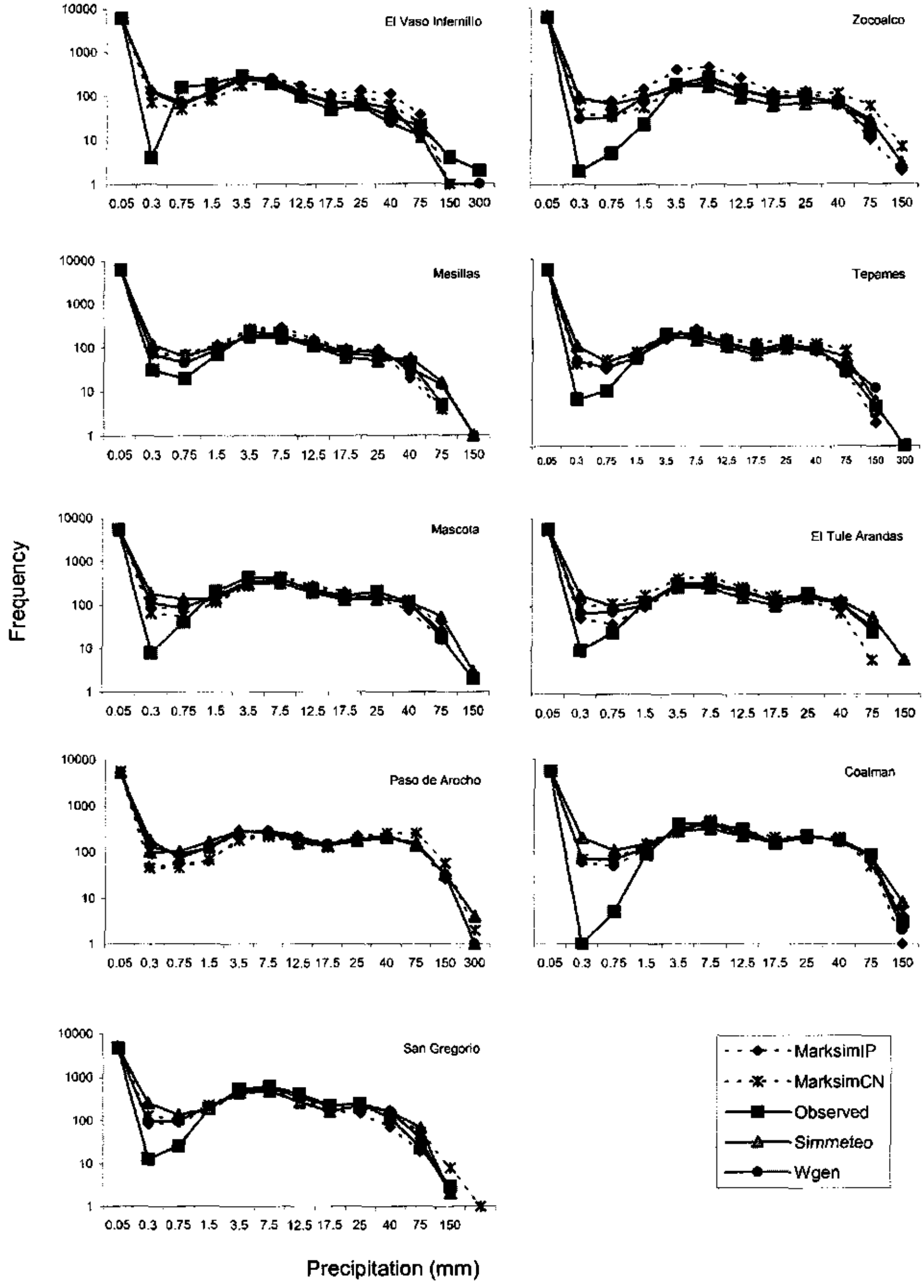

Figure 4.1 Frequency distribution of generated and observed precipitation data.

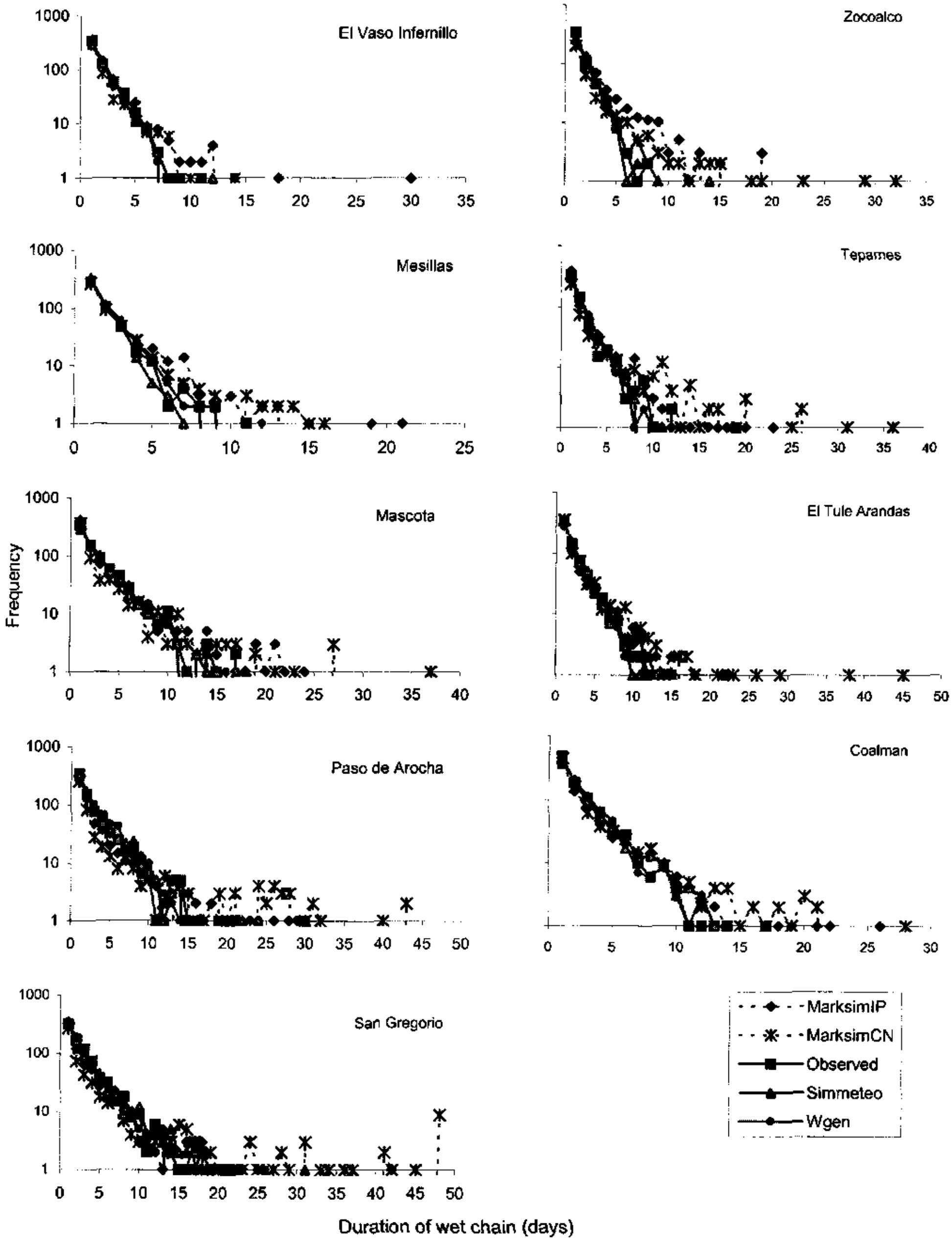

Figure 4.2a Frequency of wet chains (days) of generated and observed precipitation data (wet day > 0.1 mm).

Frequency distributions of precipitation amounts were plotted using a logarithmic frequency scale with the following intervals: 0 - 0.1 mm; 0.1 - 0.5 mm; 0.5 -1 mm; 1 - 2 mm; 2 - 5 mm; 5 - 10 mm; 10 - 15 mm; 15 - 30 mm; 30 - 50 mm; 50 -100mm; 100 - 200 mm; 200 - 400 mm (Fig. 4.1). The generated data generally matched observed data, but all weather generators overestimated small precipitation amounts.

However, since there were few observed data with values between 0.1 and 0.5 mm, it is possible that these events were not always recorded. Both MARKSIM-IP and MARKSIM-CN were less accurate than SIMMETEO and WGEN in generating extreme precipitation events, including both large and small amounts.

The duration of chains of wet days is shown in Fig. 4.2a, considering a day to be wet if the precipitation amount is more than 0.1 mm on a day. MARKSIM-IP and MARKSIM-CN consistently overestimated this duration. In all locations except for 'Paso de Arocha', the observed maximum duration of a wet chain was 18 days. MARKSIM-IP and MARKSIM-CN commonly generated wet chains of more than 22 days. Consequently, MARKSIM somewhat underestimated the amount of wet chains with a duration of 2 to 6 days. For example, in the specific case of 'Paso de Arocha', only one chain of 21 days and one of 30 days were observed in 25 years. However, MARKSIM-IP generated six chains of 21 days or more, while MARKSIM-CN generated 26 chains of over 21 days, of which six chains were between 31 days and 43 days. In the case of station 'San Gregorio', MARKSIM-CN generated the maximum duration of wet chain, where nine chains of 48 days were generated, while the maximum observed for this site was 19 days.

One may argue that chains of 0.1 mm precipitation are unrealistic as this is often the minimum amount of precipitation that is reported. However, the overall results did not change when the analysis was repeated using a limit of 0.2 mm. Figure 4.2b illustrates this for two stations purposely chosen because the average annual precipitation generated by MARKSIM IP and MARKSIM-CN was similar to the observed[1].

Maximum and minimum air temperature

Mean, maximum and minimum temperatures from SIMMETEO and WGEN were within 0.5 °C of observed values (Table 4.2). In 50% of the cases, mean temperature data from MARKSIM-IP differed more than 2 °C. Again, this could be related to the reported location of the station but more likely, was due to errors in the interpolated surfaces. MARKSIM-CN produced temperature values much closer to the observed

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[1] Choosing stations where MARKSIM generated a higher average annual precipitation would be biased towards generating longer wet chains.

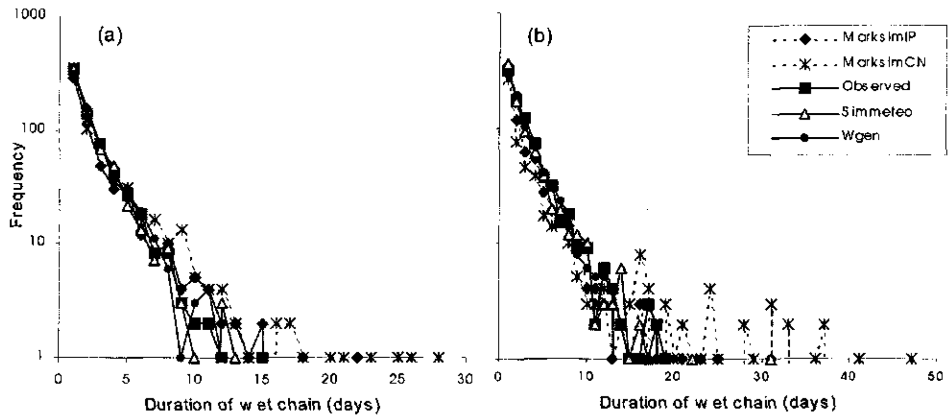

Figure 4.2b Frequency of wet chains (days) of generated and observed precipitation data (wet day > 0.2 mm) for stations El Tule Arandas (a) and San Gregorio (b).

because the climate normals are used to generate the temperature data. Maximum and minimum values for maximum and minimum temperature generally differed 1 to 2 °C. All generators seemed to have difficulty in estimating the minimum value for minimum temperature (Table 4.2). SIMMETEO performed slightly better than WGEN in the generation of the minimum and maximum values of maximum temperature but was usually worse for generation of minimum and maximum values of minimum temperature. MARKSIM-CN performed similar to SIMMETEO and WGEN.

In most cases, the range of generated temperatures was larger than in observed data (Fig. 4.3 and 4.4). The generated temperature data showed higher frequency in the minimum values for minimum temperature than the observed. For two stations where a substantial number of extreme temperature events occurred, frequency per month was analysed (Fig. 4.5). The number of days above 40 °C was commonly overestimated for the dry season, except for station Tepames (Fig. 4.5 graph B). Similarly, the number of days below 0 °C was overestimated during the dry season (Fig. 4.6). The diurnal temperature range created by weather generators during the dry season was larger than the observed data. Fortunately, this would have minimal affect on applications of weather generators for simulation of summer rainfed crops. Moreover, in the other seven stations, the frequencies of extreme values (over 40 °C or below 0 °C) was low both for observed and generated data and stayed below 5 % over the twenty year period.

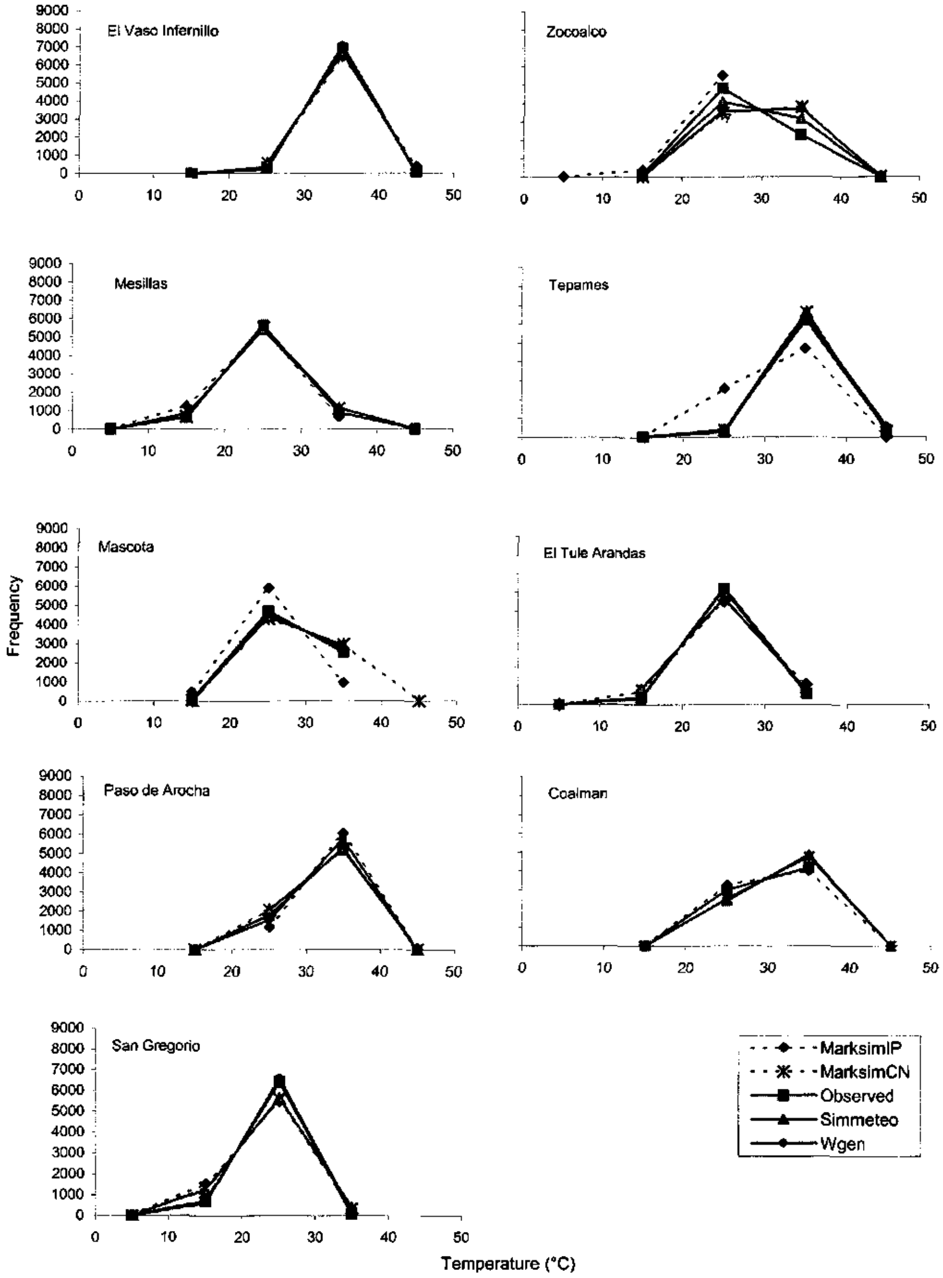

Figure 4.3 Frequency distribution of generated and observed maximum temperature data.

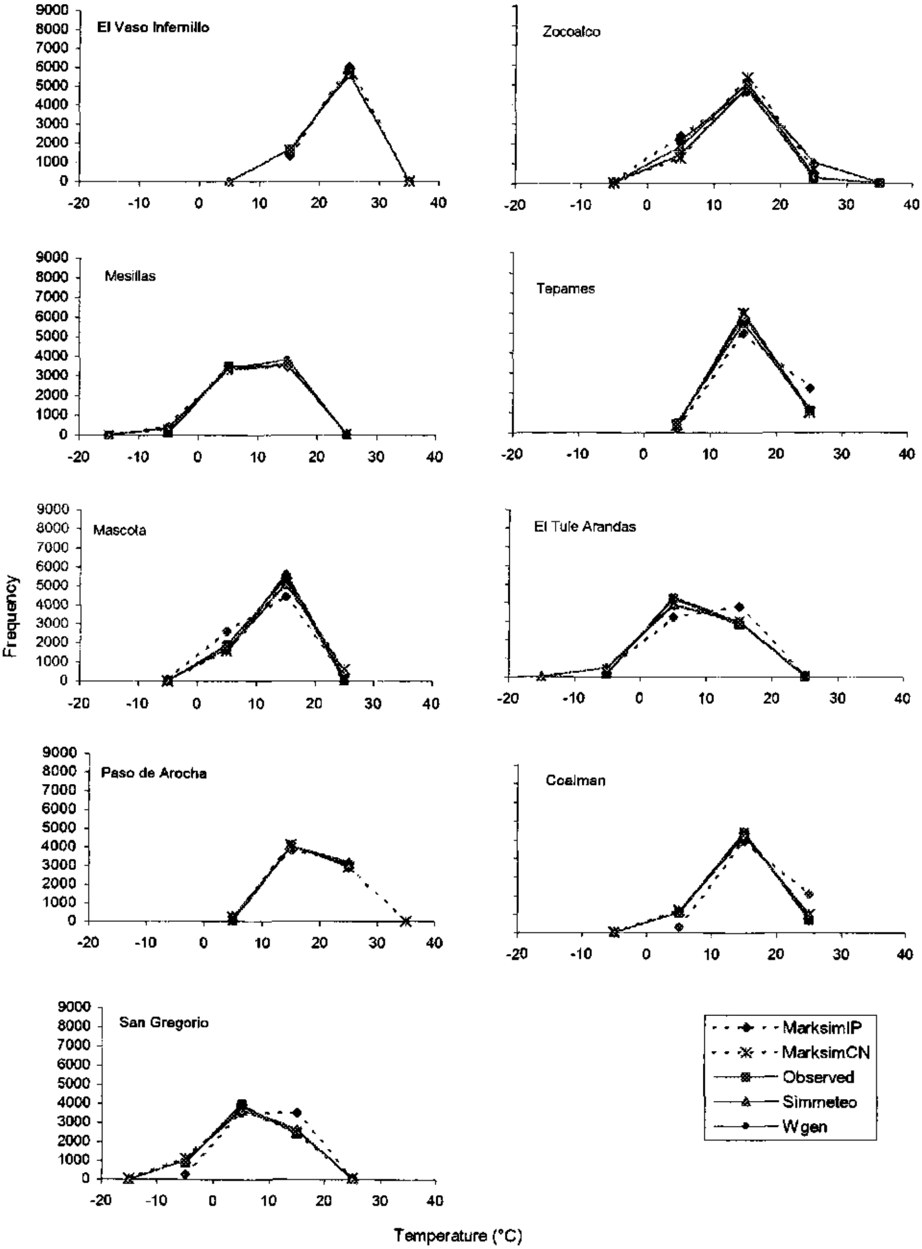

Figure 4.4 Frequency distribution of generated and observed minimum temperature data.

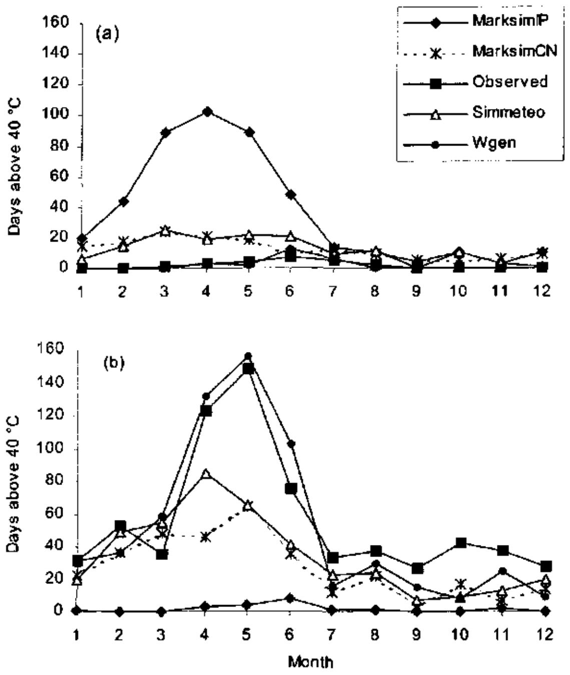

Figure 4.5 Generated and observed number of days above 40 °C for stations El Vaso Infernillo (a) and Tepames (b).

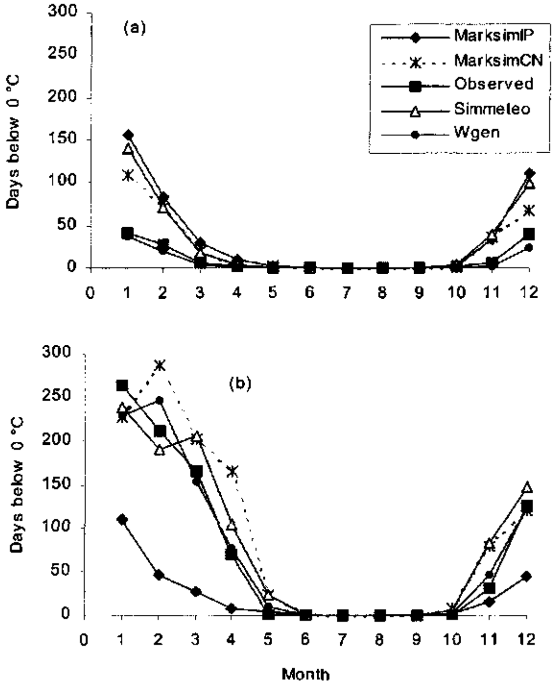

Figure 4.6 Generated and observed number of days below 0 °C for stations Mesillas (a) and San Gregorio (b).

Table 4.4 Comparison of simulated maize and bean aboveground biomass (AB) and grain yield (GY) using generated and observed weather data.

	No fertilizer application				Fertilizer application[1]			
	AB		GY		AB		GY	
	P > |*t*|	*t*	Pr > |*t*|	*t*	P > |*t*|	*t*	Pr > |*t*|	*t*
MAIZE								
observed-marksimip	0.717	0.36	0.267	1.11	0.000 *	3.95	0.000 *	5.56
observed-marksimcn	0.000 *	5.79	0.000 *	5.63	0.099	1.65	0.374	0.89
observed-simmeteo	0.162	−1.40	0.429	−0.79	0.348	−0.94	0.641	−0.47
observed-wgen	0.006 *	−2.77	0.030	−2.17	0.003 *	−2.94	0.015 *	−2.43
marksimip-marksimcn	0.000 *	6.12	0.000 *	6.71	0.000 *	5.58	0.000 *	6.42
marksimip-simmeteo	0.303	−1.03	0.751	0.32	0.003 *	3.00	0.000 *	5.07
marksimip-wgen	0.017	−2.40	0.293	−1.05	0.312	1.01	0.002 *	3.11
marksimcn-simmeteo	0.000 *	7.15	0.000 *	6.39	0.010 *	2.58	0.178	1.35
marksimcn-wgen	0.000 *	8.52	0.000 *	7.76	0.000 *	4.57	0.001 *	3.31
simmeteo-wgen	0.173	−1.36	0.171	−1.37	0.047 *	−1.99	0.051	−1.96
BEAN								
observed-marksimip	0.090	1.70	0.326	0.98	0.354	0.93	0.892	0.14
observed-marksimcn	0.000 *	3.60	0.000 *	4.44	0.000 *	4.90	0.000 *	5.6
observed-simmeteo	0.461	0.74	0.097	1.66	0.262	1.12	0.044 *	2.02
observed-wgen	0.049 *	−1.97	0.192	−1.31	0.174	−1.36	0.504	−0.67
marksimip-marksimcn	0.000 *	5.28	0.000 *	5.4	0.000 *	5.80	0.000 *	5.71
marksimip-simmeteo	0.016 *	2.43	0.009 *	2.63	0.042 *	2.04	0.033 *	2.14
marksimip-wgen	0.788	−0.27	0.747	−0.32	0.668	−0.43	0.597	−0.53
marksimcn-simmeteo	0.005 *	2.85	0.006 *	2.77	0.000 *	3.76	0.000 *	3.56
marksimcn-wgen	0.000 *	5.55	0.000 *	5.72	0.000 *	6.23	0.000 *	6.24
simmeteo-wgen	0.007 *	−2.69	0.003 *	−2.95	0.014 *	-2.47	0.008 *	−2.67

[1] 50 N kg ha^{-1} at planting and 100 N kg ha^{-1} 40 days after planting for maize and 45 N kg ha^{-1} at planting for beans.

* significant at $P < 0.05$.

Analysis of simulations for maize and dry beans

Both for simulations with and without fertilizer and for both crops, weather data from SIMMETEO resulted in outputs that differed the least from results with observed weather data (Table 4.4). Differences between observed and generated weather tended to increase at higher yield levels achieved with fertilizer ($P < 0.05$).

Cumulative probabilities for maize grain yield are shown in Fig. 4.7 and 4.8. Weather data from MARKSIM-IP and MARKSIM-CN resulted in simulated maize grain yields with more variability than simulated maize grain yield using observed weather. This may reflect the higher inter-annual precipitation variability that was found for data generated with MARKSIM-IP and MARKSIM-CN. In cases when the yield was zero, soil moisture conditions were insufficient for planting or the crop died due to frost damage. Although data from SIMMETEO and WGEN commonly had a slightly larger range in temperature distribution, this did not appear to affect simulations.

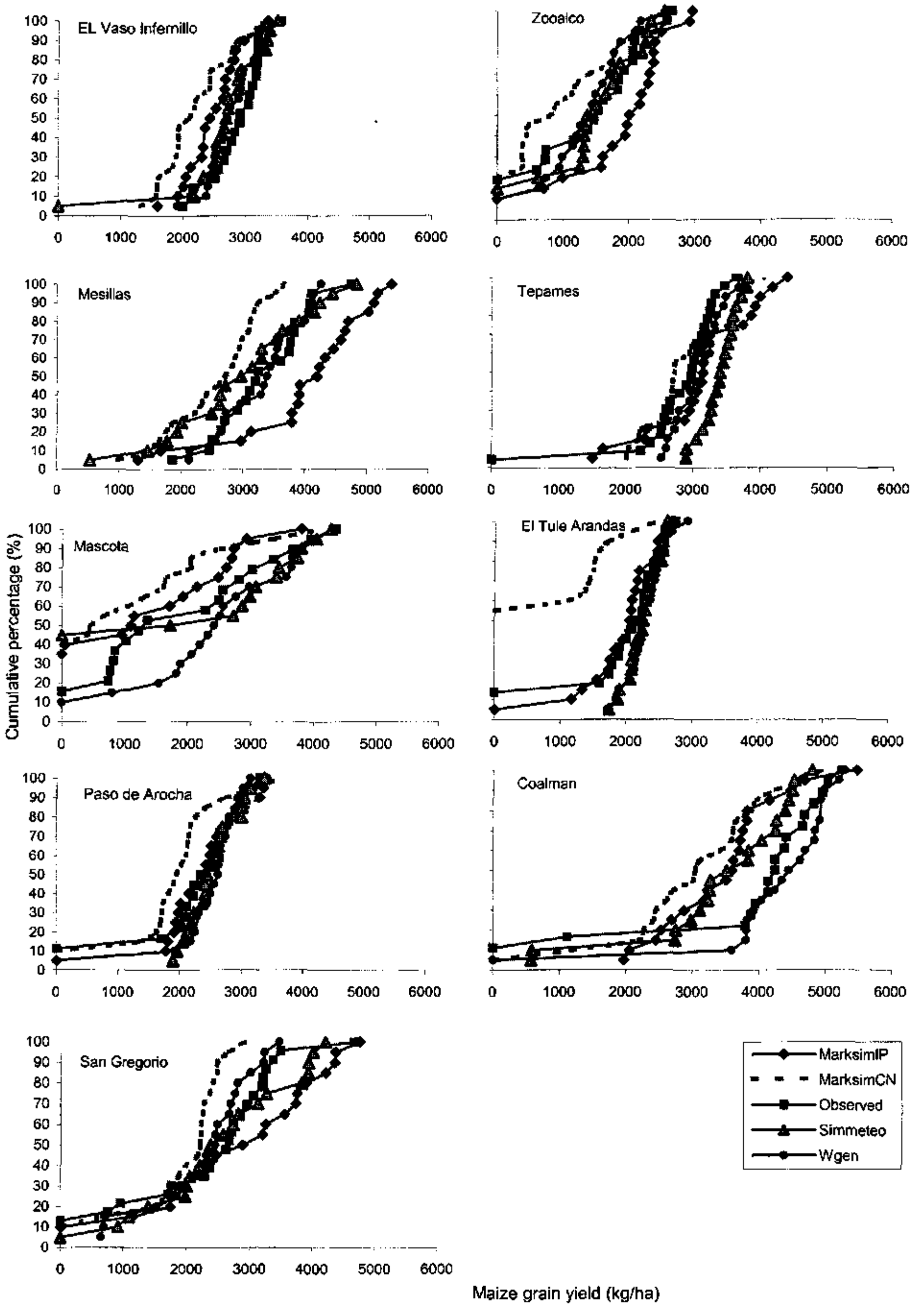

Figure 4.7 Cumulative maize grain yield probability using observed and generated weather data, assuming no fertilizer application.

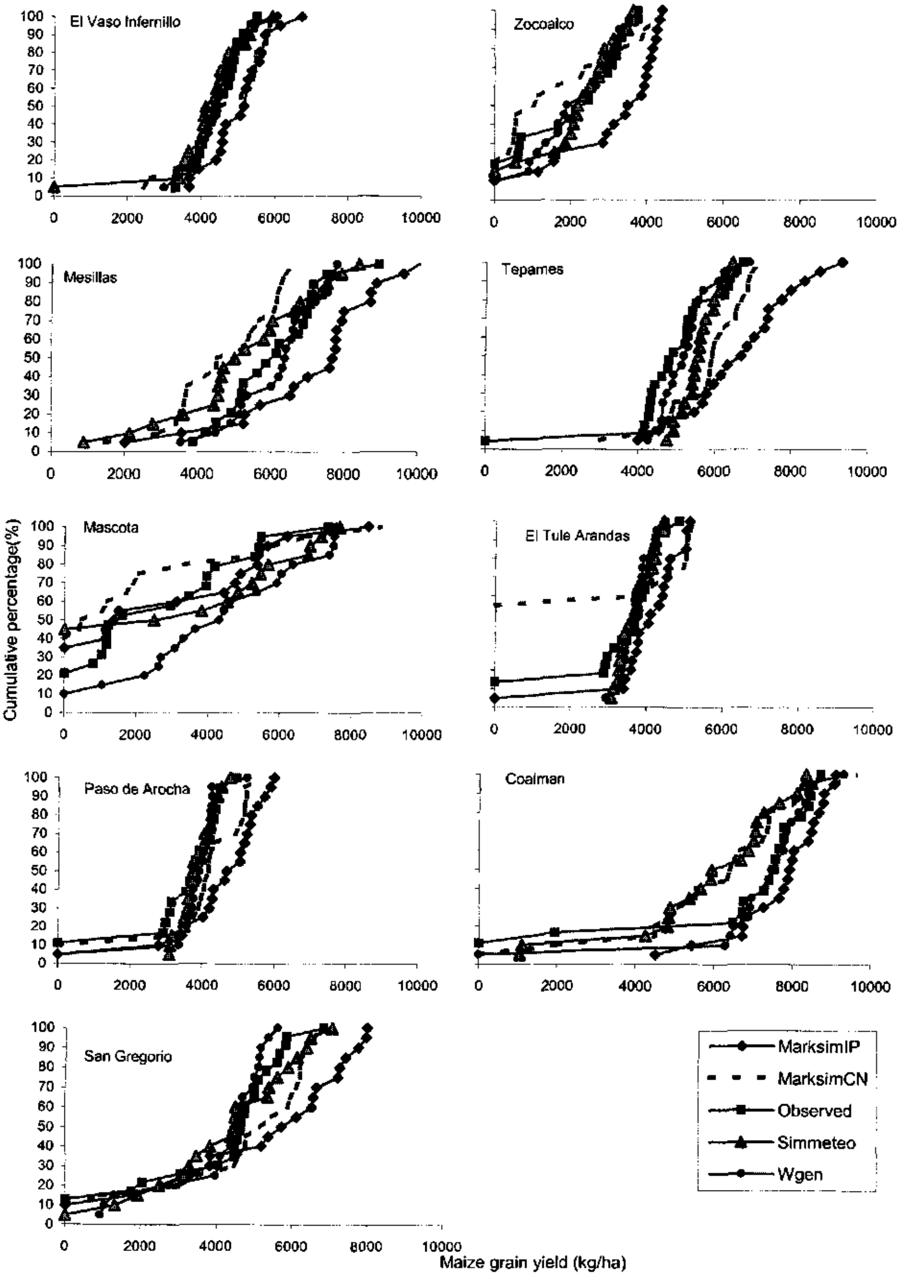

Figure 4.8 Cumulative maize grain yield probability using generated and observed weather data, assuming regional recommended fertilizer applications.

Discussion

For the subtropical locations selected in this study, SIMMETEO performed slightly better for generation of precipitation data, while WGEN performed better for temperature data. Both MARKSIM-IP and MARKSIM-CN generated a higher variability in precipitation data than was found in observed data. Furthermore, the duration of chains of wet days was generally too long for this region. We found no benefit in using the current version of MARKSIM with climate normal input. Although the generated temperatures were closer to the observed than from the interpolated climate surface data, the generation of precipitation data did not improve through the use of climate normals. Moreover, generated precipitation values, as evaluated through the inter-annual variability in precipitation as well as the length of wet chains, were substantially different from observed data. It appears that refinement of the software for parameter calculation is needed to produce better results with inputs of climate normals to MARKSIM.

Differences between generated and observed data for maximum and minimum values for maximum temperature, as well as maximum and minimum values for minimum temperature, had a minor effect on maize and bean simulations, largely because these events occurred outside the growing season. For simulations resulting in low grain yields (no fertilizer), no difference was found between using generated and observed daily weather data for maize, except for MARKSIM-CN.

Although daily weather data are increasingly available in digital format, they should be used with caution. Data checking is seldom guaranteed, and errors in observed data cause errors in generated weather. Weather generators that require daily weather data for estimating parameter, such as WGEN, are more sensitive to such errors than generators that use monthly means such as SIMMETEO.

Conclusions

For crop modelling applications at specific single point locations, and especially in developing countries, the use of SIMMETEO is currently preferred considering that only monthly means are necessary and that there is little or no difference between simulations based on generated and observed data. Extensive searching for daily weather data, and the need for extensive checking of daily data, for weather generators that require daily weather parameters (such as WGEN) is not worth the extra investment for these applications. If the distribution of weather stations is good and five to ten years of daily data or long-term climate normals are available, SIMMETEO appeared fully adequate. The use of SIMMETEO for generating daily weather data for modelling applications, that use interpolated summary weather data as input, can be approved. The results from this study are primarily valid for the selected locations, which cover a wide range of climate conditions within our region. Subsequently, the results for the locations can be considered valid for the subtropical region from which the locations were selected. For climates in different regions of the world, we suggest repeating the process of comparing weather generators, for which the procedures followed in this paper are useful.

For crop modelling applications covering large regions where daily weather station data are poorly distributed or difficult to obtain, MARKSIM is a viable option, but effects of extreme weather events should be interpreted with caution.

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5.

ADAPTATION OF THE CROPGRO GROWTH MODEL TO VELVET BEAN AS A GREEN MANURE COVER CROP: I. MODEL DEVELOPMENT

Abstract

Velvet bean (Mucuna pruriens (L.) DC. cv.-group utilis) *is widely promoted as a green manure cover crop for tropical regions. Reports of insufficient biomass production in certain environments and concerns over seed production, however, suggest a need for a more complete description of growth and development of velvet bean under different production scenarios and environments. Process-based simulation models offer the potential for facilitating an assessment of management strategies for different environments, soils and production systems. The objective of this study was to adapt the generic grain legume model CROPGRO to simulate growth and development of velvet bean. Model coefficients used to describe growth and development of soybean* (Glycine max (L.) Merr.) *were used as initial reference values. Information on velvet bean from published sources was then used to revise the coefficients of the model. Phenology, canopy development, growth and partitioning were calibrated for two velvet bean varieties using experimental data from three sites in Mexico. Compared to soybean, velvet bean has a much longer growth cycle, allowing very large numbers of nodes to form. Velvet bean has larger, thinner leaves than soybean, resulting in more rapid leaf area development, and larger seeds, which affects both early season growth and pod development. A modification to CROPGRO to permit tracking of senesced materials was incorporated. Overall, the physiological processes underlying growth and development of velvet bean appear to be similar to other tropically adapted grain legumes. The new model, incorporated as part of the DSSAT 3.5 suite of crop simulation models, has potential for evaluating management strategies in specific environments and for identifying potential regions for introduction of velvet bean as a green manure cover crop.*

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Introduction

Green Manure Cover Crops (GMCC) are widely promoted as a means to reverse or slow negative effects of land use intensification. GMCCs are used as improved fallows, or relayed and intercropped in major cereal cropping systems including rice, wheat and maize. Suggested benefits include reduced soil erosion and weed competition, as well as improved soil fertility and structure (Van Eijk-Bos, 1987; Lopez, 1993; Buckles et al., 1998). The pace and extent of adoption of GMCCs, however, have not met expectations. Anecdotal reports suggest that GMCCs have sometimes been introduced in environments where the potential growth was too low to produce the desired benefits. This may reflect in part the *ad hoc* nature of experiments and demonstrations at uncharacterized sites, as well as limited access to data sets or decision support tools that could assist selection and targeting of GMCC species.

Velvet bean (*Mucuna pruriens*) is one of the most widely used GMCCs in maize production systems in Meso America, West and South Africa. It is being tested and disseminated widely by national agricultural research programs, international centers, and non-governmental organizations (Thurston et al., 1994; Kumwenda et al., 1996; Vissoh et al., 1998; ILEIA, 1989). Velvet bean is a vigorous, large-seeded, twining annual climbing legume with a growth cycle of 120 to 280 days, depending on cultivar, planting date and environment (Piper and Tracy, 1910; Tracy and Coe, 1918; Verdcourt, 1971, 1979; Westphal, 1974). Although native to tropical Southeast Asia, it has been cultivated in temperate areas (Whyte et al., 1953), including the USA and Australia. In the humid areas of Mexico, Central America and Asia, recognized benefits include reducing soil erosion and weed competition. In semi- arid regions of Africa, it is used to improve soil fertility and structure (Van Eijk-Bos, 1987; Thurston et al., 1994; Kumwenda et al., 1996; Vissoh et al., 1998; Buckles et al., 1998; Waddington et al., 1998). Velvet bean has been used in soil regeneration projects in Indonesia (Hariah, 1992) and was found to control *Imperata cylindrica* and other major weeds in Latin America, West Africa and Asia (Van Eijk-Bos, 1987; Versteeg and Koudokpon, 1990; Guritno et al., 1992; Buckles and Perales, 1995; Buckles et al., 1998). Experiments with velvet bean relay cropping systems in Mexico suggest that soil erosion can be reduced from 50 ton ha^{-1} y^{-1} to 4 ton ha^{-1} y^{-1} (Lopez, 1993). Because velvet bean contains L-dopa (L-3, 4-dihydroxyphenylalanine; Kay, 1979), it is reported to have few diseases (Duke, 1981; Skerman et al., 1988; Buckles and Perales, 1995).

Velvet bean can be introduced into maize production systems in several temporal and spatial arrangements including in rotation, relay, and intercropping. In humid areas with increasing land pressure, it can be rotated with maize as an improved fallow (Thurston et al., 1994; Triomphe, 1996; Buckles et al., 1998). In moderately humid areas in Central America, it is sown into maize 40 to 60 days after maize is sown

(CIDICCO, 1997; Soule, 1997). In unimodal rainfall areas, it can be intercropped with maize (Skerman et al., 1988; Gilbert, 1998). Benefits of velvet bean–maize systems vary with the temporal and spatial arrangement of the crop relative to the maize crop, as well as the climate and soil environment where it is grown. Productivity gains in such systems can reflect improved soil structure through increased organic matter, which improves soil water holding capacity, as well as an increased water storage per se. Impacts on maize production can be considerable such as experienced in the republic of Benin and documented by IITA, 1993 and Vissoh et al., 1998. Systems rotated with velvet bean in West Africa and Central America, showed improvements of 80 to 100% in grain yield (Versteeg and Koudokpon, 1993; Buckles and Perales, 1995). A ten-fold yield increase was reported by AICAF, 1995. Benefits of rotating velvet bean and use of mulch lead to higher yield gains than intercropping (Fishler, 1996). Carsky et al. (1998) reviewed research on the increase of maize yield through use of velvet bean and found nitrogen fertilizer replacement values between 40 and 150 kg ha^{-1} when incorporated, but only 10 and 30 kg ha^{-1} if left as mulch. Lobo-Burle et al. (1992) suggest fertilizer substitution rates in maize of 60 to 80 kg ha^{-1} can be attained. Following trial findings the Regional Maize Research Network in Central America (PRM) recommended reducing fertilizer application by half in maize-velvet bean intercropping (Gordon et al., 1993, 1997).

While previous research has demonstrated the potential of velvet bean as a GMCC, it falls short of permitting a systematic, quantitative approach for assessing the potential of velvet bean under differing management scenarios while accounting for effects of soil, climate and management. A process-based model offers the potential for integrating our physiological understanding of velvet bean and examining how potential growth and major limitations to production might vary in different environments and with different management scenarios. This information should lead to more efficient experimentation and targeting of velvet bean. Many annual legumes have similar patterns of growth and development, so rather than develop a new model, the CROPGRO model for legumes was used as a framework for reviewing the physiology of velvet bean and converting this information into quantitative predictions. This model was chosen because it has performed well with other legume species and is widely used in the international agricultural research community (IBSNAT, 1993; Tsuji, 1998; Uehara and Tsuji, 1998). The CROPGRO model has been implemented within the Decision Support System for Agrotechnology Transfer – DSSAT (Tsuji et al., 1994) to provide a user-friendly interface. DSSAT crop models can be linked to analyze rotation systems (Thornton et al., 1997), as described in studies by Timsina et al., 1997; Singh et al., 1999a, 1999b).

Different species and cultivars are simulated in CROPGRO using species and cultivar coefficients, which are read from separate input files. This approach has been implemented for chickpea (*Cicer arietinum* L.; Singh and Virmani, 1994) as well as other crops such as tomato, *Lycopersicon esculentum* L.; Scholberg et al., 1997), cowpea (*Vigna unguiculata*, Hoogenboom et al., 2001), and *Brachiaria decumbens* (Giraldo et al., 2001), among others. The objective of this study was to adapt CROPGRO (Hoogenboom et al., 1992; Boote et al., 1998a) to simulate growth and development of velvet bean as a function of soil and weather conditions and different management scenarios. To estimate impacts of introducing velvet bean as a green manure cover crop, the capability to track senesced leaves and stems was required. It was expected that accounting for the long growth duration of velvet bean and enabling the model to track senescence of aboveground biomass would require modifying the source code.

Model description

CROPGRO is a process-orientated model that simulates a crop carbon balance, a crop and soil water balance and a crop and soil nitrogen balance. State variables are the amounts, masses and numbers of tissues, and rate variables are the rates of inputs transformations and losses from state variable pools (Jones and Boote, 1987). For example, the crop carbon balance includes daily inputs from photosynthesis and conversion of C into crop tissues, C losses due to abscised parts, and C losses due to growth and maintenance respiration. The simulation of growth includes leaf area expansion, pod addition, seed addition, seed growth rate, shell growth rate, nodule growth rate, senescence and carbohydrate mobilization. Addition of pods and seeds and their growth rates determine partitioning during the seed-filling phase (Boote et al., 1998a). Prior to the seed growth phase, the growth rate of leaves, stems and roots are determined by the partitioning of respective tissue types multiplied by the rate of total growth. Important ancillary processes include leaf appearance, reproductive development, increase in height and width of the canopy, and root depth increase (Boote et al., 1998b). The soil water balance processes include infiltration of rainfall and irrigation, soil evaporation, crop transpiration, distribution of root water uptake, drainage of water through the soil profile (Ritchie, 1998). The crop nitrogen balance processes include nitrogen uptake, N_2 fixation, nitrogen mobilization from vegetative tissues, rate of nitrogen use for new tissue growth and rate of nitrogen loss in abscised parts (Boote et al., 1998a, 1998b). The main time step in CROPGRO is one day, but vegetative and reproductive development and leaf-level photosynthesis are calculated hourly. Final seed yield, biomass and other information are output at maturity (Boote et al. 1998a). Detailed descriptions of the model can be found in Hoogenboom et al. (1993) and Boote et al. (1998a).

CROPGRO was created incorporating features of SOYGRO (Wilkerson, 1983, 1985), PNUTGRO (Boote et al., 1987) and BEANGRO (Hoogenboom et al., 1990, 1994). Early versions of CROPGRO are described by Hoogenboom et al. (1991, 1992, 1993). Differences among species and cultivars are represented in CROPGRO through coefficients for species, ecotype and cultivars. For each crop, the species file describes tissue compositions and coefficients for photosynthetic, respiratory, partitioning, phenology, senescence, N-assimilation and growth processes. The ecotype file contains information that describes broad groups of cultivars, such as determinate vs. indeterminate growth habit groups. Cultivar differences are represented in a file containing 15 coefficients (see e.g. Table 5.1). In DSSAT version 3.5, species, ecotype and cultivar files are available for soybean, groundnut (*Arachis hypogea* L.), dry bean (*Phaseolus vulgaris* L.), and chickpea, as well as tomato.

Soil water balance

The soil water balance in CROPGRO was developed by Ritchie (1985, 1998). The balance is updated on a daily basis as function of precipitation, irrigation, transpiration, soil evaporation, runoff and drainage from the profile. The user defines input coefficients for each layer of a one dimensional soil profile. Soil water is distributed in several layers, but depth increments are recalculated internally by the model. The water content in the topsoil layer changes with soil evaporation, infiltration due to rain or irrigation, root absorption or flow to the second layer. The soil water content in the other layers can change as a function of downward or upward flow or of root absorption. Each layer has a characteristic drained upper limit (DUL) or field capacity, a lower limit of plant extractable water (LL) or permanent wilting point, and a saturated soil water content (SAT). Soil water flow, drainage and runoff occur based on the status of water in each horizon in relation to DUL and SAT. Each day, the potential demand, estimated as potential evapotranspiration, is compared to moisture available through root uptake. If demand exceeds available moisture, a stress index is used to modify processes such as development, photosynthesis, partitioning, and senescence.

Nitrogen balance

The soil and plant nitrogen balances describe plant uptake, biological fixation and leaching of nitrogen. Deficits in plant nitrogen reduce photosynthesis and affect various other processes using an index similar to that for water deficit. The source code of the soil nitrogen balance in the CROPGRO model is identical to that of the generic cereal model CERES (Godwin and Singh, 1998).

Material and methods

Experiments

Field experiments with velvet bean were conducted in the 1997-1998 season at Santa Rosa (lat. 18.3° N; long. 95.1° W; alt. 450 m) and Tlaltizapán (lat. 18.7° N; long. 99.1° W; alt. 940 m), Mexico. The soil at Santa Rosa is a humic Hapludult under the USDA classification (Martinez and Pech, 1997) and the soil at Tlaltizapán is a clay isothermic udic Pellustert (Bell and Van Keulen, 1995).

Table 5.1 Cultivar-specific coefficients for the soybean maturity group 8 and the two principle velvet bean cultivars used in calibrating CROPGRO for velvet bean.

Description of variable	Parameter	Units	Soybean	Velvet bean	Velvet bean
Cultivar unique code	VAR#	none	990008	CI0004	CI0005
Cultivar name	Name	none	M GROUP 8	Veracruz Black	Veracruz White
Code for the ecotype to which this cultivar belongs	ECO#	none	SB0801	VB0001	VB0001
Critical Short Day Length below which reproductive development progresses with no daylength effect	CSDL	(hour)	12.07	12	12
Slope of the relative response of development to photoperiod with time (positive for shortday plants)	PPSEN	(1/hour)	0.33	0.6	0.6
Time between plant emergence and flower appearance (R1)	EM-FL	(photothermal days)	21.5	54	54
Time between first flower and first pod (R3)	FL-SH	(photothermal days)	10	6	6
Time between first flower and first seed (R5)	FL-SD	(photothermal days)	16	13	13
Time between first seed (R5) and physiological maturity (R7)	SD-PM	(photothermal days)	36	60	60
Time between first flower (R1) and end of leaf expansion	FL-LF	(photothermal days)	18	65	65
Maximum leaf photosynthesis rate at 30 °C, 350 vpm CO_2, full light	LFMAX	(mg CO_2 m^{-2} s^{-1})	1	1	1
Specific leaf area of cultivar under standard growth conditions	SLAVR	(cm^2 g^{-1})	375	455	455
Maximum size of full leaf (three leaflets)	SIZLF	(cm^2)	180	420	450
Maximum fraction of daily growth that is partitioned to seed + shell	XFRT		1	1	1
Maximum weight per seed	WTPSD	(g)	0.18	0.74	0.82
Seed filling duration for pod cohort at standard growth conditions	SFDUR	(photothermal days)	23	22	22
Average seed per pod under standard growing conditions	SDPDV	(#/pod)	2.05	4.5	4.8
Time required to reach final pod load under optimal conditions	PODUR	(photothermal days)	10	20	20

Two velvet bean cultivars from Veracruz, Mexico (black and grayish-white seeded) were planted in four randomized complete blocks. Individual plots consisted of seven 0.8 m-wide rows that were 7 m in length. Experiments were sown on 27 June 1997 at Santa Rosa and on 21 June 1997 at Tlaltizapán. Following local practice, two seeds per hill were sown at a depth of approximately 50 mm, with a spacing of 0.5 m between hills. During the growth cycle, plots were hand weeded three times. The Santa Rosa site was rainfed, while Tlaltizapán received irrigation as needed to avoid water deficits. No fertilizer was applied, and no visual stress was observed at Santa Rosa. At Tlaltizapán, slight chlorosis occurred at the beginning of the growing season due to the high soil pH (7.8).

Two supplementary experiments were conducted at El Batan, Mexico (lat. 19.3° N, long. 98.5° W; alt. 2245 m) in a clay loam Ustalf (Bell and Van Keulen, 1995) to examine growth and development in cool environments. These were planted on 21 June 1997 and on 12 and 26 June 1998. The experiments were irrigated and hand weeded but not fertilized.

Measurements

Soil characteristics were determined by sampling prior to planting. A soil profile description for Santa Rosa was available from recent literature (Martinez and Pech, 1997). At Tlaltizapán, both soil sampling and soil profile description were carried out. Pedotransfer functions available in DSSAT (Tsuji et al., 1994) were used to create the soil surface and profile coefficients required to run the model. At Santa Rosa, precipitation data were taken on site, while temperature and radiation data were collected from nearby weather stations (approx. 7 km). At Tlaltizapán and El Batan, weather data were available on site.

The vegetative and reproductive stages of velvet bean were defined using the system of Fehr et al. (1971) for soybean. Reproductive stages recorded were beginning of flowering, first pod occurrence, full pod, first seed occurrence, full seed, physiological maturity (50% of plants with pods yellowing) and harvest maturity (50% of plants with 95% of pods brown).

Non-destructive plant measurements (row width and height, leaf number) were recorded during the first three months at Santa Rosa. Leaf number was determined at both lowland sites during the first two destructive harvests. Aboveground biomass sampling (dry weight stems, leaves, petioles, pods and seeds) were conducted every 5 to 6 weeks (in four replications) at both sites. Specific leaf area and leaf size were determined from two randomly selected sets of twelve green leaves per replicate. Litter was collected with each biomass sample. At El Batan, leaf number and canopy size measurements were recorded every five to seven days at the start of the season and at longer intervals as the weather cooled. One end-of-season dry matter sample was taken. Because of the variation in observed data, we have decided to show complete replicated data, rather than mean values.

Model calibration and results

Species and cultivar files of soybean were used initially to parameterize CROPGRO for velvet bean. Cultivar coefficients for soybean maturity group 8 were used (Table 5.2). Data on plant and seed composition values were compiled from published sources (Duke, 1981; Göhl, 1982; Ravindran, 1988) and included in the species and ecotype file (see Table 5.2). Root length density (RFAC1) was changed from 7500 cm g^{-1} to 9500 cm g^{-1} based on data from Hariah (1992). Ecotype and cultivar coefficients were further calibrated to the cultivar and phenology data observed at the Santa Rosa and Tlaltizapán trial locations. Calibration of phenology was conducted by minimizing the error between observed and simulated flowering and maturity dates. Consequently the model was calibrated for velvet bean growth, based on time series analysis and minimizing the error between observed and simulated final yield and biomass.

Table 5.2 Tissue compositions (concentrations as g g^{-1} tissue dry weight) of soybean and velvet bean as used in CROPGRO or reported for velvet bean in the literature. (Duke, 1981; Göhl, 1982; Ravindran, 1988).

Description	Coefficient	Soybean	Velvet bean	Velvet bean Literature values
Protein leaf	PROLFG	0.285	Same	0.20 - 0.248
Protein stem	PROSTG	0.110	0.130	0.10 - 0.15
Protein shell	PROSHG	0.196	0.147	0.03 - 0.145
Protein seed	SDPROG	0.400	0.265	0.234 - 0.286
Protein seed min. and max.	PROMIN,	0.030	0.030	
	PROMAX	0.080	0.050	
Lipid leaf	PLIPLF	0.025	Same	0.016 - 0.028*
Lipid stem	PLIPST	0.020	Same	
Lipid shell	PLIPSH	0.020	Same	0.7 - 3.8
Lipid seed	PLIPSD	0.200	0.043	0.021 - 0.057
Lignin leaf	PLIGLF	0.070	0.060	(0.067) 0.039 - 0.09*
Lignin stem	PLIGST	0.070	0.090	(0.180)
Lignin shell	PLIGSH	0.280	0.090	0.087
Lignin seed	PLIGSD	0.020	0.010	0.008
Mineral Leaf	PMINLF	0.094	0.100	0.062 - 0.149*
Mineral stem	PMINST	0.046	0.050	
Mineral shell	PMINSH	0.030	0.038	0.038 - 0.059
Mineral seed	PMINSD	0.025	0.032	0.030 - 0.036

* Leaf and stem fractions were not reported separately but together as one vegetative fraction.

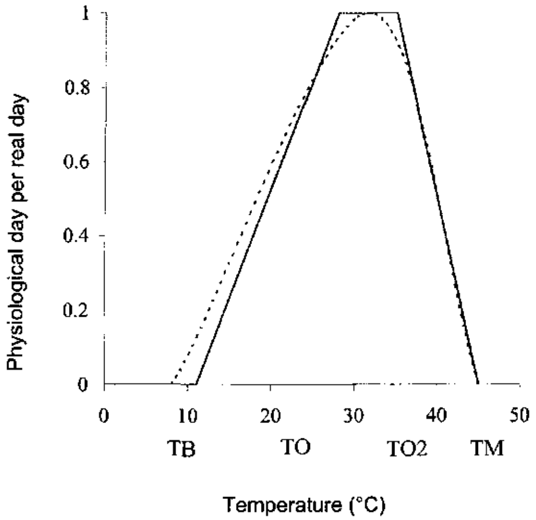

Figure 5.1 Relation between physiological day per real day and temperature for main stem leaf number, or V-stage (solid line) and reproductive (broken line) development used in the velvet bean species file. (TB = Base temperature; TO1 = Optimum temperature 1; TO2 = Optimum temperature 2; TM = Maximum temperature).

Phenology and development

In the CROPGRO model it is assumed that the rate of vegetative development (V-stage) increases linearly with temperature up to an optimal value, above which there is a plateau at the maximum rate, and then declines above a supra-optimal limit (Fig. 5.1). Optimum mean growing season temperature was reported to be between 20 to 30 °C (Kay, 1979; Duke, 1981; AICAF, 1995) or more narrowly, 19 to 27 °C (Carsky et al., 1998). These temperature response curves are similar to those for soybean phenology, and only the base temperature was set slightly higher than soybean (see Table 5.3). The rate of main stem leaf appearance is assumed 0 for temperatures at or below 11 °C, increases linearly to a relative maximum rate of 1 at 28 °C, and then decreases above temperatures of 35 °C, and is 0 at temperatures at or higher than 45 °C (Fig. 5.1).

Velvet bean has vigorous growth upon seedling emergence. Using soybean coefficients, early-season main stem leaf number was slightly underestimated, while subsequent rate of main stem leaf appearance was too high. To increase initial main stem leaf number, the modifier for rate of the first main stem leaves (EVMODC) was increased from 0 to 5, as done for groundnut. To reduce subsequent main stem leaf number, or V-stage, the main stem leaf appearance rate (TRIFL) was reduced from 0.33 to 0.30 main leaf stem per thermal day (Fig. 5.2).

evaluations (Fig. 5.3). Reproductive development of velvet bean is also affected by temperature and water status. Coefficients for effects of stress on development functions were maintained as for soybean with the exception of the effect of water stress on very early vegetative growth (first main stem leaves), which was decreased slightly as suggested by observed data for main stem leaf number.

Canopy growth

Canopy width and height coefficients were changed slightly from soybean values, allowing a wider but lower canopy. At Santa Rosa and El Batan, in the absence of mechanical support, the maximum height of velvet bean was between 1.0 and 1.2 m, reached at time of canopy closure (Fig. 5.4). Subsequently, the height of the crop was stable for 4 to 5 weeks, although node production continued. As the crop aged further, the canopy tended to collapse. The maximum height of the canopy coincided with time of flowering and early pod development.

Reference values for specific leaf area (SLAREF) and leaf size area (SIZREF) for velvet bean were set to 500 $cm^2\ g^{-1}$ and 550 cm^2 respectively, following observed data. For the 'Veracruz white' cultivar, SLA had an average of 455 $cm^2\ g^{-1}$ and leaf size had an average of 500 cm^2, following trial results. The 'Veracruz black' cultivar showed an average SLA of 420 $cm^2\ g^{-1}$ and an average leaf size area of 450 cm^2. This agreed with the general observation that the 'Veracruz black' cultivar has smaller, thicker and darker green leaves than the 'Veracruz white' cultivar. The simulated lines follow the data points, except for points measured just before flowering at Tlaltizapán (Fig. 5.5). Observed leaf area index for Veracruz Black at Tlaltizapán was somewhat higher than simulated values (Fig. 5.6a). This may reflect the high values of specific leaf area, which CROPGRO used to calculate leaf area index from leaf weight.

Photosynthesis, biomass production and partitioning

The temperature effect on photosynthesis was set equal to that for groundnut, presumed to be a more tropically adapted legume than soybean. The leaf photosynthesis, or hedgerow, model fitted measured biomass data better than the canopy model. This is probably due to the prostrate growth habit of the velvet bean crop and the collapsing of the canopy after reaching a maximum height of 1 to 1.20 meters.

To reflect the larger seed of velvet bean compared to soybean, the fraction of initial seed dry weight that is converted to plant mass at emergence (WTFSD) was increased from 0.55 to 0.90 g in the species file. Velvet bean partitions more assimilates to stem growth than soybean, especially at the start of the growing season. The crop is almost a perennial, and the production of many more nodes than soybean resulted in a relatively large stem biomass. Resultant stem and leaf weight accumulation (Fig. 5.7) corresponds to the stage from which senescence occurs (see section on senescence).

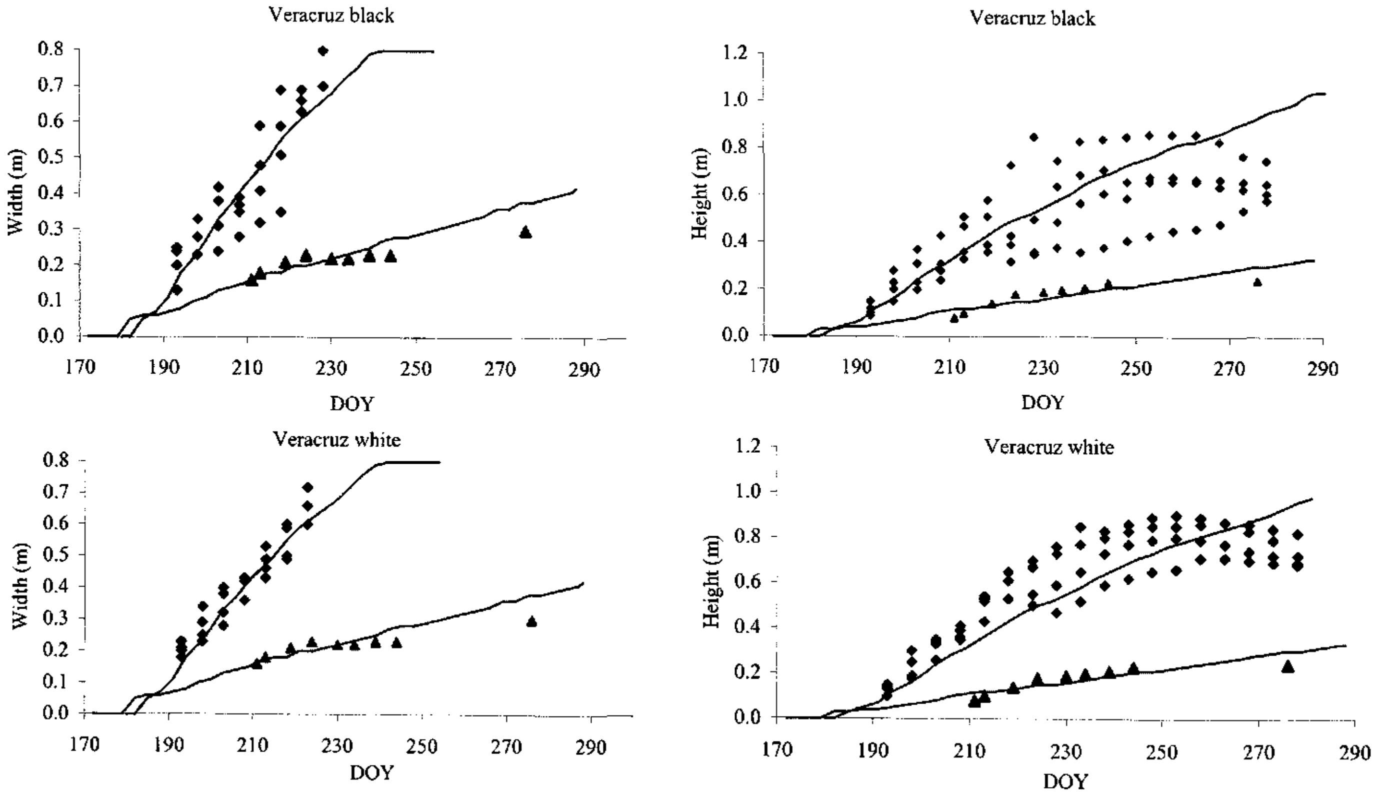

Figure 5.4 Simulated (lines) and observed (data points) canopy width and height development for 'Veracruz black' and 'Veracruz white', at sites Santa Rosa (diamonds) and El Batan (triangles). (DOY= Day of Year).

Notwithstanding the uncertainties in the calibration data and deficiencies of CROPGRO in handling the indeterminate growth of velvet bean, this new implementation shows promise for examining management strategies (plant densities, rotation sequence systems) where adequate biomass accumulation and ground cover are the primary focus. Thus, the velvet bean model should prove useful for targeting the crops to environments and for production systems where it might provide adequate ground cover (soil erosion and weed control), nitrogen accumulation, and soil organic matter to make its use attractive to farmers. However, the model first needs to be evaluated for a wider range of environments. The following chapter evaluates the performance of the model using independent field data as well as testing the sensitivity of the model to a wide range of simulation environments.

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6.

ADAPTATION OF THE CROPGRO GROWTH MODEL TO VELVET BEAN AS A GREEN MANURE COVER CROP: II. CULTIVAR EVALUATION AND MODEL TESTING

Abstract

Velvet bean (Mucuna pruriens (L.) DC. cv.-group utilis) *is widely promoted as a green manure cover crop in tropical and sub-tropical regions. To realize proposed benefits, which include reduced weed growth and soil erosion and enhanced soil fertility, the crop must attain rapid ground cover and develop substantial aboveground biomass. To assist biophysical targeting of the crop to environments that can provide adequate growth conditions, the CROPGRO model was adapted to simulate velvet bean growth and development. This paper evaluates the performance of the model for phenology, growth, senescence and N accumulation, for multiple locations that represent a wide range of environmental and for a range of agronomic management scenarios. Vegetative development, as described by main stem leaf appearance rate, followed a thermal time approach. Time to flowering showed departures from the linear photoperiod response used in the model. Additional research is required to determine whether the crop is influenced by factors besides photoperiod and air temperature, especially water and nutrient deficits. The linear response to photoperiod, however, did provide reasonable values for partitioning to vegetative, reproductive and senesced materials. Simulation of nitrogen concentration for various plant components matched observed data. Sensitivity analyses evaluating the ability of the crop to provide ground cover, intercept light and develop adequate growth for soil protection and weed suppression indicated that a mean temperature of over 22 °C and a soil moisture holding capacity of at least 100 mm are required. The CROPGRO model provided a reliable decision support tool for guiding analyses of velvet bean response to crop management and environmental conditions.*

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Introduction

The rapid growth and apparent disease and pest tolerance of velvet bean has contributed to this species being widely promoted as a green manure cover crop in tropical and sub-tropical regions (Duke, 1981; Buckles et al., 1998a, 1998b). Proposed benefits include weed suppression and reduced soil erosion due to its dense canopy and high litter fall. If crop residues are allowed to decompose in the field, additional benefits include improved soil fertility and soil structure (Bunch, 1989; Buckles et al., 1998a, 1998b; Gilbert, 1998). To obtain these conditions, the crop must attain rapid ground cover and develop substantial aboveground biomass. Anecdotal evidence suggests that velvet bean has been promoted among farmers in regions where a prior analysis of climatic and edaphic constraints would have lead to the selection of alternate species.

Quantitative assessments of velvet bean growth are scarce, and descriptions of management and soil and weather conditions are often incomplete. Researchers or extension workers often face the task of predicting crop growth and adaptation with minimal data from growth analysis studies or other sources. To assist this initial targeting, crop simulation models offer the possibility of assessing potential growth under different weather, soil and management scenarios. Chapter 5 described how the generic grain legume model CROPGRO was adapted for simulation of velvet bean growth and development. The objective of this study was to evaluate the model at multiple locations that provide a wide range of environmental conditions and agronomic management scenarios. Additionally, sensitivity analyses using several temperature and rainfall regimes were used to identify suitable regions for production of velvet bean as a GMCC. Since access to detailed sets of data is problematic for such novel crops, we also examine issues relating to use of models in 'data scarce' situations.

Material and methods

In this study the model CROPGRO as modified for velvet bean was used (Chapter 5). Multi location data describing velvet bean growth and development were assembled from diverse sources. Although the concept of a minimum data set (Nix, 1984; IBSNAT, 1988, 1990) was used to guide data collection, data on management, growth and development measurements, and completeness of data varied greatly (Table 6.1). Cultivar specific data, such as flowering date, growth cycle duration, leaf size, specific leaf area, seed weight) were derived as much as possible from the original sources. The model was first fitted to flowering data. If flowering data were unavailable pod development data were used to estimate phenology. Observed growth data were then compared to growth data simulated by the model. Because of the variation in observed growth data, we decided not to show mean values but provide complete replicate data when available.

Table 6.1 Experimental locations where a minimum data set for velvet bean was available.

Location	Country	Year	Longitude degree (°)	Latitude degree (°)	Elevation (m)	Planting month	Mean temperature (°C)	Seasonal rainfall (mm)	Plant population (pl. m^{-2})	Measurements[1]
Chapada	Brazil	1983	–47.70	–15.59	1137	Dec.	21.7	980	18.0	CWF ; LW
Planaltina	Brazil	1986	–47.71	–15.59	1000	Dec.	22.6	739	10.0	CWF ; LW
Palmira	Colombia	1997	–76.37	3.50	965	Nov.	25.5	502 i[2]	2.8	PH ; VCW ; LW ; RW ; YC; NC
La Ceiba	Honduras	1995	–86.87	15.73	26	Jun.	25.4	4138	4.5	PH ; CWT ; LW ; YC
Chitedze	Malawi	1996	33.63	–13.98	1150	Dec.	21.9	687	4.8	VCW ; YC
Chitedze	Malawi	1997	33.63	–13.98	1150	Nov.	22.4	995	6.0	VCW ; LW ; NC
Chitedze	Malawi	1998	33.63	–13.98	1150	Nov.	21.5	1258	6.0	VCW ; LW ; NC
Tlaltizapan	Mexico	1998/99	–99.14	18.68	924	Jul.	22.4	684 i[2]	2.0 (3.0)	PH ; WH; CWF ; LW
El Batan	Mexico	1998	–98.50	19.31	2260	Jun.	16.0	610 i[2]	2.3	PH ; WH ; CWF
Santa Rosa	Mexico	1997	–95.12	18.31	400	Jul.	22.9	560	4.0	PH ; CWF ; NC
Tabasco	Mexico	1994	–93.59	18.00	100	Jan.	27.2	603	5.5	PH ; WH ; VCW ; LW ; RW ; YC; NC
Tabasco	Mexico	1995	–93.59	18.00	100	Jul.	26.2	1945	0.08	PH; VCW; YC
Ibadan	Nigeria	1997	3.900	7.50	228	May	25.5	1176	2.0	PH
Zaria	Nigeria	1997	7.700	11.07	601	Jun.	24.8	633	2.0	PH
Fashola	Nigeria	1997	3.770	7.90	206	May	25.5	558	2.0	PH

[1] Key to measurements:
PH = Phenology
WH = Canopy development in width and height
CWT = Canopy dry weight – time series
CWF = Canopy dry weight – final only
VCW = Vegetative components dry weight
LW = Litter or senesced dry weight
RW = Root dry weight
YC = Yield components data
NC = Nitrogen and tissue composition data
[2] i = trial was irrigated

Sensitivity analyses were conducted for five temperature regimes with means 18 °C, 22 °C, 26 °C, 30 °C and 34 °C, assuming a daily range of 10 °C and daily solar radiation of 20 MJ m^{-2} day^{-1}. Temperature and density were selected as first determinants for growth and development of GMCC in tropical environments. The cultivar Veracruz black was sown at three densities (1 plants m^{-2}, 5 plants m^{-2}, 15 plants m^{-2}) with a row width of 0.8 m on June 30, at a fictitious site at 20° N latitude. Water and nutrients were assumed non-limiting.

To assess sensitivity to edaphic conditions, additional simulations were conducted using twelve years of historical weather data for Palmira (Colombia), Ibadan (Nigeria) and Plains, USA (32.04° N latitude; –84.37° W longitude). A density of 5 plants m^{-2} with a row spacing of 0.8 m was assumed. Planting took place in accordance to the growing season: at the end of June for Palmira and Ibadan, and on May 1 for Plains.

Results and discussion

In CROPGRO the development of crops is determined by progression through vegetative stages (V-stage) and reproductive stages (R-stage) (see IBSNAT, 1988).

Vegetative development

Main stem leaf appearance was evaluated using data from 1994 at Cardenas, Mexico, (Ortiz, 1995) and 1998-1999, Tlaltizapán, Mexico, with monthly sowing dates (Fig. 6.1). Main stem leaf numbers were slightly underestimated around 85 days after planting for the December plantings in Tlaltizapán, Mexico (Fig. 6.1) due to a reduction in the simulated main stem leaf appearance rate. This may reflect an exaggerated effect of flowering on main stem leaf appearance rate in the model. Overall, the model appears to be able to predict main stem leaf numbers based on leaf appearance rate of 0.30 main stem leaf per photo-thermal day, a base temperature of 11 °C, and an optimum temperature between 28 °C and 35 °C.

Reproductive development

Simulated flowering for winter plantings at Tlaltizapán, Mexico was somewhat earlier than observed values (Fig. 6.2). The model assumes a critical short daylength of 12 h and a 0.6 day h^{-1} delay in flowering above a 12 hour daylength. However, changing these values did not improve simulation. Delayed flowering in winter plantings was also reported by Ortiz (1995), who planted the same cultivars in January 1994 at a site with almost the same latitude and a similar temperature regime as Tlaltizapán. The December, January and February plantings at Tlaltizapán all showed abortion of unopened flowers, making it difficult to assess when 50% flowering occurred. Circled data points of Fig. 6.2 should be taken as estimates. For additional field observations collected in Nigeria for anthesis for the cultivars Veracruz black, Veracruz white and mottled, it was not possible to predict time to flowering within five days of observed

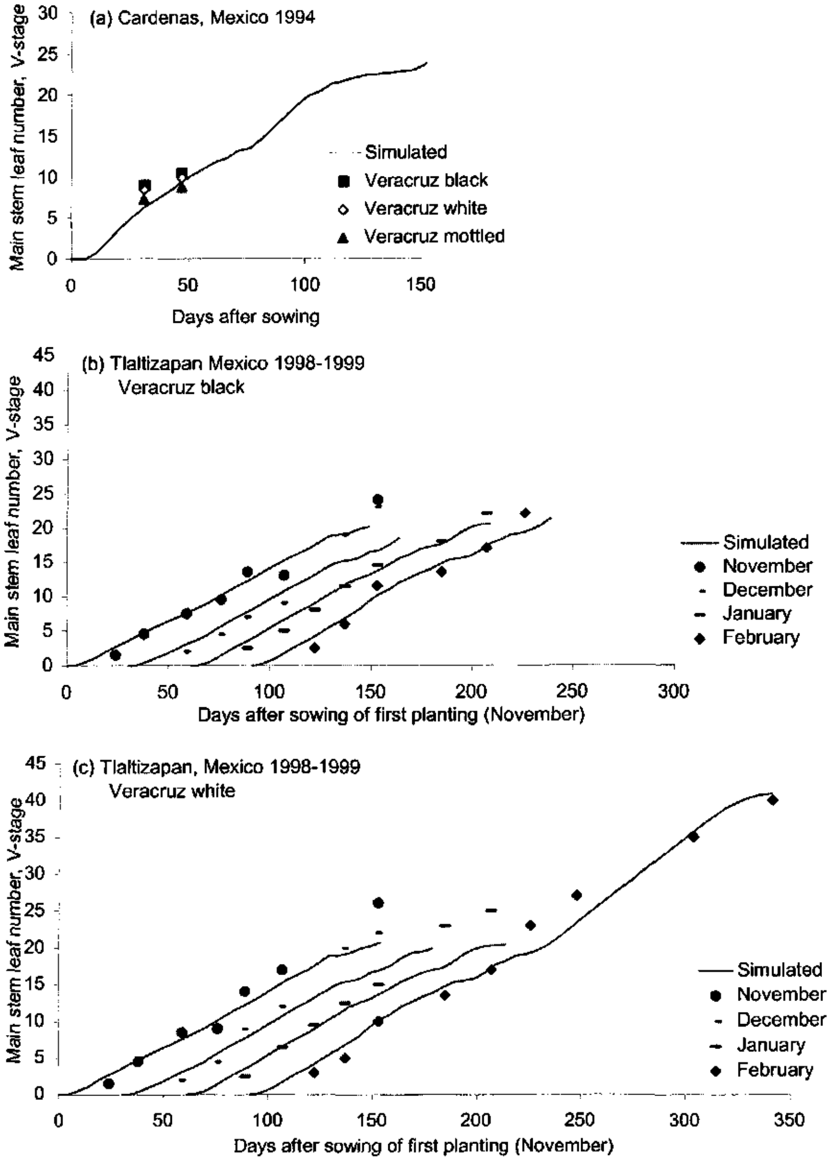

Figure 6.1 Simulated (lines) and observed (data points) main stem leaf number, or V-stage progression of velvet bean for cultivars (a) 'Veracruz black', 'Veracruz white' and 'Veracruz mottled' at Cardenas, Mexico; (b) 'Veracruz black' and (c) 'Veracruz white' for various planting dates at Tlaltizapán, Mexico.

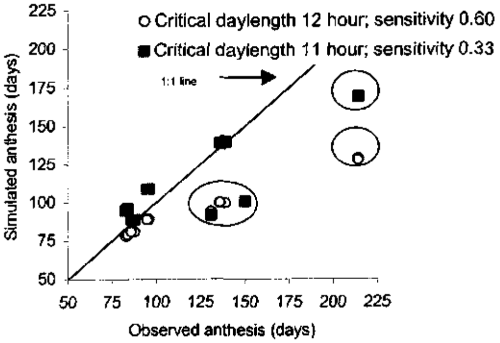

Figure 6.2 Simulated versus observed anthesis date for cultivars 'Veracruz black' and 'Veracruz white' at Tlaltizapán, Mexico for 1998 and 1999 plantings. Circled points should be taken as estimates.

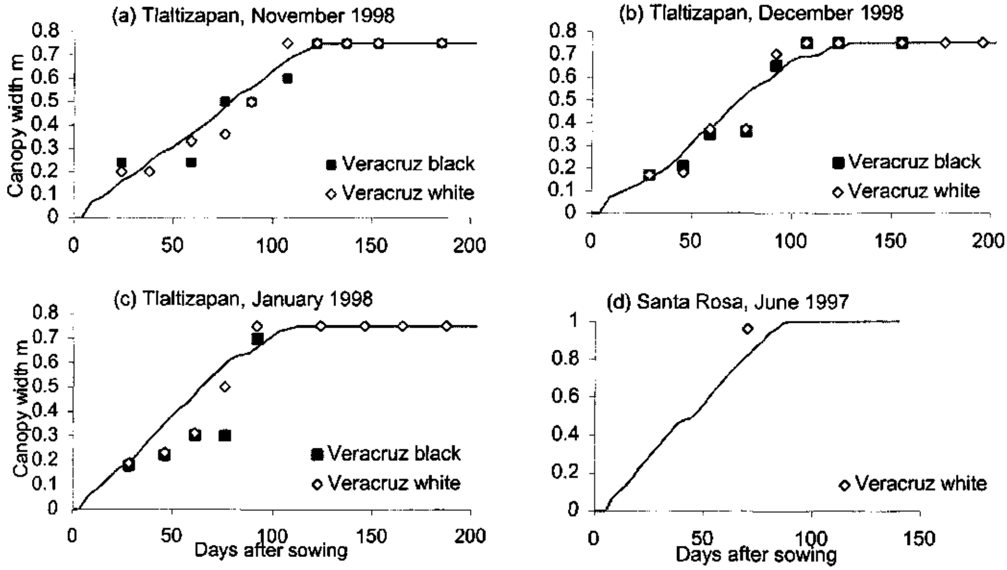

Figure 6.3 Simulated (lines) and observed (data points) canopy width development for cultivars 'Veracruz black' and 'Veracruz white' for different plantings at Tlaltizapán, Mexico (a-c), and d) for 'Veracruz White' at Santa Rosa, Mexico.

values. However, researchers may have differed in their criterion for measuring 50% flowering. Furthermore, onset of flowering is difficult to observe, because of the dense canopy structure of velvet bean flowers may be easily overlooked.

In general, estimation of time to flowering in field experiments has, so far, proven successful only under decreasing daylength. In controlled greenhouse studies, Keatinge et al. (1998) found that a *Mucuna pruriens* accession from Honduras showed a photoperiodic response for rate of progress to flowering (1/f, the reciprocal function of time to flowering – f –). The accession showed no thermal response for progress to flowering. In a more detailed greenhouse study of phenology of velvet bean varieties, Qi et al. (1999) suggested that there is a temperature effect on flowering, with temperatures above 32 °C being supra optimal. They also fund no photothermal plane model for flowering for a cultivar originating from Veracruz could be determined (Qi et al., 1999). This indicates that the flowering of this material may not be accurately predicted with linear response models. Non-linear responses have been suggested for soybean (Sinclair et al., 1991) and rice (Yin, 1996). The rate or direction of change of daylength may affect flower development, as reported in other legumes (Constable and Rose, 1988; Acock et al. 1994) and many cereal species (Kirby et al., 1985; Kirby and Perry, 1987; Jamieson et al., 1995; Cousens et al., 1992). Alternately, low temperatures may reduce photoperiod sensitivity, as reported for common bean (White et al., 1996). Additional research is needed to determine whether this also holds for velvet bean, or if deviation can be attributed to water and nutrient stresses.

Canopy development

Canopy width is a useful indicator of row closure and ground cover. At 75 days after planting simulated canopy width was higher than in the observed data for the December and January 1998 plantings at Tlaltizapán (Figs. 6.3a-c). For these winter plantings this may partially reflect low winter temperatures that were close to values causing permanent leaf damage. Additionally, water deficits may have reduced leaf area and shortened internodes, resulting in a narrower canopy. For the 1997 trial at Santa Rosa, simulated time of row closure was close to observed (Fig. 6.3d, data from Guevarra, 2000).

Dry matter production and partitioning

At Chitedze, Malawi, canopy and pod weights were measured over three years (Figs. 6.4a-c). Observed onset of pod development was later than the simulated date, assuming the same soil initial conditions for all three years. Discrepancies in prediction may be caused by a difference in soil fertility, not only between seasons but also between plot locations. In the 1998-1999 trial at Chitedze senesced material weight was also measured (Fig. 6.4c). The simulated senescence is slightly higher than the observed, probably reflecting decomposition of accumulated residue.

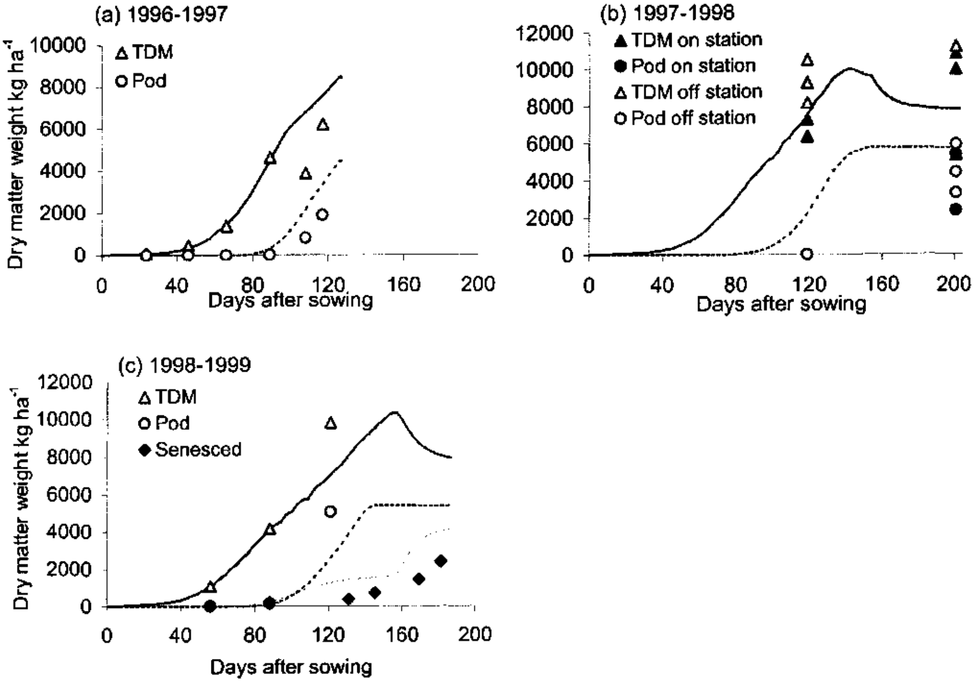

Figure 6.4 Simulated (lines) and observed (data points) total aboveground dry matter (TDM) and pod weight at Chitedze, Malawi for seasons (a) 1996-1997; (b) 1997-1998 and (c) 1998-1999.

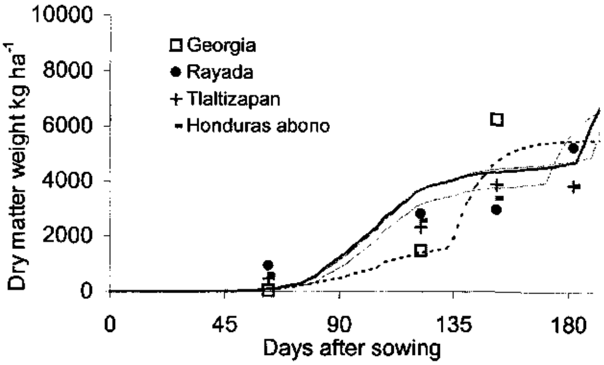

Figure 6.5 Simulated (lines) and observed (data points) accumulation of aboveground senesced tissue weight for several varieties at La Ceiba, Honduras. 'Georgia' = very early; 'Rayada' = early; 'Tlaltizapán' and 'Honduras-abono' = intermediate.

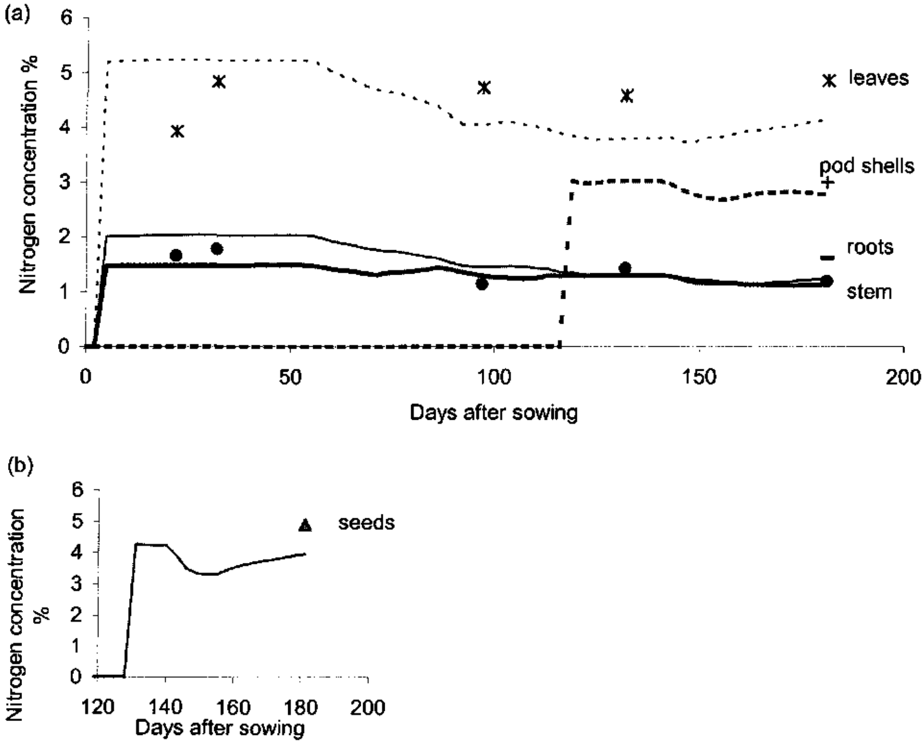

Figure 6.6 Simulated (lines) and observed (data points) nitrogen concentration of (a) leaves, stems, roots, pod shells and (b) seeds at Palmira, Colombia.

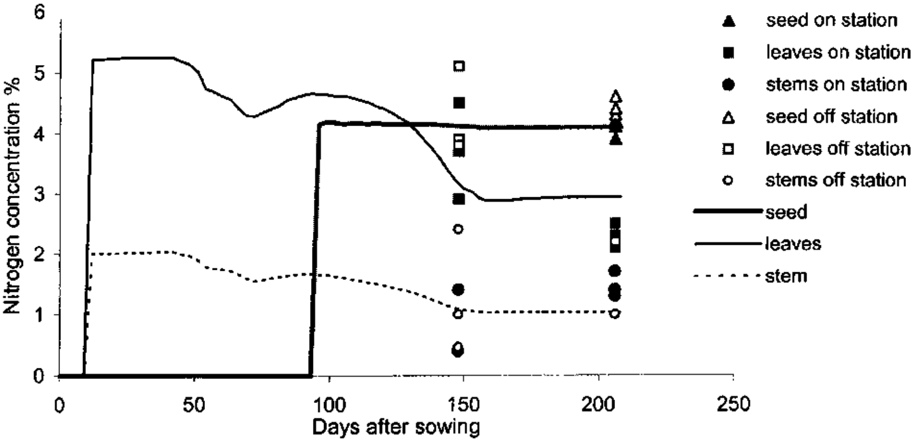

Figure 6.7 Simulated (lines) and observed (data points) nitrogen concentration of seeds, leaves and stems at Chitedze, Malawi.

At La Ceiba, Honduras (data from Brizuela and Barreto, 1996), observed and simulated senescence showed a similar pattern, which varied depending on the duration of the cultivar (Fig. 6.5). Onset of leaf senescence in the model might be predicted slightly late. However, in the observed data earlier leaf senescence may have been caused by a soil fertility effect such as phosphorus deficiency to which velvet bean is sensitive (e.g. Becker and Johnson, 1998; IITA, 2000). This effect is not included in the current version of the model.

Nitrogen

Simulated nitrogen concentration in various tissues were close to observed values at Palmira, Colombia (Fig. 6.6). Leaf, stem and seed nitrogen were measured in the 1997 trial at Chitedze, Malawi (Fig. 6.7). Seed and vegetative material nitrogen concentration was also measured at Santa Rosa, Mexico in 1997 (Fig. 6.8). The observed seed nitrogen values for Palmira and Santa Rosa are higher than simulated values. Slight adjustment in the cultivar or species file may be needed.

For all experiments where crop nitrogen contents were reported, velvet bean accumulated 200-350 kg ha^{-1} nitrogen in aboveground biomass (Fig. 6.9), depending on time of harvest and presence of pods and seeds. The model estimated around 150 kg ha^{-1} nitrogen in the seed if the crop was allowed to mature. An additional 50-100 kg ha^{-1} nitrogen was released during the season in senesced materials (litter), leaving around 100 kg ha^{-1} nitrogen in the vegetative materials at maturity. If no seeds are set, around 200 kg ha^{-1} nitrogen could be in the vegetative biomass at maturity and around 50-100 kg ha^{-1} nitrogen in the litter which at the end of the season contains approximately 30 to 50 kg ha^{-1} nitrogen. This agrees with data reported by Triomphe (1996) for nitrogen dynamics in velvet bean systems in the northern Honduras.

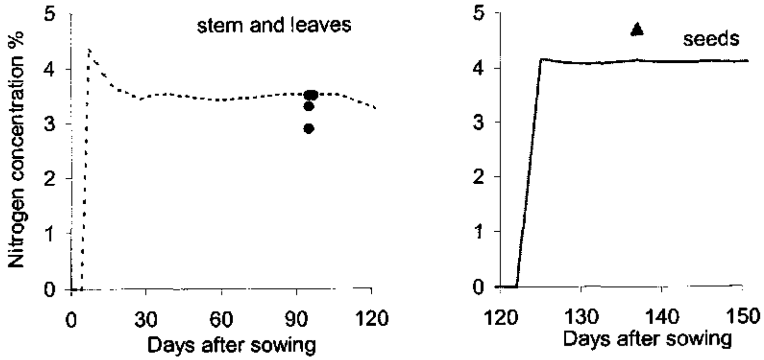

Figure 6.8 Simulated (lines) and observed (data points) nitrogen concentration of vegetative materials and seeds for cultivar 'Veracruz white' at Santa Rosa, Mexico.

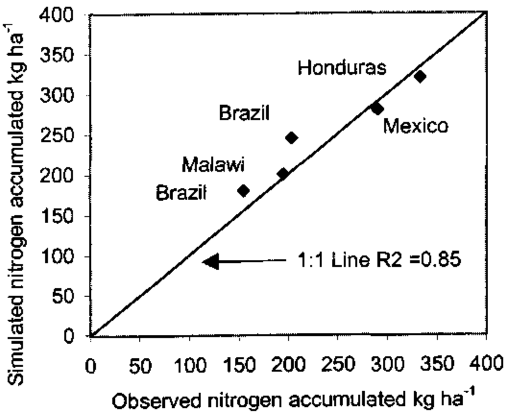

Figure 6.9 Simulated and observed total nitrogen fixed by velvet bean during the season at several locations.

Sensitivity analyses of validated model

Potential production varying mean temperature

The ability to provide a quick ground cover is an important characteristic for a green manure cover crop. Anecdotal reports suggested, however, that velvet bean develops insufficient cover and biomass in cooler environments. Therefore, a sensitivity analysis was conducted to examine temperature effects on potential productivity, assuming that water and nutrients were non-limiting. The production of biomass, light interception and row closure (canopy width) were evaluated at 60 days after planting for three different planting densities at a hypothetical site (Table 6.2; Fig. 6.10).

Table 6.2 Simulated total aboveground dry matter weight accumulation (no water limitation) and light interception at 60 days after planting for cultivar 'Veracruz black' for five hypothetical temperature environments and three plant densities.

	Plant density (plants m^{-2})					
	1	5	15	1	5	15
Mean temperature (°C)	Dry matter weight (kg ha^{-1})			Light interception (% of PAR[1])		
34	931	2576	3967	53	87	96
30	1114	2987	4525	58	90	97
26	871	2669	4270	51	88	96
22	287	1226	2532	20	59	80
18	46	229	642	4	16	32

[1] PAR = Photosynthetically Active Radiation

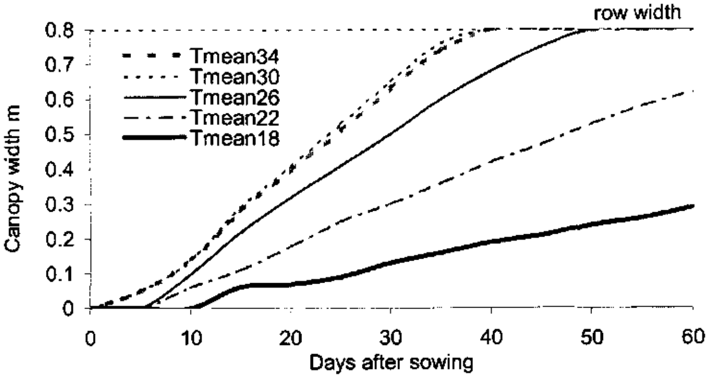

Figure 6.10 Canopy width for five hypothetical temperature environments assuming a row width of 0.8 m.

Prior to the sensitivity analysis, the model was tested further against growth data from Tabasco 1995, Mexico, where the density was 0.08 plant m^{-2} (Ortiz, unpublished data see Table 6.1). Environments with mean temperatures of 18 °C and 22 °C resulted in light interception < 80% PAR even at the highest plant population (15 plants m^{-2}), and the canopy did not close within 60 days after sowing. At a density of 1 plant m^{-2}, none of the environments produced adequate biomass (2 ton ha^{-1}), and light interception was insufficient for weed suppression (< 80% PAR). This suggests that velvet bean should be grown at densities closer to 5 plants m^{-2}, considering that densities of 1 plant m^{-2} are highly unsuitable.

The effect of soil depth and type

The effect of soil depth and water holding capacity was evaluated for Ibadan (Nigeria), Palmira (Colombia) and Plains, (USA), assuming densities of 5 plants m^{-2} and using 12 years of historical weather data (Tables 6.3 and 6.4). Growing velvet bean was least variable in Ibadan, and almost 2 ton ha^{-1} aboveground biomass was accumulated on soils of 0.2 m. Light interception was also poor in these soils. For optimum light interception, soils with a depth of 0.8 m or deeper, i.e. 100 mm soil water holding capacity, are preferred. The water holding capacity difference between soil textures affects velvet bean less than soil depth, as described in this study.

The fixation of nitrogen increased markedly in 0.4 m soils as compared to 0.2 m soils. Similar to results in soybean (Yinbo, 1999), a small amount of 'starter' nitrogen fertilizer can improve the performance of a legume crop. However, at some point, fertilizer or high nitrogen content of the soil suppresses the need for the legume to biologically fix nitrogen from the air. Consequently, in these circumstances nitrogen uptake from the soil is higher. These effects hold for velvet bean as well. In soils with higher nitrogen concentration, biological nitrogen fixation is lower and nitrogen uptake from the soil is higher (compare silty clay soils with sandy loam soils). For soils in Ibadan with a depth 0.4 m, biological nitrogen fixation by the plant was as high as 300 kg ha^{-1} nitrogen, of which 120 kg ha^{-1} nitrogen is removed from the system if seeds are harvested (data not shown). For the Palmira and Plains locations, the overall performance of velvet bean was more variable due to higher variability in climate.

Table 6.3 Simulated (mean, standard deviation, 10th and 90th percentile) total aboveground dry matter weight, light interception for cultivar 'Veracruz black' for 12 soil types at Ibadan (Nigeria), Palmira (Colombia) and Plains (USA).

	Soil		Ibadan				Palmira				Plains			
Soil type	WHC[1]	depth	mean	st.dev	10th	90th	mean	st.dev	10th	90th	mean	st.dev	10th	90th
Dry matter weight (kg ha^{-1})														
v. shall. silty clay	26	20	1980	459	1461	2612	808	538	511	1474	467	351	221	721
v. shall. clay loam	26	20	1835	416	1296	2377	796	596	448	1532	486	361	220	819
v. shall. sandy loam	22	20	1457	371	1003	1987	600	504	209	1233	392	285	162	704
shall. silty clay	52	40	7235	932	5981	8461	3414	3236	932	8120	2334	1611	686	3775
shall. clay loam	53	40	7147	978	5882	8382	4027	3379	1301	8941	2693	1591	833	4094
shall. sandy loam	44	40	6445	1063	5298	7841	4183	3166	1672	8779	2543	1364	865	3737
medium silty clay	104	80	8945	727	8007	9747	5195	4028	1683	11911	3604	1970	1418	5530
medium clay loam	106	80	8814	751	7798	9645	6307	4085	2315	12841	4002	1923	1632	6197
medium sandy loam	88	80	8164	851	6925	9261	6378	3877	2642	12016	3732	1778	1545	6012
deep silty clay	234	180	10761	571	10167	11376	10132	3415	6863	15269	5868	1911	3218	8220
deep clay loam	238	180	10727	595	10117	11362	11061	3095	7962	15362	6278	1777	3809	8288
deep sandy loam	198	180	10060	690	9233	10921	10307	3427	6793	15215	5656	1828	3254	8200
Light interception (% PAR[2])														
v. shall. silty clay	26	20	48	4	45	53	13	8	6	22	22	8	10	30
v. shall. clay loam	26	20	44	3	41	48	12	7	6	21	20	7	10	26
v. shall. sandy loam	22	20	34	2	31	37	10	4	6	15	15	5	8	19
shall. silty clay	52	40	87	1	85	89	34	15	21	53	56	22	28	79
shall. clay loam	53	40	87	2	86	89	40	16	25	59	58	20	33	79
shall. sandy loam	44	40	86	3	85	88	35	17	21	63	54	21	26	75
medium silty clay	104	80	88	1	87	89	72	8	61	81	72	12	55	82
medium clay loam	106	80	88	1	87	89	77	4	72	82	74	9	60	82
medium sandy loam	88	80	88	1	86	89	72	6	65	80	71	11	57	83
deep silty clay	234	180	88	1	87	89	78	3	75	83	74	8	62	82
deep clay loam	238	180	88	1	88	89	80	2	78	82	76	7	69	82
deep sandy loam	198	180	88	1	87	89	77	3	75	80	74	8	62	83

[1] WHC = Water Holding Capacity of soil profile

[2] PAR = Photosynthetically Active Radiation

Table 6.4 Simulated (mean, standard deviation) nitrogen fixation and uptake for cultivar 'Veracruz black' for 12 soil types at Ibadan (Nigeria), Palmira (Colombia) and Plains (USA). Data generated form 12 years of actual weather data.

			Ibadan		Palmira		Plains	
Soil type	WHC[1]	Soil depth	mean	st.dev	mean	st.dev	mean	st.dev
N fixed (kg ha^{-1})								
very shallow silty clay	26	20	71	20	13	19	20	17
very shallow clay loam	26	20	69	18	16	23	26	19
very shallow sandy loam	22	20	63	16	17	21	28	16
shallow silty clay	52	40	288	25	130	127	201	122
shallow clay loam	53	40	296	25	167	131	233	119
shallow sandy loam	44	40	298	28	189	122	234	105
medium silty clay	104	80	267	23	209	144	273	117
medium clay loam	106	80	288	22	269	139	314	112
medium sandy loam	88	80	310	23	286	139	315	114
deep silty clay	234	180	150	39	287	63	326	43
deep clay loam	238	180	213	30	357	58	381	36
deep sandy loam	198	180	291	21	388	81	401	62
N uptake (kg ha^{-1})								
very shallow silty clay	26	20	24	2	24	4	21	2
very shallow clay loam	26	20	19	1	18	3	16	2
very shallow sandy loam	22	20	10	1	9	2	8	1
shallow silty clay	52	40	48	6	41	8	35	6
shallow clay loam	53	40	39	4	31	8	26	5
shallow sandy loam	44	40	20	2	17	4	13	2
medium silty clay	104	80	110	14	67	16	64	13
medium clay loam	106	80	87	9	51	15	46	11
medium sandy loam	88	80	47	4	31	9	24	6
deep silty clay	234	180	278	41	170	50	148	33
deep clay loam	238	180	208	28	125	48	105	30
deep sandy loam	198	180	113	14	70	31	52	17

[1] WHC= Water Holding Capacity of soil profile

Conclusions

For the velvet bean version of CROPGRO, simulated phenology, canopy development, growth, senescence, and nitrogen accumulation followed the trends that were found in the observed data. It can therefore be concluded that the model can be used to estimate biomass production and canopy cover. Further testing for a range of environments varying in daylength is required to refine adaptation zones for different cultivars.

Based on specific objectives, such as weed suppression, erosion control or fertility management, thresholds may be estimated to determine the success of the crop. Using cultivars originating from Veracruz, Mexico, mean temperature during the velvet bean season should be above 22 °C. Plant densities should be close to 5 plants m^{-2} to ensure biomass production greater than 2 ton ha^{-1}, light interception greater than 80% PAR, and rapid ground cover through a canopy closure within 60 days after sowing. To ensure benefits from velvet bean cultivation in rainfed conditions, the soil depth should be at least 0.8 m to provide adequate soil moisture equivalent to a water holding capacity of 100 mm. Soils of 0.4 m depth permit biomass production of 2 to 3 ton ha^{-1}, but light interception will be too low for weed suppression (< 80%) and nitrogen fixation will be too low (< 200 kg ha^{-1}) to benefit subsequent non-leguminous crops. Similar analyses could be conducted to assess the potential of velvet bean for improved fallows where carbon sequestration or sustainable soil management are primary objectives.

With adequate rainfall, velvet bean can be grown as a ground cover. Due to the short-day response of velvet bean, seed production may be problematic when sown in long-day environments. Besides the effect of photoperiod on flowering, research on soybean and groundnut indicates that the photoperiod effect persists during reproductive development (Brink, 1998). Growing small plots in the summer season, when daylength is decreasing, would help ensure seed production and availability.

Developing and validating a model for a little-studied crop such as velvet bean provided special challenges due to limited availability of field data. While the minimum data set concept provides a useful reference concept, few researchers dealing with GMCC appear prepared to record this 'minimum' requirement. Our experience suggests, however, that by focusing on key measurements and treatments, the velvet bean model could be improved substantially. Frequent measurements of canopy width or ground cover would assist refinement of canopy development. In studies where biomass accumulation is the primary focus, an additional measurement a few weeks prior to the final sample could provide valuable insights into dynamics of canopy development. More careful attention to time of flowering could improve our confidence in modelling seed production. A relatively small set of planting date treatments at different latitudes, not necessarily with biomass measurements, would be especially valuable for testing simulation of phenology. For situations where a full characterization of the initial soil profile is not possible, information on soil texture (by horizon) and maximum effective soil depth would be a marked improvement over the common practice of describing the soil in terms of a qualitative assessment of soil texture and depth (e.g., for the 'shallow sandy loam').

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7.

REGIONAL APPLICATION OF CROPPING SYSTEMS SIMULATION MODELS: I. AN IMPROVED MAIZE–FALLOW SYSTEM IN HONDURAS

Abstract

The productivity of smallholder maize production systems in Central America is being undermined by degradation of the soil and water resource base. Various stakeholders from NARS, networks, NGOs and research institutes seek to develop and target productivity-enhancing resource-conserving management practices such as improved fallow rotation systems including green manure cover crops. To support this process a methodology for biophysical assessment with explicit spatial and temporal dimensions was developed. Using expert knowledge, agronomic descriptions of cropping systems and management practices were synthesized and used as input to the cropping systems simulation model DSSAT. Gridded climate profile surfaces and a wide range of soil scenarios formed the basis of the regional input. The objective of the study was to regionally assess the maize–velvet bean cropping system in Honduras, as an example of methodology application. The assessment considers velvet bean production per se, as well as the effects of velvet bean on maize production and soil resources. To increase the understanding of variation in regional results, we analysed responses to water and nitrogen conditions at individual site locations and for a selection of soil scenarios. Benefits of increased maize production from cropping velvet bean are expected in areas where off-season climate and soil conditions enable velvet bean growth and in nitrogen limiting soils with low nitrogen fertilization management. An increase in maize grain yield of up to 2 ton ha^{-1} *was found under illustrated conditions. Increases in soil organic carbon and nitrogen from cropping velvet bean were substantial as evaluated over the 12-year simulation period. The assessment provided more insight in the regional potential for and the soil and climate conditions under which successful introduction of velvet bean in Honduras may be achieved.*

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Introduction

Maize production systems in Central America are an important source of income and employment for resource poor farmers and are key to the food security of consumers, particularly of low-income urban population. Smallholders in the region commit more land, throughout a diverse range of ecologies, to maize than to all other food crops combined (see Smoock and Silva, 1989; Barreto and Hartkamp, 1999). The productivity of these systems, however, is being undermined by degradation of the soil and water resource base (Hawkins, 1984; Lopez et al., 1994; Bolaños, 1997). Maize systems are being intensified through double cropping and the shortening of fallow periods. Productivity enhancing resource conserving maize production practices have been developed by NARS (e.g., INIFAP, IICA, DICTA), networks (e.g., PRM – Regional Maize Program for Central America), NGOs (e.g., CIDICCO, Rockefeller Foundation, Proyecto Sierra Santa Marta in Veracruz Mexico), and international research institutes (e.g., CIMMYT, CIAT). Improved fallow rotation systems that involve green manure cover crops (e.g., *Mucuna* spp., *Canavalia ensiformis*) is one group of practices that has been proposed, also by producers, to improve productivity while conserving soil and water resources.

Experimental evidence of the benefits of green manure cover crop (GMCC) technology has been found on-station and on-farm at various locations throughout Central America (Barreto et al., 1992; Lopez et al., 1993; Buckles and Perales, 1995; Brizuela and Barreto, 1996; Triomphe, 1996; Van Eijk-Bos, 1997; Gordon et al., 1997; Buckles et al., 1998; Eilittä, 1998). These benefits include reduction of soil surface runoff and soil loss through increased ground cover, fixing of nitrogen for next season maize crop, weed control and soil structural improvement through, amongst others, an increase in organic matter. Ultimately, an increase in production can be expected due to these processes. In maize production systems of Central America, GMCC control erosion, suppress weeds, and contribute up to 200 kg ha^{-1} nitrogen (Lopez, 1993; Buckles and Perales, 1995; Triomphe, 1996; Van Eijk-Bos, 1997; Buckles et al., 1998).

The experimental successes of GMCC, however, are site specific and analysis of system dynamics has been difficult, as long-term field trials at multiple locations are scarce. In a number of instances, adoption of green manure practices by farmers has been followed by abandonment, in part due to poor growth of the legume (Eilittä, 1999). Therefore quantification of growth and development in target environments – 'cropping system niches' – is needed to gain more insight in the conditions that need to be fulfilled to enable successful introduction of cropping systems that include GMCC in rotations.

Regional and national agricultural development programmes aim to extrapolate promising agronomic practices from experimental sites to larger target regions. Primarily, it is necessary to evaluate *where,* from a biophysical point of view, these target regions may be located. Subsequently, areas for socio-economic adaptation research and technology introduction can be identified. Inappropriate introduction can be prevented and ultimately gaps in the underlying knowledge, experimental data or theoretical concepts of the cropping system may be identified.

Methodologies for scaling-up from site- and term[1]-specific research experiences are scarce and seldom robust. This is largely caused by the inability to explicitly account for the spatial and temporal variability of climate and soil conditions in interaction with crop characteristics and agronomic management strategies. Process based modelling can integrate complex interactions of climate, soil, crop characteristics and management practices. The process of running simulation models for many environmental combinations or sites can be facilitated through use of Geographical Information Systems (GIS). A methodology was developed that explicitly accounts for the spatial and temporal variability in climate and soil conditions in interaction with crop characteristics and agronomic management strategies. An example of methodology application focusing on maize–velvet bean cropping – one of the most widespread improved fallow systems in Honduras – is presented in this paper. The objective of the study was to use the methodology to assess maize-velvet bean cropping in terms of production (biomass, seed, nitrogen fixation) and resource (surface runoff water, soil organic carbon and nitrogen content) dimensions. The assessment considers velvet bean production *per se*, as well as the effects of velvet bean on maize production and soil and water resources of the system. To increase the understanding of variation in regional results, we analysed responses to water and nitrogen conditions for a selection of locations and soil scenarios.

Material and methods

System simulation models

The Decision Support System for Agrotechnology Transfer (DSSAT) software package (IBSNAT, 1993; Tsuji et al., 1994; Uehara and Tsuji, 1998) was used in this study. The DSSAT package includes a computer software shell that integrates crop simulation models of over 15 food crops, database entry and management utilities, and simulation application programs. The crop simulation models predict development, growth and partitioning, and senescence as a function of crop and cultivar specific characteristics, weather and soil conditions and selected agronomic management practices. Basic information required by the models is summarized in Table 7.1. Plant growth and rates of change in the soil-plant-atmosphere system are integrated daily. Simulation of the soil water balance can be initialized before or at planting. The plant

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[1] *Term* refers to a specific fixed period of time or time horizon for which the research was executed and is valid. In other words, how can we scale up from short- term experiences to medium or longer-term expectancies?

Table 7.1 Information required by crop simulation models under DSSAT (adapted from Hoogenboom et al., 1995).

Daily weather information

- Daily total solar radiation
- Daily total precipitation
- Daily minimum and maximum air temperature
- Latitude – to calculate daylength
- CO_2 concentration (for climate change applications)

Soil information

General

- *Soil water simulation*
  - Runoff as specified by the Soil Conservation Service runoff curve number
  - Soil albedo
  - Permeability and drainage
  - Soil evaporation
- *Soil N simulation*
  - Weight of organic residues of previous crop
  - C/N ratio of residues of previous crop
  - Depth of residue incorporation

For each soil layer

- *Soil water simulation*
  - Soil layer thickness
  - Saturated soil water content
  - Drained upper limit of extractable plant water (field capacity)
  - Lower limit of extractable plant water (permanent wilting point)
  - Initial soil water content
  - Relative root distribution
- *Soil N simulation*
  - Soil pH
  - Bulk density
  - Initial soil nitrate concentration
  - Initial soil ammonium concentration
  - Organic C

Crop and management information

- *Crop and cultivar selection*
  - Thermal time to development stages
  - Photoperiod sensitivity
  - Leaf, grain or seed characteristics
  - Growth, partitioning and senescence
- *Agronomic management*
  - Planting date
  - Planting density, row spacing, planting depth
  - Depending on model application:
  - Dates and amount of irrigation
  - Dates amounts and types of fertilizer

component of the model is initiated at planting and crop phenology is simulated including emergence, vegetative development, flower initiation, flowering, fruit set, seed development and maturity. The DSSAT system includes modules for vegetative and reproductive development, plant carbon balance, soil and plant water balance, and soil and plant nitrogen balance (Hoogenboom et al., 1995; Hoogenboom et al., 2000). The model requires several soil profile parameters (albedo, soil surface runoff, pH, bulk density, water permeability and drainage, initial organic carbon and total nitrogen) to be defined by the user. The soil water balance processes include infiltration of precipitation and irrigation, soil evaporation, crop transpiration, distribution of root water uptake, drainage of water through the root zone and soil surface runoff (Ritchie, 1998). The crop nitrogen balance processes include N uptake, biological nitrogen fixation, N mobilization from vegetative tissues, rate of N use for new tissue growth and rate of N loss in abscised parts. Plant N deficiencies reduce photosynthesis and affect development. The soil nitrogen processes include N mineralization, immobilization, nitrification, denitrification and leaching (for details see Godwin and Singh, 1998). To simulate maize production, the CERES (v 3.5) model was used with coefficients calibrated for growth and development of the tropical cultivar HB 83 (Alvarez, 1996). To simulate the fallow season, the CROPGRO (v 3.5) model (Hoogenboom, 1992; Boote et al., 1998) was used. To simulate performance of velvet bean (*Mucuna pruriens*), a modified version of CROPGRO was used that tracks the accumulation of litter weight (Chapters 5, 6). The amount of litter that senesces during the growing season can be quantified, however this litter is considered lost from the system. As a consequence, the contribution of – decomposing – litter to the system, such as to the nitrogen content of the soil, is not included in model calculations. The model will underestimate to some extent the benefit from cropping velvet bean in terms of contribution to soil nitrogen. Growth and development coefficients of velvet bean cultivar 'Veracruz black' were used. To simulate crop rotation and fallows over multiple seasons, a sequence driver was used linking CERES and CROPGRO (Thornton et al., 1995).

Climate input

Long-term monthly normals based on 25-30 years of meteorological data[2] were interpolated on a 1-km^2 grid by Jones (1996) to obtain climate surfaces, covering an area of 600 by 400 km^2. For each climate grid cell of 1-km^2, climate data were available. Grid cells containing similar climate data were clustered to yield 200 discriminant climates, using an approach proposed by Collis and Corbett (1997). This considerably reduced the number of simulation runs. For each discriminant climate, stochastic climate profile files were created, which were used as input to the SIMMETEO weather generator (Geng et al., 1986; Geng et al., 1988) to generate daily weather data.

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[2] For instance, precipitation data from over 540 meteorological stations was used.

Soil input

Very few quantitative soil profile descriptions for the region were available for Honduras. Moreover, soil characteristics that determine crop production, such as soil depth and water holding capacity, may vary considerably even within the area of a climate grid cell of 1-km^2. The validity of using a single soil profile description for such an area is questionable (see also Lagacherie et al., 2000). Instead, 15 representative soil profile descriptions at two topography levels were used that covered the wide range of soil depths, water-holding capacities, and potential soil surface runoff values occurring in Honduras (Table 7.2). Simulation for the entire region was repeated for each of these 15 soil scenarios.

Agronomic input

Using expert knowledge and existing literature sources agronomic cropping system and management information was collected for the most important maize production systems present in Honduras (Appendix 7.1). Table 7.3 synthesizes a selection from this information used in this paper: a maize–fallow system and a maize–velvet bean system. Two nitrogen fertilizer management levels for the maize crop were explored. The low nitrogen fertilization level of 23 kg ha^{-1} represents a maize small-holder fertilization rate, whilst the 200 kg ha^{-1} level represents a very rich fertilization rate.

Simulation files

For each cropping system a template DSSAT experiment file defined the crops, agronomic management, number of simulation years, and the number of weather repetitions. To allow for an effect of crop rotation over time, each combination was run for 12 years of generated weather which was repeated 15 times to capture climate-induced variability. A simulation file for each unique combination of climate profile with soil scenario was created. The sequence driver (Thornton et al., 1995) subsequently ran each 12-year maize–fallow system sequence for 15 weather repetitions, 200 climate profiles and 15 soil scenarios. Summary output files stored the results of each single simulation.

Output management

The importation and basic statistical processing (calculation of the minimum, maximum, mean, and standard deviation of each output variable) of simulation output files into the GIS database file format was partially automated using software developed by Collis and Corbett (1997). For each cropping system and soil scenario, output files containing cropping system attribute variables were created to allow mapping and analysis in the GIS. The variables available for analysis were those available in the summary output files created by the sequence module (see Thornton et al., 1995). Figure 7.1 illustrates the steps involved in the application of the methodology.

Table 7.2 Soil scenarios used in the spatial simulations.

Soil name	Texture classification	Available soil water mm[1]	Depth cm	Topography[2]	Runoff curve number[3]
Shallow silty clay, no slope	Silty clay	52	40	No slope	82
Shallow clay loam, no slope	Clay loam	53	40	No slope	77
Shallow sandy loam, no slope	Sandy loam	44	40	No slope	72
Medium silty clay, no slope	Silty clay	104	80	No slope	80
Medium clay loam, no slope	Clay loam	106	80	No slope	75
Medium sandy loam, no slope	Sandy loam	88	80	No slope	70
Deep silty clay, no slope	Silty clay	234	180	No slope	78
Deep clay loam, no slope	Clay loam	238	180	No slope	73
Deep sandy loam, no slope	Sandy loam	198	180	No slope	68
Shallow silty clay, slope	Silty clay	52	40	Slope	92
Shallow clay loam, slope	Clay loam	53	40	Slope	87
Shallow sandy loam, slope	Sandy loam	44	40	Slope	82
Medium silty clay, slope	Silty clay	104	80	Slope	90
Medium clay loam, slope	Clay loam	106	80	Slope	85
Medium sandy loam, slope	Sandy loam	88	80	Slope	80

[1] Available soil water is calculated from drained upper limit- lower limit for each soil layer defined by the user.

[2] Non-sloping topography corresponds to slopes of 0 - 5%; Sloping topography corresponds to slopes of 30%.

[3] USDA Soil Conservation Service runoff curve number as determined by soil texture, depth and slope; larger values indicate greater potential for soil surface runoff (USDA, 1972).

Table 7.3 Agronomic management practices used as input for DSSAT crop models.

Planting window main season	June 1 - July 10	
Planting window off-season	December 20- February 10	
Planting density at emergence	Maize	4.0 plants m^{-2}
	Velvet bean	3.5 plants m^{-2}
Planting depth	5.0 cm	
Row spacing	Maize	0.80 m
	Velvet bean	0.80 m
Nitrogen management level	N1=23 kg N ha^{-1} at planting (Farmer practice)	
	N2=50 kg N ha^{-1} at planting; 150 kg N ha^{-1} 35 days after planting	

Presentation of results

The assessment focused on production and soil and water resources. The results were presented in workshops with regional and national stakeholders (see Chapter 9). Since qualitative spatial trends were similar over the fifteen soil profiles, spatial results for only three soil scenarios are presented in this paper. The three soils (S1, S2, S3) selected were shallow sandy loam on sloping topography, shallow sandy loam non-sloping topography and deep sandy loam non-sloping topography. Three locations

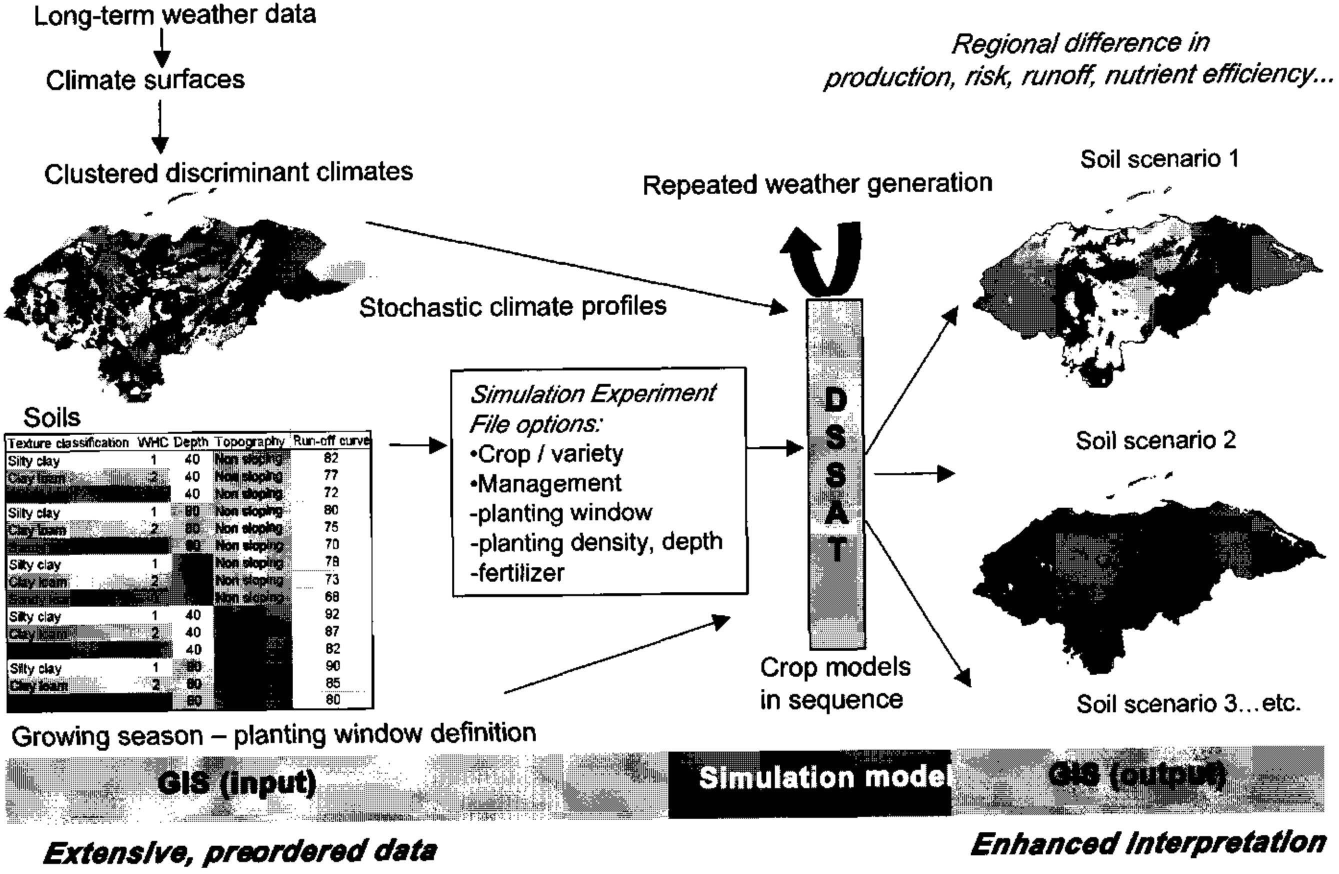

Figure 7.1 Schematic representation of the methodology used in the regional application of crop simulation models.

Table 7.4 Aggregated climate characteristics of three locations.

	Annual		Main season[1]				Off-season	
Location	Precip. mm	Tmean °C	Precip. mm	Tmean °C	Tmax °C	Tmin °C	Precip. Mm	Tmean °C
A	1055	25.4	754	25.3	30.5	20.1	308	27.1
B	2281	24.0	1294	24.7	30.1	19.3	987	23.4
C	2892	19.2	2020	21.5	25.5	15.4	872	18.9

[1] Main season encompasses 5 months; Precip = precipitation; Tmean, Tmax, Tmin = mean, maximum, minimum temperature, respectively.

with different seasonal precipitation patters were selected to illustrate water and nitrogen processes underlying regional results. Annual, growing season and off-season climate characteristics of the selected locations are shown in Table 7.4. Results for maize production in a maize–bare fallow are presented first. Subsequently results for velvet bean and effects of velvet bean on maize production in the maize–improved fallow are discussed. Finally, regional effects of velvet bean on soil and water resources are presented.

Results and discussion

Maize production in a maize – (bare) fallow

The response to nitrogen fertilizer management (from N1 to N2) in interaction with water availability on maize grain yield in maize–fallow systems is illustrated for three soils for the selected locations (A, B, C) in Fig. 7.2a and subsequently at the regional scale for Honduras in Fig. 7.2b. In environments with low precipitation during the main growing season (A) there is hardly any response to nitrogen fertilization under all soil and topography conditions. Here, maize production is determined by water availability. In environments with more precipitation throughout the year (B, C), the water availability in the soil, as determined by water storage capacity and topography, becomes important in determining whether nitrogen fertilization will have an effect on maize production. On deeper soils (S3) there is only a small response to the increase in nitrogen fertilization, because of the already higher yield level and higher nitrogen availability in this soil. On shallow sandy loams (S1, S2) the effect of fertilization was highest; increasing nitrogen fertilization can increase maize grain yield with up to 3.8 ton ha^{-1} in environments of ample water availability. In environment C on deep soils (S3) an increase in average maize grain yield of up to 1.6 ton ha^{-1} is found through the same increase in fertilizer rate. In environment C, colder temperatures allow for a longer grain filling period than in environment B.

In our example of shallow sandy loam soils no effect of slope was apparent on maize grain yield. If precipitation is low, all water infiltrates and there is no difference in water availability irrespective of slope. In more wet environments the effect of slope is small because the sum of runoff and drainage of non-sloping and sloping shallow sandy loam soils happens to result in equal water availability (see runoff and drainage for soils S1, S2 in Table 7.5). Additionally, higher infiltration of shallow sandy loam soils on non-sloping topography causes more nitrogen leaching than on shallow sandy loam soils on slopes (see e.g. nitrogen leaching for soils S1, S2 in Table 7.6).

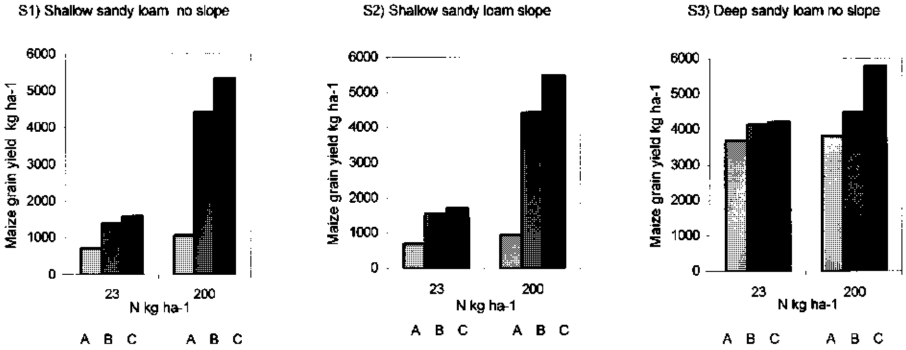

Figure 7.2a Average maize grain yield for maize–fallow for two fertilizer levels, three soil scenarios (S1, S2, S3) and three locations (A, B, C) climatically characterized in Table 7.4.

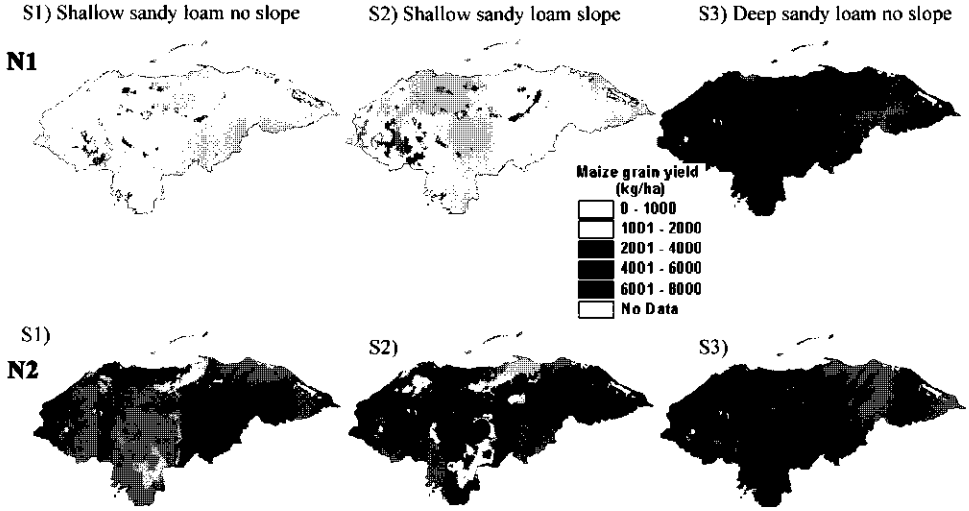

Figure 7.2b Average growing season maize grain yield for three soil scenarios (S1, S2, S3) and two nitrogen fertilizer levels: N1=23, N2 =200 kg ha^{-1}.

Table 7.5 Maize–fallow runoff and drainage during the maize-growing[1] season at two fertilizer levels and three soils.

	Fertilizer[2]	Runoff (mm)			Drainage (mm)		
Soil	kg N ha^{-1}	A	B	C	A	B	C
S1) Shallow sandy loam no slope	23	119	150	441	250	721	1261
S1) Shallow sandy loam no slope	200	119	155	450	249	717	1249
S2) Shallow sandy loam slope	23	212	309	735	166	562	968
S2) Shallow sandy loam slope	200	212	314	742	165	559	958
S3) Deep sandy loam no slope	23	99	123	373	117	733	1325
S3) Deep sandy loam no slope	200	98	124	377	120	733	1320

[1] Maize-growing season defined as the season between planting of maize and physiological maturity.

[2] Fertilizer applied in the maize-growing season.

Table 7.6 Nitrogen leaching during the maize-growing season[1] of maize–fallow and maize–velvet bean systems at two fertilizer levels and three soils.

		Fertilizer[2]	N_leach kg ha^{-1}		
Soil	System	N kg ha^{-1}	A	B	C
S1) Shallow sandy loam no slope	Maize–fallow	23	18	39	30
S1) Shallow sandy loam no slope	Maize–velvet bean	23	18	57	43
S1) Shallow sandy loam no slope	Maize–fallow	200	145	125	147
S1) Shallow sandy loam no slope	Maize–velvet bean	200	149	164	167
S2) Shallow sandy loam slope	Maize–fallow	23	17	37	29
S2) Shallow sandy loam slope	Maize–velvet bean	23	16	51	40
S2) Shallow sandy loam slope	Maize–fallow	200	141	123	141
S2) Shallow sandy loam slope	Maize–velvet bean	200	143	158	158
S3) Deep sandy loam no slope	Maize–fallow	23	27	118	120
S3) Deep sandy loam no slope	Maize–velvet bean	23	25	118	134
S3) Deep sandy loam no slope	Maize–fallow	200	135	239	219
S3) Deep sandy loam no slope	Maize–velvet bean	200	137	248	258

[1] Maize-growing season defined as the season between planting of maize and physiological maturity.

[2] Fertilizer applied in the maize-growing season.

Table 7.7 Velvet bean biomass production and nitrogen during the velvet bean off-season at two fertilizer levels and three soils.

	Fertilizer[1] N kg ha^{-1}	Biomass kg ha^{-1}			N_fix kg ha^{-1}			N_uptake kg ha^{-1}			N_litter kg ha^{-1}			N_seed kg ha^{-1}		
Soil		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
S1) Shallow sandy loam no slope	23	300	2346	1363	3	91	44	7	27	15	0	9	10	0	7	0
S1) Shallow sandy loam no slope	200	427	2463	1380	2	75	41	14	51	19	0	10	9	0	7	0
S2) Shallow sandy loam slope	23	285	2261	1245	2	88	40	7	28	15	0	9	9	0	6	0
S2) Shallow sandy loam slope	200	407	2376	1263	1	71	36	15	53	20	0	10	9	0	7	0
S3) Deep sandy loam no slope	23	534	8109	4557	5	192	100	15	124	68	0	19	15	0	76	4
S3) Deep sandy loam no slope	200	599	8136	4574	2	186	93	23	132	77	0	19	16	0	76	4

[1] Fertilizer applied in the maize-growing season.

In Fig. 7.2b, the regional pattern in maize production follows water availability in the same manner as illustrated at the three locations. On shallow sandy loam soils in areas to the south of Honduras hardly any response to nitrogen fertilization can be expected due to limited water availability. On deep sandy loams the response to nitrogen fertilization is small and concentrated in areas of ample precipitation.

Velvet bean in a maize – velvet bean system

In environment B velvet bean growth and nitrogen fixation is consistently higher than in environment A, because more precipitation is available in the off-season. In environment C temperatures limit velvet bean growth (Table 7.7). A very small response on velvet bean growth to increasing nitrogen fertilizer rate in the maize-growing season was found in water limiting situations (A on shallow soils S1, S2). The response is non-significant when water is abundant (B, C on deep soil S3). In areas of ample water availability nitrogen availability is of little importance as velvet bean biologically fixes nitrogen. Biological nitrogen fixation decreases due to increased availability of nitrogen. A small amount of 'starter' fertilizer is necessary for velvet bean growth. However, at some point, fertilizer or high nitrogen content of the soil suppresses the need for the legume to biologically fix nitrogen from the air. Thus increased nitrogen availability results in less biological nitrogen fixation and more nitrogen uptake from the soil profile (see figures for two fertilizer levels in Table 7.6). Velvet bean reallocates nitrogen from senescing tissue material. This explains why the amount of nitrogen in litter is low and generally did not exceed 25 kg ha^{-1}.

As growth of velvet bean is similar at the two nitrogen management levels in the maize-growing season, results for velvet bean are presented for the lower maize nitrogen fertilizer level only (N1). The production of biomass, litter (fallen leaves and petiole stems), seeds, the percentage intercepted PAR (Photosynthetic Active Radiation) and nitrogen fixation of velvet bean in the off-season at the regional scale is presented in Fig. 7.3. On shallow soils, off-season velvet bean biomass production showed little potential, except for patches in the North and Northeast of Honduras[3]. On high potential deep soils velvet bean can produce around 2 ton ha^{-1} of biomass in almost all climates of Honduras. This 2 ton ha^{-1} has been referred to as the necessary threshold level for successful introduction of velvet bean by the CIAT Hillsides Program (CIAT Hillsides, 1997). The production of sufficient biomass is only one criterion that needs to be evaluated for successful introduction of a GMCC. The production of litter and seeds, interception of light and nitrogen fixation are other criteria that are equally important. Litter will reduce soil evaporation and runoff water will be decreased. Also, decomposition of the mulch (litter and end-season biomass) will contribute to organic carbon and nitrogen status of the soil. The spatial pattern of litter accumulation is similar to that of biomass. Depending on soil, results show that

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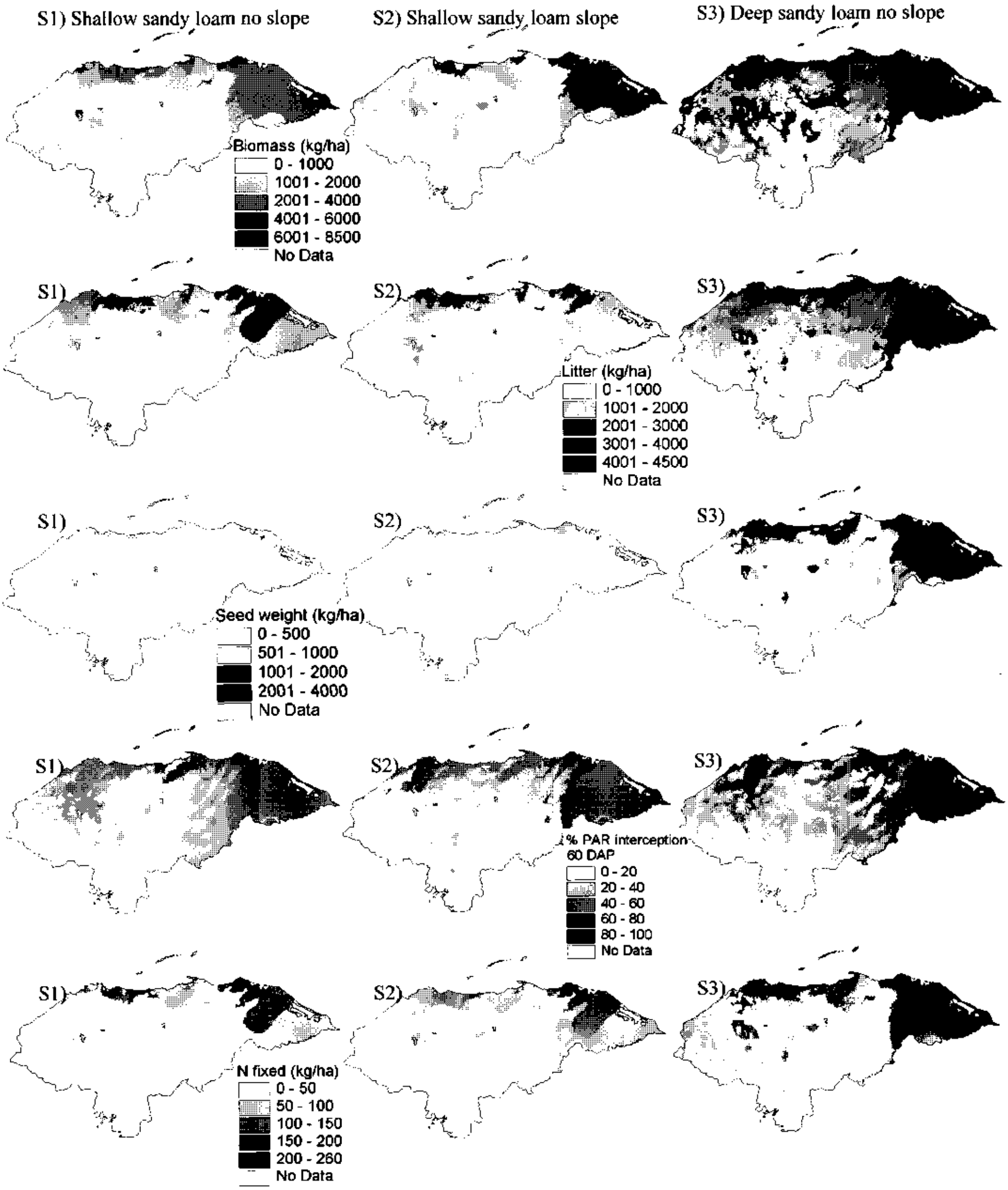
[3] The Northeast of Honduras is an area of indigenous forest where agriculture is not practiced.



S1) Shallow sandy loam no slope

S2) Shallow sandy loam slope

S3) Deep sandy loam no slope

Figure 7.3 Average off-season velvet bean aboveground biomass weight, litter weight, seed weight, light interception, nitrogen fixation for three soil scenarios (S1, S2, S3), and assuming low nitrogen fertilizer management (N1).

approximately one third to half of the total dry matter is accumulated as litter on the ground and the remaining dry matter is left as standing biomass at harvest time[4]. On shallow water-limited soils (S1, S2) velvet bean senesces relatively more than on deep soils (S3), leading to relatively higher litter accumulation. As rule of thumb velvet bean needs to intercept around 80% of the incoming PAR at 60 days after planting to effectively control weeds (see Hariah et al., 1993). According to our simulations only few areas meet this criterion. Seed weight is generally low because of low rainfall and sub optimal daylength conditions for velvet bean as daylength increases in the off-season. On deep sandy loam soils nitrogen fixation can amount to over 200 kg ha^{-1} in the northern regions of Honduras where off-season precipitation is high.

In Fig. 7.4, results for velvet bean biomass production, biological N fixation and litter are shown across aggregated climate characteristics of precipitation and temperature to roughly indicate general climate requirements for velvet bean. Velvet bean cropping is not successful at mean temperatures in the off-season of below 20 °C. On deep soils (S3) at least 600 mm and on shallow soils (S1, S2) at least 750 mm off-season precipitation is needed for biomass and litter production. As indicated above nitrogen availability is of less importance in velvet bean cropping, as it is able to fix nitrogen from the air. In order for velvet bean to fix substantial levels of nitrogen (> 150 kg ha^{-1}) off-season precipitation needs to be 1400 - 1500 mm on shallow soils (S1, S2). On deep soils (S3) about 1000 mm off-season precipitation is needed to achieve this amount of biological nitrogen fixation.

Maize production in a maize – velvet bean system

In Fig. 7.5, the difference in maize grain yield between maize–fallow and maize –velvet bean systems is illustrated for the same three selected locations (A, B, C) and the three soils (S1, S2, S3) introduced earlier. In environment A, there is hardly any effect of velvet bean cropping on maize production because of the low production potential of velvet bean in this environment. In environments of ample water availability (B, C) and on shallow sandy loam soils (S1, S2) maize grain yield was increased with up to 2 ton ha^{-1} through cropping velvet bean in the off-season at the low maize nitrogen fertilizer level. The benefits in environment B are somewhat higher due to the more favourable growth conditions for velvet bean in the off-season. On deep soils (S3), there is less benefit to maize grain yield from cropping velvet bean in the off-season, due to the higher nitrogen availability. At a high maize fertilizer level, the benefit to maize grain yield of velvet bean cropping in the off-season disappears as velvet bean fixes less nitrogen from the air. The benefit to maize grain yield from cropping velvet bean is found in areas of sufficient water availability in the off-season and nitrogen-limiting soils with low nitrogen fertilization management.

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[4] At time of harvest velvet bean may not be mature as the off-season is determined by the maize-growing season and velvet bean may not have completed its physiological cycle.

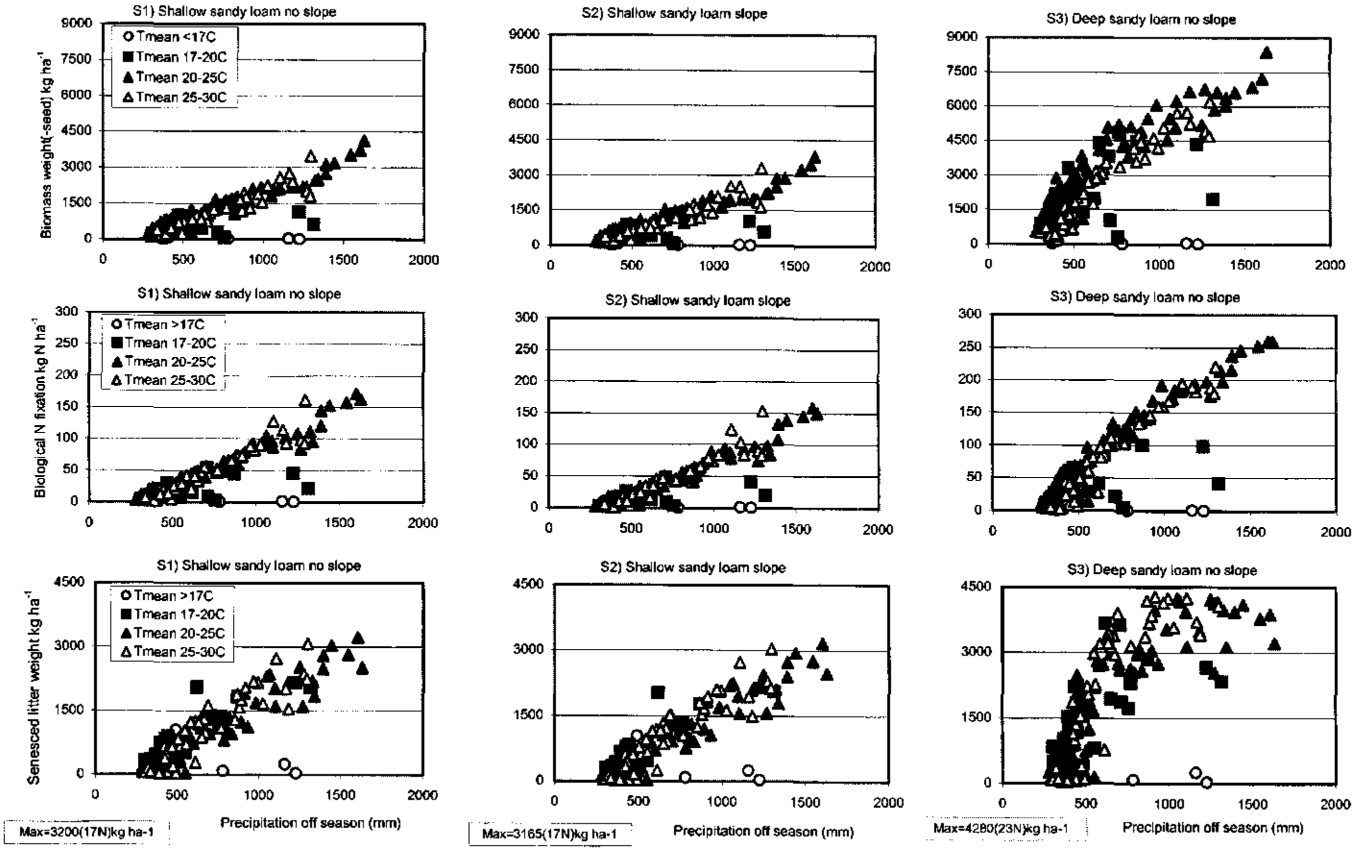

Figure 7.4 Velvet bean biomass production (without seeds), biological nitrogen fixation and litter production for three soil scenarios (S1, S2, S3) under prevailing off-season precipitation.

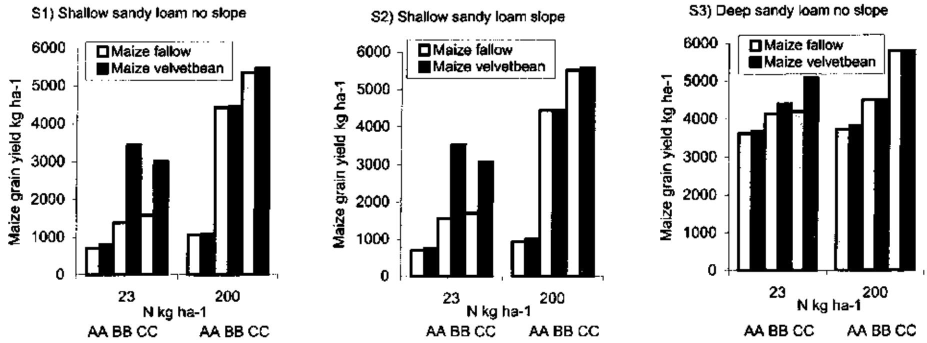

Figure 7.5 Average maize grain yield in maize–fallow and maize–velvet bean systems for two fertilizer levels, three soil scenarios (S1, S2, S3) and three locations (A, B, C) climatically characterized in Table 7.4.

As mentioned before, because of the higher infiltration and subsequent higher nitrogen leaching of shallow sandy loam soils on non-sloping topography compared to shallow sandy loam soils on slopes, the effect of slope on maize grain yield is non-significant (< 150 kg ha^{-1}). Although, nitrogen leaching is higher (Table 7.6), the growth of velvet bean on shallow sandy loam soils on non-sloping topography (S1) is higher than on shallow sandy loam soils on slopes (S2). The difference in maize grain yield between these soils increases however remains insignificant over the simulated 12-year period.

As indicated earlier, the current DSSAT suite of models, residues from crop biomass can be retained and litter that senesces during the growing season can be quantified but is thereafter not included in the soil modules. For velvet bean systems the amount of accumulated litter is substantial, however, due to efficient nitrogen reallocation before senescence, only a small amount of nitrogen remains in the litter. In our example environments approximately 10% of the total nitrogen that is biological fixed in the growing season, at most 10 - 25 kg ha^{-1} remains in the litter (Table 7.7). The benefit from velvet bean to maize production in terms of contribution to nitrogen content in the soil is therefore only slightly underestimated in our simulations.

Soil resources in a maize – velvet bean system

Besides benefits to maize grain yield production, there are other benefits from cropping velvet bean in the fallow season. The contribution of biomass – left behind as mulch – to soil organic carbon and soil organic nitrogen is expected to be substantial (Fig. 7.6). In some areas soil organic carbon may increase by up to 2.6% and soil organic nitrogen by up to 4.4% due to cropping velvet bean during a 12-year

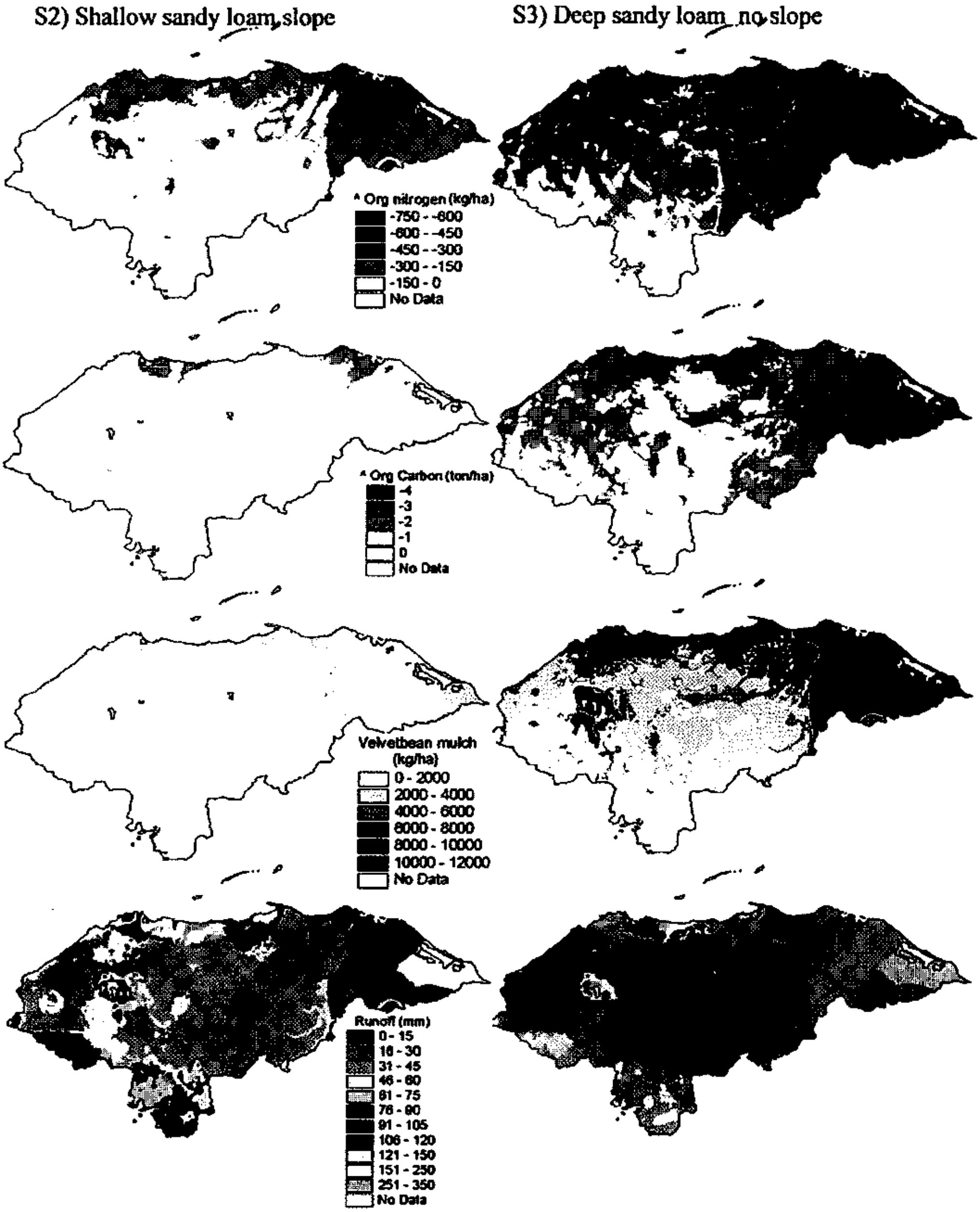

Figure 7.6 Difference in soil organic carbon and nitrogen of maize–fallow compared to maize–velvet bean, velvet bean mulch and soil surface runoff in the maize–fallow system for two soil scenarios (S2, S3), and assuming low nitrogen fertilizer management (N1).

period. The quality of the soil is considerably improved through the increase in these soil characteristics. Litter and biomass production, together available for mulch, prevent weed germination and growth. Cropping velvet bean reduces surface runoff.

Fig. 7.6 shows the amount of annual soil surface runoff in maize–fallow system. By comparing the runoff maps to the production of mulch, an idea can be obtained of how much runoff may be saved. To fully assess the amount of soil surface runoff water that can be saved, it is necessary to simulate mulch effects on infiltration and evapotranspiration (see Chapter 8). However, dry climatic regions can already be identified where soil surface runoff cannot be conserved through maize–velvet bean cropping systems. For these areas, the need for – the design of – alternative soil and water conservation measures such as crop residue retention, vegetative barrier systems need to be explored.

Conclusions

The analysis of responses to water and nitrogen conditions as illustrated for selected soils and locations help understand the mode for introducing velvet bean in maize production systems. Results confirm that the benefit of increased maize production from cropping velvet bean is found in areas where soil conditions and off-season climate conditions enables velvet bean growth and in nitrogen limiting soils with low nitrogen fertilization management. Nitrogen availability is less important to velvet bean growth as it is able to fix nitrogen from the air. Increased nitrogen fertilization is beneficial to maize production *per se*, but decreases benefits from biological nitrogen fixation from velvet bean. Under the favourable conditions for velvet bean cropping to maize production for selected soils and locations, an increase in grain yield of the succeeding maize crop of up to 2 ton ha^{-1} was observed. The contribution of velvet bean in terms of nitrogen is slightly underestimated, as litter that senesces during the growing season is not yet included in the current simulation application. A capacity to integrate a litter layer is desirable for future applications in order to fully assess the value of the green manure cover crop, including increased water availability because of increased infiltration and decreased evapotranspiration from these systems. Increases in soil organic carbon and nitrogen from cropping velvet bean were substantial as evaluated over the 12-year simulation period.

The analyses of results on the basis of aggregated climate characteristics at selected locations and for selected soils are restricted to their illustrative use. Quantification of water and nitrogen processes on the basis of daily weather events in interaction with prevailing soil conditions and crop management is achieved through dynamic simulation modelling. Regional application of these models can facilitate further assessment of the extent of the responses to such interactions at the regional scale. In this chapter we described a methodology that enables a regional assessment of maize–velvet bean cropping in terms of production and resource dimensions over a wide range of soil scenarios and climatic conditions of Honduras. More insight is obtained in the regional potential for and the conditions under which successful introduction of velvet bean may be achieved.

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8.

REGIONAL APPLICATION OF CROPPING SYSTEMS SIMULATION MODELS: II. CROP RESIDUE RETENTION IN MAIZE PRODUCTION SYSTEMS OF JALISCO, MEXICO

Abstract

To ensure the productivity of smallholder maize production systems in Central America increased attention must be paid to conserving soil and water resources. Various stakeholders from NARS, networks, NGOs and research institutes seek to develop and target productivity enhancing resource conserving management practices such as crop residue retention systems. To support this process a methodology with explicit spatial and temporal dimensions was developed and applied to the case study of residue retention in maize production systems of Jalisco, Mexico. Systems where crop residues were partially or totally retained were compared to systems with no residue retention. Variables considered included crop production, soil surface runoff water, soil organic carbon and soil organic nitrogen content. Gridded climate surfaces and a wide range of soil profile scenarios formed the basis of the regional input. Expert knowledge on present agronomic management was synthesized to yield three nitrogen application practices. Simulation models for maize and fallow were run in sequence for 12 consecutive years. Results demonstrate that nitrogen management practice affected benefits much less than soil water holding capacity and topography. Benefits to maize production from residue retention were found mainly in areas mainly in the Northeast of the study region, where precipitation limits maize production. Benefits of soil surface runoff reduction from residue retention were most evident in high rainfall areas in the central east of the study area. Although the effect of soil loss is not accounted for in crop simulation models, these latter areas of pronounced soil surface runoff reduction are hypothesized to be areas of productivity gain in the longer term. The assessment provided more insight in the regional potential for and the soil and climate conditions under which successful introduction of residue retention in maize cropping systems in Jalisco may be achieved.

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Introduction

The state of Jalisco is located in west-central Mexico (Fig. 8.1). The main cropping season is from May-June to November. Agriculture is predominantly rainfed, with annual rainfall ranging from 400 to over 1500 mm. Maize occupies at least 60% of agricultural land. Jalisco is also the country's largest producer of maize, accounting for 15% of Mexico's total production (INEGI, 1994; SAGAR, 1997, 2000). Average maize grain yield is 1.8 ton ha^{-1} (INEGI, 1994), but variability in annual rainfall and rainfall distribution result in variation in yields. The main alternative crops in the region are sugarcane, in wet riverbed areas, and sorghum, in the drier areas (INEGI, 1994). Demand for maize continues to increase in Mexico and maize imports were at least 5 million tons in 1999 (SAGAR, 2000). Options are sought to improve the production of maize in Jalisco state, acknowledging the need for a more efficient use of soil and water resources. Major natural resource management problems related to agricultural production are soil erosion and contamination of soil, water and aquifers (INIFAP, 1996).

The introduction of conservation tillage with crop residue retention (CTCRR) into maize production systems in the region has been proposed to increase moisture use efficiency and productivity and to prevent soil erosion (Lal, 1989; Scopel, 1994). The CTCRR practice is broadly defined as 'any tillage or planting system that leaves 30% or more of the soil surface covered with residues at planting time' (CTIC, 1994). Collaborative on-station and on-farm projects between NARS, international research

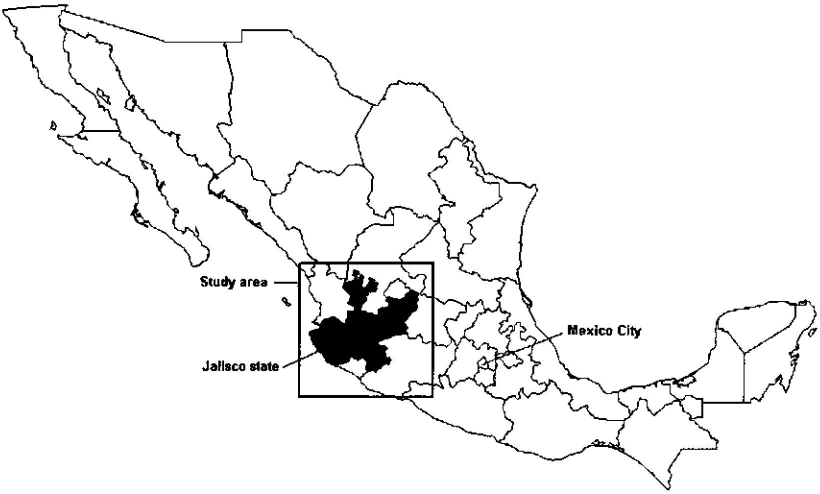

Figure 8.1 The state of Jalisco in Mexico and the case study area.

institutes, development cooperation institutes and NARS have established experimental evidence for benefits of conservation tillage with crop residue retention (Scopel, 1994, 1995; Arreola-Tostada, 2000). Maize grain yields were doubled at low rainfall sites of La Tinaja (19.62° N; 103.82° W) and La Croix (19.72° N, 103.87° W), even when only small amounts of crop residues (1.5 ton ha^{-1}) were retained, providing only 25% of soil surface cover at the start of the maize-growing cycle (Scopel et al., 1998). Soil surface runoff water losses at these sites can be diminished by 50%, run off of soil particles by up to 80%, while over the total crop cycle the amount of available water can be increased up to 40% (Scopel and Chavez, 1997; Scopel et al., 1999).

However, such experimental successes are site specific, and analysis of residue retention system dynamics over the entire area has been difficult. Within an area of 20 km^2, the variability in precipitation and soils is such that benefits from CTCRR can vary from nil to over a 100% yield increase (Scopel, 1997). Regional and national agricultural development programs aim to extrapolate promising practices from experimental sites to larger target regions. Primarily, it is necessary to evaluate *where* these target regions are located because it can prioritize areas for socio-economic adaptation research and technology transfer, reduce inappropriate introduction, and ultimately identify gaps in the underlying knowledge, experimental data and theoretical concepts.

Formal methodologies for scaling-up from site- and term-specific research experiences are scarce and seldom robust. This is largely caused by the inability to explicitly account for the spatial and temporal variability of climate and soil conditions in interaction with crop characteristics and agronomic management strategies. For the Jalisco case of CTCRR, the biophysical potential has until now, been evaluated for only two rainfall regions (see Scopel, 1994; Erenstein, 1999; Jourdain et al., 2000). Process-based modelling can integrate complex interactions of climate, soil, crop characteristics and management practices. The process of running simulation models for many environmental combinations or sites can be facilitated through use of Geographical Information Systems (GIS).

The principal objective of the present study was to assess residue retention in maize cropping systems across the state of Jalisco. The assessment focused on maize production and soil and water resource dimensions of the residue retention systems. A methodology was developed to explicitly account for the spatial and temporal variability in climate and soil conditions in interaction with crop characteristics and agronomic management strategies. To increase the understanding of variation in regional results, we first analyse the response to residue retention for a selection of locations and soil scenarios.

Material and methods

In this case study, the same system simulation methodology based on the DSSAT suite of models (Tsuji et al., 1994) was used as described in Chapter 7. Maize–fallow systems over multiple seasons were simulated through a sequence driver that linked CERES (v 3.5) and CROPGRO (v 3.5) models (see Thornton et al., 1995). In this paper, modified versions of these models were used to allow for dynamic simulation of crop residue retention via an additional surface mulch layer. In this study, crop residues are defined as the total aboveground maize biomass (excluding maize grain yield) that is available at the end of the maize cropping season.

Simulation of the mulch layer for residue retention

Residue retention and tillage/no-till options were incorporated into the CERES (v 3.5) and CROPGRO (v 3.5) models by Grace et al. (2000). The original structure of residue decomposition and data requirements were not changed. A separate surface residue or 'mulch' layer was added to the soil module. This mulch layer affects the soil water balance through altered soil surface evaporation and infiltration (following Dadoun, 1993). Decomposition of surface residue is regulated by its water content and air temperature, after which partitioning of carbon and nitrogen into the topsoil is regulated. The model was calibrated using data from Stott et al. (1990) and data from an 8-year no-tillage-residue-retention trial in Mexico (unpublished data). The model was subsequently evaluated with independent trial data from a long-term trial in Michigan (see Grace et al., 2000).

Climate input and soil input

Gridded climate surfaces of 1 km^2 were created from daily long-term meteorological station data, covering the study area of 600 by 600 km^2 (Chapter 3; Boer et al., 2001). Simulation was repeated for the entire region for a wide range of 'soil scenarios' (see Chapter 7; Table 7.2).

Agronomic input

Using expert knowledge and literature sources (o.a. Scopel, 1997; Arreola, 2000; Jourdain et al., 2001; INIFAP pers. communication), information on maize cropping systems and agronomic management information (plant densities, dates, residue and fertilizer amounts) was compiled. In this study, four levels of crop residue retention were evaluated for a single nitrogen input level, while the response to three nitrogen management levels was assessed for two levels of residue retention (Table 8.1).

Output management

The importation and basic statistical processing (calculation of the minimum, maximum, mean, and standard deviation of each output variable) of simulation output files into the GIS database file format was partially automated using software

Table 8.1 Agronomic management practices for maize–fallow used as input to the simulation models.

Planting window growing season	June 1 - July 10
Planting density at emergence	4.0 plants m^{-2}
Planting depth	5.0 cm
Row spacing	0.75 m
Residue retention levels	0%, 33%, 66%, 100% of end-season maize biomass
Nitrogen management level	N0 = 0 kg ha^{-1} (no nitrogen)
	N1 = 50 kg ha^{-1} at planting; 100 kg ha^{-1} 35 days after planting
	N2 = 85 kg ha^{-1} at planting; 160 kg ha^{-1} 35 days after planting

developed by Collis and Corbett (1997). For each cropping system and soil scenario, output files containing cropping system attribute variables were created to allow mapping and analysis in the GIS. The attribute variables for analysis were identical to those available in output files created by the sequence module (see Thornton et al., 1995).

Presentation of results and analyses

Presentation and analysis of results focused on production and soil and water resources expressed in performance variables: maize grain yield, maize biomass production (excluding grain yield), soil surface runoff water, soil organic carbon and soil nitrogen contents. The presentation and analysis of the vast variation in results was structured around understanding water and nitrogen processes that determine system response to soil depth, water holding capacity, soil nitrogen availability and nitrogen fertilizer application and topography. The water processes encompass infiltration, drainage, soil surface runoff and evapotranspiration. The nitrogen processes are related to nitrogen supply (initial soil nitrogen content and fertilizer application), crop nitrogen uptake, leaching and immobilization of nitrogen. Since qualitative spatial trends were similar over the fifteen soil profiles, spatial results are illustrated for a selection of soil scenarios in this paper.

We first illustrate response to different levels of residue retention at individual site locations varying in precipitation. Subsequently we focus on the difference between systems *without* residue retention ('control') and systems *with* residue retention as described by delta variables:

$\Delta X = X_{\text{no residue}} - X_{\text{residue retention}}$, where X represents a single performance variable.

Benefits of residue retention are reflected by:

- *negative values for* ΔX in the case of maize grain yield, biomass, soil organic carbon and soil organic nitrogen.
- *positive values for* ΔX in the case of soil surface runoff and yield variation.

Using a student *t*-test significance levels for ΔX were determined using SAS (SAS Institute, 1997). These figures facilitate the interpretation as to where production enhancement and resource conservation is expected through residue retention systems. Maps were made of the variables to present regional patterns in production and resource benefits and formed the basis for workshops with regional stakeholders (see Chapter 9). To explore the association of variables with general seasonal climate variables, multivariate and univariate analyses were executed.

Results and discussion

Different levels of residue retention

The effect of retention of different levels of end-season biomass as residue – 0%, 33%, 67% and 100% – on soil surface runoff during the maize-growing season and the fallow season is illustrated for the medium fertilizer management level (N1) for three soils (S1, S2, S3) at four locations (A, B, C, D) in Fig. 8.2. Annual, growing season and off-season climate characteristics of the selected locations are shown in Table 8.2. More residue retention leads to a lower soil surface runoff, especially on shallow soils on sloping topography and in areas of high rainfall. In areas of high rainfall not only more water can be saved but also the production of biomass that may be retained as residue is higher (over 10 ton ha^{-1} at sites A, B, C). At site A up to 275 mm and up to 15 mm soil surface runoff is saved due to residue retention during the maize-growing season and fallow season respectively. At sites of low rainfall the amount of residue that can be retained is small, however the amount of soil surface runoff in low rainfall environments is also small. For over 80% of all of the environments in the semi arid region of Jalisco, soil surface runoff reduction during the growing season was higher than during the fallow season (data not shown). Compared to 100% residue retention, retaining 33% end-season biomass as residue may reduce soil surface runoff generally by 50% (Fig. 8.3).

Table 8.2 Aggregated climate characteristics of four selected locations.

	Annual		Growing season[1]				Fallow season	
Location	Precip. mm	Tmean °C	Precip. mm	Tmean °C	Tmax °C	Tmin °C	Precip. mm	Tmean °C
A	1458	19.2	1331	21.1	24.9	17.2	127	17.9
B	1317	20.1	1126	21.1	25.8	16.5	191	19.4
C	897	20.2	784	21.4	27.3	15.4	113	19.3
D	440	19.9	345	21.4	26.3	16.4	95	18.8

[1] Growing season climate data encompass 5 months.
Precip= pecipitation; Tmean=mean temperature;
Tmax=maximum temperature; Tmin=minimum temperature.

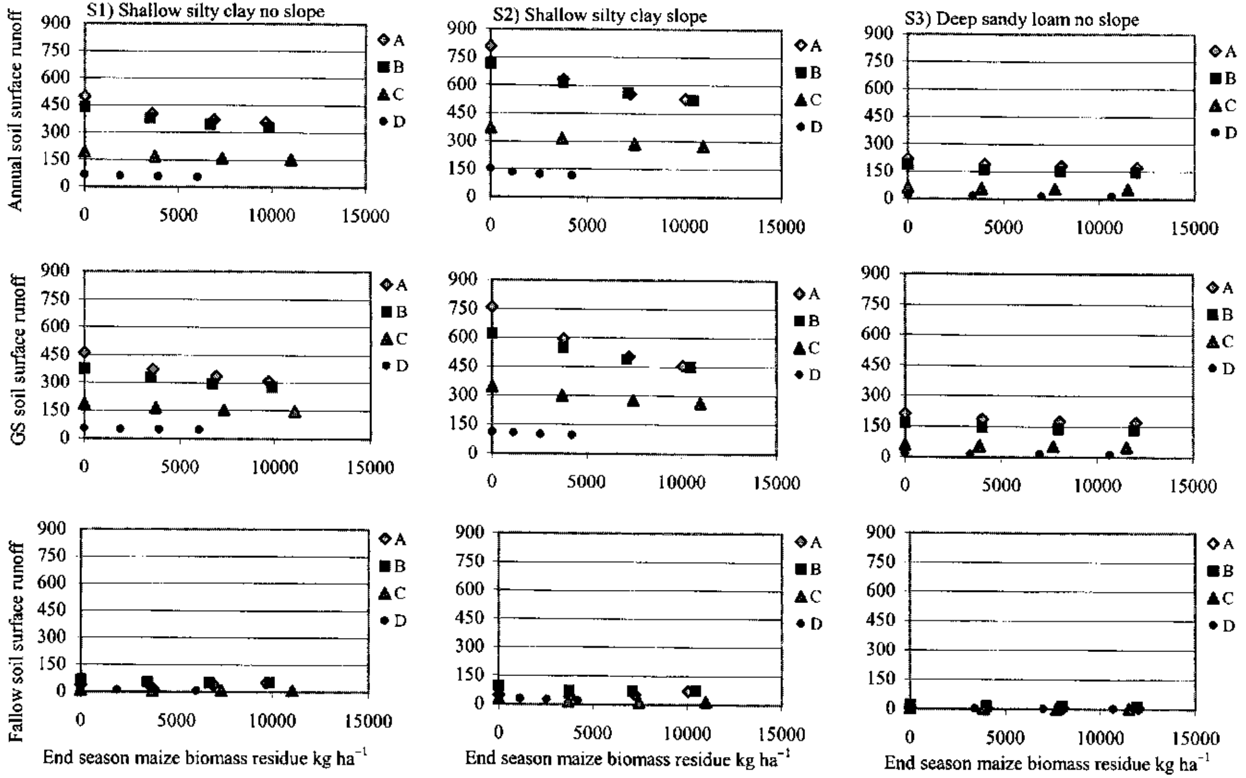

Figure 8.2 Amount of annual, growing season (GS) and fallow soil surface runoff at different levels of residue retention for medium fertilizer level for three soil scenarios (S1, S2, S3) at four sites (A, B, C, D).

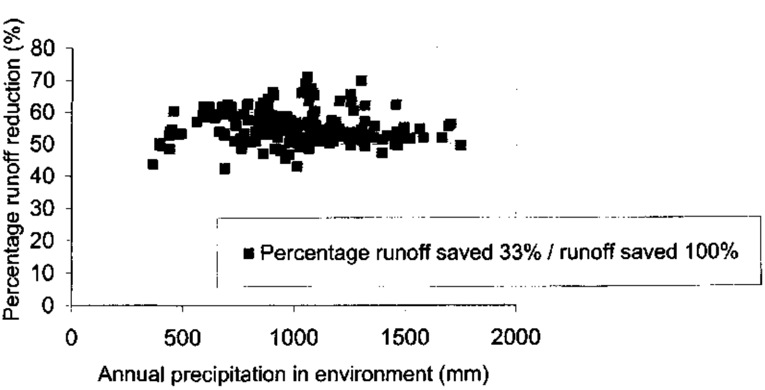

Figure 8.3 Percentage of soil surface runoff saved by retention of 33% residues compared to soil surface runoff saved by retention of 100% residues for the medium nitrogen management for a shallow silty clay soil on slope (S2) across annual precipitation of environments in Jalisco.

Besides reduction in soil surface runoff, residue retention saves water by reducing soil evaporation. This effect is most pronounced during the fallow season in environments of high rainfall and high temperatures and can result in a reduction in soil evaporation of up to 50 mm (data not shown).

Depending on the amount of available soil nitrogen and temperature, end-season maize biomass retained as residue may (temporarily) immobilize nitrogen. At the beginning of the fallow season this potential nitrogen immobilization may amount to up to 30 kg ha^{-1} (data not shown). As the fallow season progresses, crop residues decompose, nitrogen mineralizes and immobilized nitrogen gradually becomes available for crop uptake again.

The effect of different levels of residue retention on maize grain yield throughout Jalisco is presented for the two contrasting soils (S2, S3) in Fig. 8.4. Compared to no residue retention, 33% residue retention results in considerable yield benefits, while the effect of further increasing residue retention to 66% and 100% levels on yield is much smaller. The North and Northeast of the study area benefit most from residue retention on shallow silty clay soils (S2). The maps demonstrate that the effect of residue retention on yield is higher on these soils of low water holding capacity (S2). The remainder of this paper focuses on understanding differences between systems without and systems with 100% residue for all three nitrogen management levels in Jalisco.

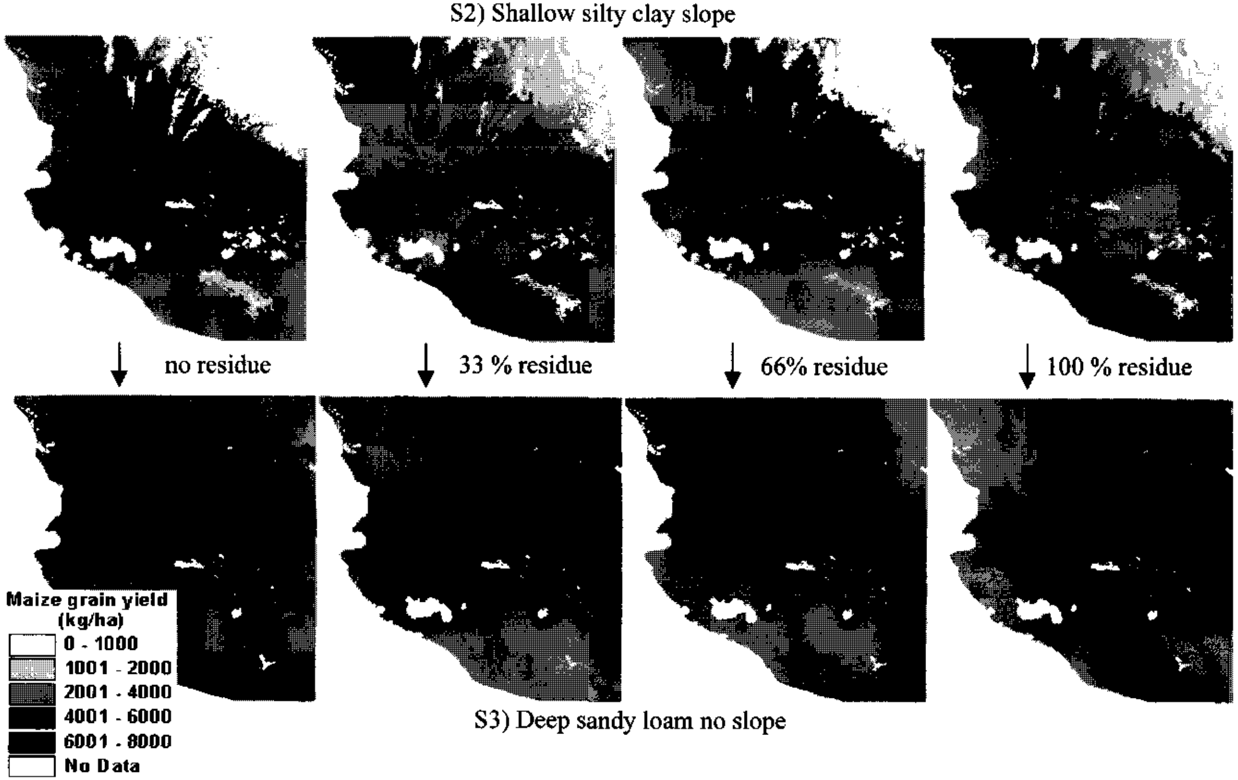

Figure 8.4 Simulated effect of different levels of residue retention on maize grain yield for two soil scenarios (S2, S3) and assuming medium farmer nitrogen management practice (150 kg ha^{-1}).

Difference between no residue retention and 100% residue retention

Table 8.3 summarizes least significant differences for delta performance variables derived from the student *t*-test (Appendix 8.1). The difference in soil surface runoff due to residue retention increases with rainfall, however soil water holding capacity and topography are important determinants (Fig. 8.5). Soil water holding capacity and topography have a greater effect on the pattern of benefit from residue retention than nitrogen management level. Largest benefits of soil surface runoff reduction are to be expected in high rainfall areas, on soils with low water holding capacity on sloping topography (S2). Deep sandy loam soils (S3) have higher water holding capacity, infiltration and drainage than shallow silty clay soils (S1, S2). Soil surface runoff is low in deep soils, even without residues. Moreover with higher production levels in deep soils, crop water use is higher. Deep sandy loam soils are therefore generally drier and less liable to fill up, the occurrence of runoff is smaller and the benefit of runoff reduction due to residue retention remains small (less than 50 mm year^{-1}). Shallow soils show higher benefits of soil surface runoff reduction of up to 150 mm year^{-1} on non-sloping topography (S1) and on sloping topography of up to 330 mm year^{-1}. In locations with similar annual precipitation totals, the expected soil surface runoff reduction may be different as a result of differences in rainfall distribution or differences in temperatures affecting biomass production available for residues.

Nitrogen fertilization does not change the pattern of soil surface runoff reduction over the annual precipitation range of environments. Under the conditions of low nitrogen availability of shallow silty clay soils on slopes (S2), soil surface runoff reduction by residue retention is slightly higher in systems of no nitrogen fertilization than in systems with nitrogen fertilization. The uptake of water by the non-fertilized crop is smaller than the uptake of water by the well-fertilized crop. Hence the soil profile remains wetter and fills up more quickly, resulting in a higher potential for it to runoff. The potential amount of soil surface runoff that can be saved by residue retention is therefore higher at the lower nitrogen management level. However, in the low nitrogen fertilization level the production of biomass that is available as residue is

Table 8.3 Least significant difference values (P > 0.95) for variables for three soil scenarios.

	Δ Maize		Δ	Δ Organic	
Variable	Grain yield	Biomass	Runoff	Carbon	Nitrogen
Soil scenario	kg ha^{-1}	kg ha^{-1}	mm	ton ha^{-1}	kg ha^{-1}
S1) Shallow silty clay on no slope[1]	225	200	All	All	All
S2) Shallow silty clay on slope	300	300	All	All	All
S3) Deep sandy loam on no slope	150	100	All	All	–15

[1] No maps presented in this paper for this soil scenario.

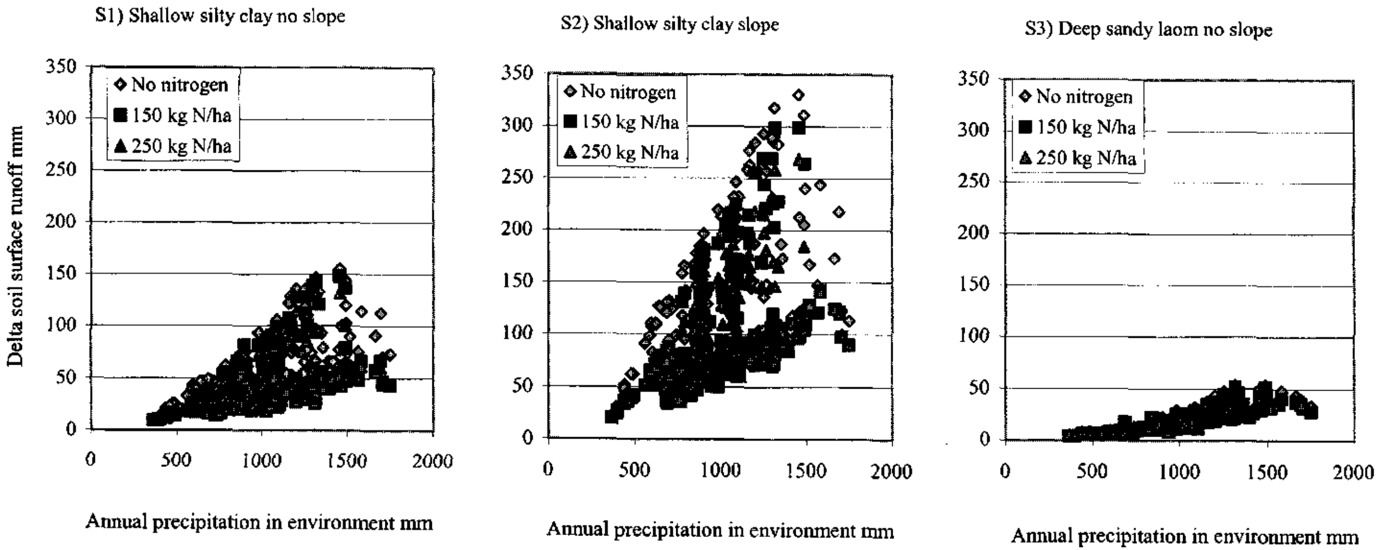

Figure 8.5 Relation between delta soil surface runoff (no residue retention-100% residue retention) and annual precipitation in environments for three soil scenarios (S1, S2, S3) and three nitrogen management levels.

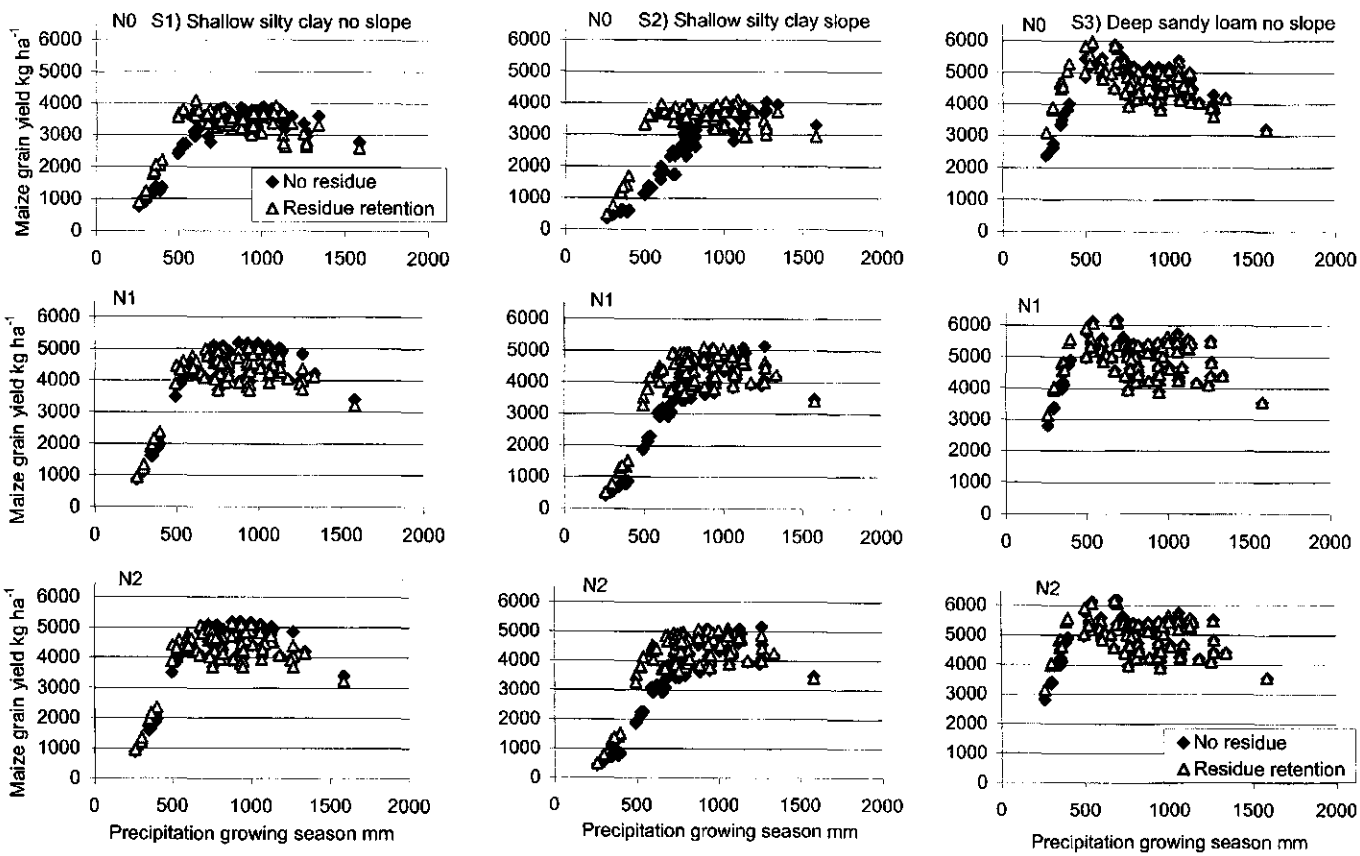

Figure 8.6 Average maize grain yield for a range of precipitation environments (mean temperature 21 °C< x < 25 °C) for three soil scenarios (S1, S2, S3) and three nitrogen management levels (N0=0; N1=150; N2=250 kg ha^{-1}).

lower. This lower amount of residue is less apt to reduce soil surface runoff than the higher amount of residue in the more fertilized management level in the same rainfall environment. Overall the amount of soil surface runoff reduction is similar for the different nitrogen management levels.

The effect of residue retention on average maize grain yield is illustrated for environments with mean temperatures between 21 °C and 25 °C, a temperature range to which the selected cultivar is adapted (Fig. 8.6). Because we use aggregated rainfall totals within a temperature range, absolute yield levels will still vary and in a few cases seem contra intuitive (e.g. data point at > 1500 mm). The focus of Fig 8.6 is on differences in yield level between systems without and systems with residue retention.

The amount of nitrogen in the medium nitrogen fertilizer practice (N1) is beneficial to maize production compared to the no nitrogen fertilizer practice, but in most cases there was not much gain in adding more nitrogen (N2), which confirms agronomic findings by Jourdain et al. (2001). Benefits of residue retention to maize grain yield are to be expected in areas where maize production is limited by water availability and where the contribution of residues to soil surface runoff reduction is high. The precipitation amount at which maize production is limited by water availability differs per soil because of soil water holding capacity (texture and depth) and topography. Residue retention favours maize grain yield in shallow silty clay soils on non-sloping topography (S1) in environments with precipitation totals in the growing season of below 650 mm, in shallow silty clay soils on slopes (S2) in environments with precipitation totals in the growing season of below 850 mm and in deep sandy loams on non-sloping topography (S3) in environments with precipitation totals in the growing season of below 500 mm. The amount of precipitation in the growing season under which systems with residue retention are limited by water availability can be estimated at 550 mm, 500 and 450 for soils S1, S2 and S3, respectively, which confirms that the contribution of residue retention to increased water availability through soil surface runoff reduction approximates 150, 250 and 50 mm.

In Fig. 8.7, the difference in maize grain yield between systems without residue retention and systems with residue retention is shown for all temperature classes. Maize grain yield is increased with more than 2 ton ha^{-1} in shallow silty clay soils on sloping topography (S2). In deep sandy loam soils on non-sloping topography the benefit of maize grain yield is almost 2 ton ha^{-1} in the zero nitrogen management level and amounts to 1 ton ha^{-1} in the nitrogen management levels N1 and N2.

Maize grain yield losses due to residue retention are hardly significant for deep soils (S3). In shallow soils on sloping topography (S2), maize grain yield losses due to residue retention are found in cold wet environments (precipitation > 1000 mm, mean

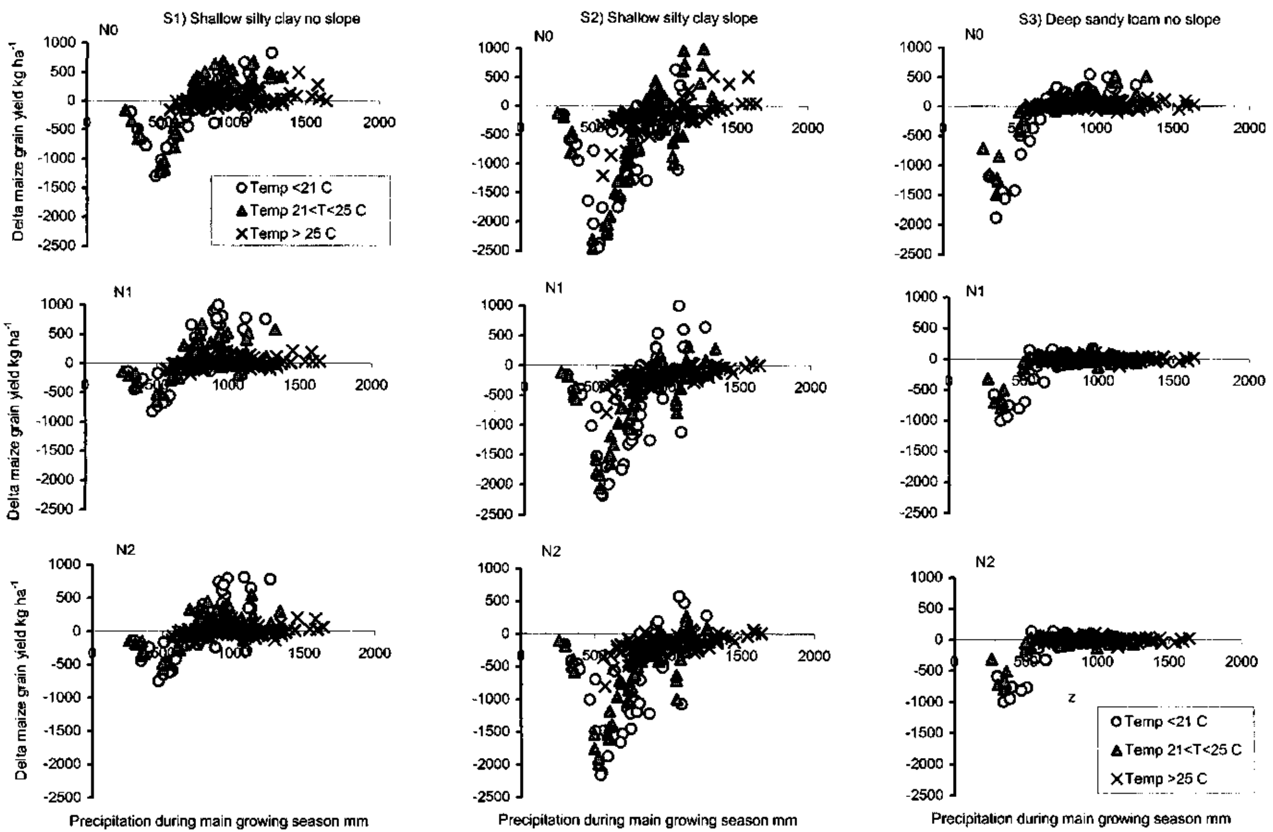

Figure 8.7 Relation between delta maize grain yield (no res. retention - 100% res. retention), three mean temperature classes and precipitation for three soil scenarios (S1, S2, S3) and three nitrogen management levels (N0=0 ; N1=150; N2=250 kg ha^{-1}).

temperatures < 21 °C during the growing season). Maize grain yield loss due to residue retention may amount to 1 ton ha^{-1} in the medium nitrogen fertilizer level (N1) and is caused by two processes. Increased infiltration leads to increased leaching of nitrogen, making it unavailable for crop uptake. Moreover, increased amounts of residue immobilize nitrogen and low temperatures slow residue decomposition and mineralization of nitrogen from the residues. The lower nitrogen availability in systems of residue retention under these soil and climate conditions limit maize production. In the higher nitrogen fertilizer management level (N2) this effect is much smaller, as more nitrogen is available.

Regional patterns: Interconnectivity of productivity and resource conservation

In Fig. 8.8, regional effects of residue retention are presented for two soil scenarios (S2, S3) and the three nitrogen management levels. As concluded from Fig. 8.5, soil water holding capacity and slope appear to have a greater effect on the pattern of benefit from residue retention than nitrogen management level. Benefits of residue retention are more pronounced for shallow soils, especially in low nitrogen management systems (N0). Following regional patterns of water availability, production increases due to residue retention are expected in the Northeast of the study area, while benefits of soil surface runoff reduction are found in central east of the study area. In shallow silty clay soils on sloping topography benefits to maize biomass and grain yield production are substantial, resulting in increases of over 2 ton ha^{-1}. As observed in Fig 8.7, maize production losses in shallow soils on sloping topography of up to 1 ton ha^{-1} are expected in cold and wet environments of Jalisco. As discussed earlier, these are areas where soil surface runoff reduction is high leading to higher nitrogen leaching, and where decomposition of residues is slow, leading to slow nitrogen mineralization from residues and initial net immobilization of nitrogen. This response is to be expected only in small areas in our case study, such as areas to the south, surrounding the volcano of Colima. For deep sandy loam soils the difference in maize production is less than 0.5 ton ha^{-1} in most areas and generally not significant. The benefit from residue retention on deep soils is sought in increases in soil organic carbon and generally reflects a higher production of biomass. Soil organic nitrogen content decreases with increasing crop residue retention. Especially for the zero nitrogen management level, soil organic nitrogen is higher in systems without residue retention. This occurs under cool temperatures in the Northwest areas of the Sierra Madre Occidental and in areas of high soil surface runoff reduction in central Jalisco.

Regional trade-off

The regional pattern of benefits from soil surface runoff reduction differ most from other production and resource benefits. Benefits of runoff reduction from residue retention are highest in soils of low water holding capacity on sloping topography and

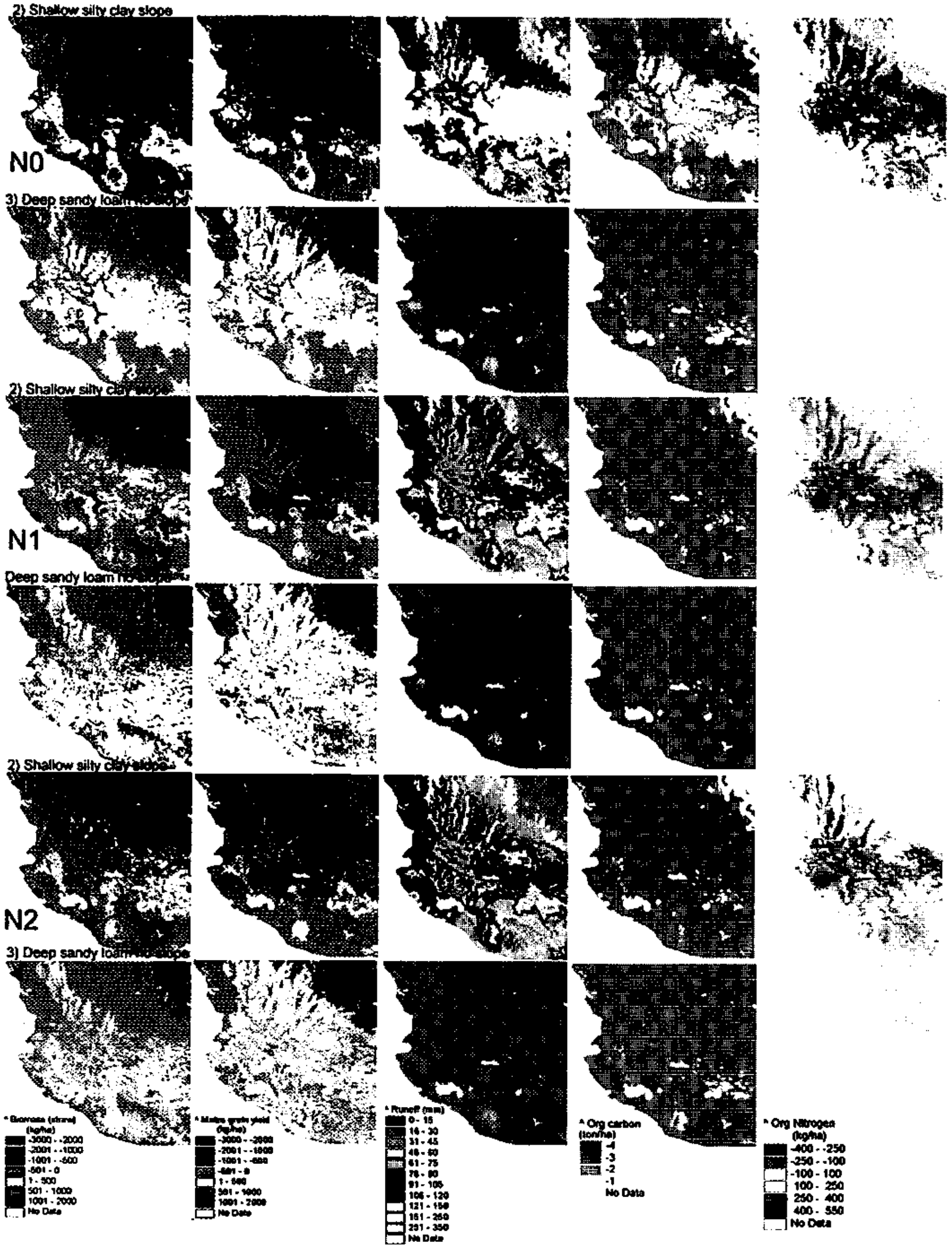

Figure 8.8 Delta variables (no residue retention – 100% residue retention) for two soil scenarios (S1, S2) and three nitrogen management levels: 0, 150, and 250 kg ha^{-1}.

in high rainfall areas, while benefits of maize production are obtained in areas of low rainfall. Higher nitrogen availability – in areas of sufficient water – leads to better maize production and more residues available for retention, which in turn enables more runoff water to be saved. However, at the same time, higher water infiltration results in higher nitrogen leaching and more residues results in higher immobilization of nitrogen. The interaction between these water and nitrogen processes leads to a trade-off in runoff and production benefit from residue retention. In Fig. 8.9, this trade-off between maize grain yield and soil surface runoff is illustrated for the selected soils and nitrogen management scenarios. Results show that soil surface runoff water may be reduced with residue retention without any significant effect on maize grain yield. Alternatively, yield benefits in deep sandy loams on non-sloping topography are expected in areas where the reduction in soil surface runoff reduction in small. With increasing nitrogen, the systems without residue retention and with residue retention become less different. The difference between nitrogen fertilizer management levels N1 and N2 is small. When no nitrogen is applied (N0) there is more variation in response to residue retention as interaction between water and nitrogen availability is strong.

The limitation to our approach is that only on-site effects of residue retention are considered. Off-site effects due to runoff and soil losses could not be considered. A longer-term productivity loss due to soil surface runoff and soil loss is not incorporated in crop simulation models. As a rule of thumb, for our study region 45 mm soil surface runoff water approximates a runoff soil loss of 1 ton ha^{-1} on an annual basis (Scopel and Chavez, 1997). This amount of annual soil loss would eventually also affect maize production. Therefore areas with substantial potential soil surface runoff reduction deserve attention.

To explore the association of benefits from residue retention with general seasonal climate variables, statistical analyses were executed. Multivariate canonical correlation analysis, multivariate and univariate regression analysis of production and resource variables with general climate variables did yield significant influence of these factors in determining benefits, but results were difficult to interpret, as R^2 remained low even when squared and polynomial components of climate variables were included (Appendices 8.2 and 8.3). Runoff did show a high R^2 with rainfall amount and number of rainy days. Therefore benefits of soil surface runoff reduction can be predicted more easily with general aggregated climate variables than effects on production or soil organic carbon and nitrogen content.

Conclusions

The analysis of responses to water and nitrogen conditions as illustrated for selected soils and locations help understand the relative importance of underlying processes

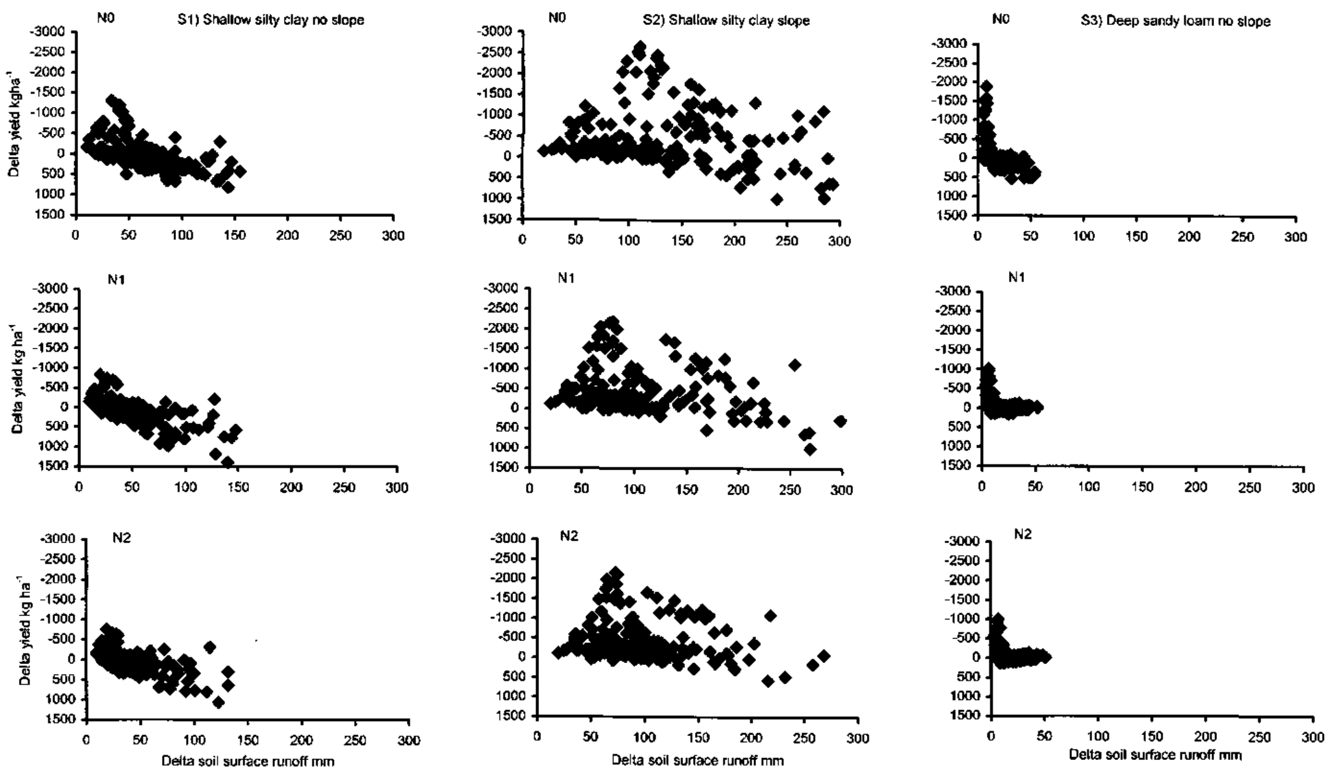

Figure 8.9 Trade-off between delta maize grain yield and delta runoff (no res. retention – 100% res. retention) for three soil scenarios (S1, S2, S3) and three nitrogen management levels (N0=0; N1=150; N2=250 kg ha^{-1}).

and subsequently the mode for the introduction of the residue retention practice in maize production systems. As was illustrated at selected locations and soil scenarios a substantial benefit is already obtained with 33% residue retention, while the 66% and 100% residue retention levels did not further increase yield substantially. It is also confirmed by results from experiments in the region (Scopel, 1995; Scopel and Chavez, 1997). Considering the need for soil organic nitrogen for decomposition of carbon in the soil surface mulch layer, levels of 33% residue retention are to be preferred in most areas. Regions where full residue retention did still increase yield have been identified in this study.

Nitrogen management practice affected benefits from residue retention less than soil water holding capacity and topography. Benefits to maize production from residue retention are larger on soils of low water holding capacity and sloping topography than on soils of high water holding capacity on flat lands, and are to be expected in areas where precipitation limits maize production. These are different areas to those where maximum benefit of soil surface runoff reduction and longer-term soil conservation and productivity benefits are to be expected. For the range of soils considered in this study, there were only small areas within Jalisco where residue retention was disadvantageous to maize production. These areas are characterized as cold wet environments where soil surface runoff reduction is high, causing high nitrogen leaching and nitrogen immobilization.

The analyses on the basis of aggregated climate characteristics are restricted to a few sites, the general process level and the use of average climatic data over seasons. Further statistical analyses did not help identify straightforward indicators for estimating regions of benefits, which justifies the need for a dynamic approach to assessment of residue retention systems. Quantification of water and nitrogen processes on the basis of daily weather events in interaction with prevailing soil conditions and crop management is achieved through dynamic simulation modelling. Regional application of these models can facilitate assessment of the geographical extent of the responses to such interactions at the regional scale. In this paper we described a methodology that enables regional assessment of residue retention systems in terms of production and resource dimensions over a wide range of soil scenarios and climatic conditions. More insight is obtained in the regional potential for production enhancement and resource conservation and the conditions under which successful implementation of the residue retention practice may be achieved.

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9.
INTERACTION WITH REGIONAL STAKEHOLDERS

In this thesis stakeholders were consulted for the selection of practices and assembly of agronomic management information necessary for application of the methodology. Additionally, regional stakeholders participated in workshops to discuss and evaluate the results of the case study applications and the methodology per se. *Although interaction with stakeholders was not the focus of the thesis, this chapter briefly describes the approach and results of the interaction in the workshops.*

Approach

Regional stakeholders from national and international agricultural R&D institutes and extension services (IICA, CIAT, INIFAP, CIRAD, CENAPROS) and NGO's (CIDICCO, Rockefeller Foundation, World Neighbors) took part in formal workshops that were held for the Jalisco case study in Guadalajara in July 2000 and for the Honduras case study in Tegucigalpa, August 2000.

After a brief description of the methodology used, regional results were first discussed and evaluated using poster materials. These materials presented results of the case studies in production (maize grain yield, biomass, velvet bean biomass litter production, light interception etc.) as well as soil-water dimensions (soil surface runoff, soil organic carbon, soil organic nitrogen).

Computer based sessions were carried out under the framework of the Almanac Characterization Tool (ACT; Corbett et al., 1999). Results of other methodologies for guiding crop (management) introduction, or targeting, such as agro ecological zones, crop requirement mapping and site similarity analysis can be organized under this same framework. The ACT framework also permits examining other sources of spatial data (e.g., administrative units, demography, and topography).

For both case study regions, national approaches to agro-ecological zones were available and included under the ACT framework. Maize adaptation mapping, velvet bean requirement mapping and site similarity studies of known experimental stations were also added[1]. For Jalisco, a detailed spatial study on the effects of residue retention on the water balance and production potential was included (Arreola, 2000).

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[1] For description of site similarity studies see Hodson et al., 1998.

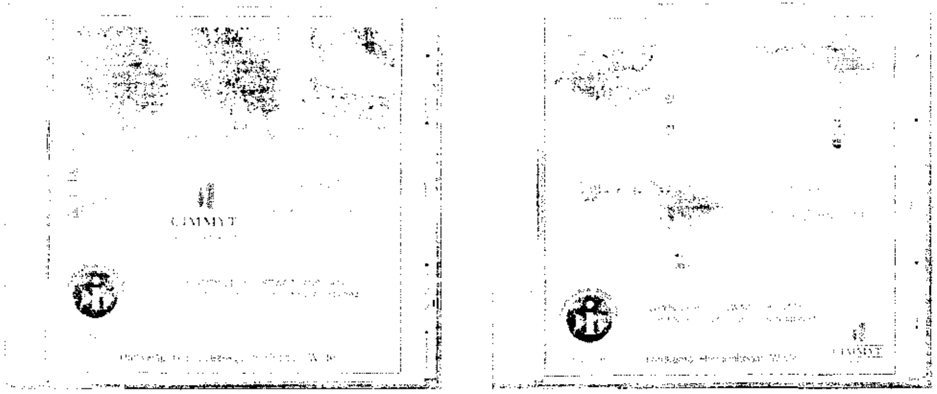

Figure 9.1 CD-ROM material provided data and results of various other methodologies under a GIS database framework of the Almanac Characterization Tool (Corbett et al., 1999).

After a demo session on how to work with the ACT tool, the results of various methodologies were presented and discussed. CD-ROM media containing the data and results of the various methodologies for both case study regions were provided to stakeholders (Fig. 9.1).

To evaluate the various methodologies with stakeholders, the card method (GTZ, 1991; Lewis, 1998) was used from which a 'matrix of evaluation' was created.

Results: Evaluation of case studies

Overall, the regional distribution of production potential for these maize-cropping systems matched expert knowledge. For high altitude areas in Honduras, discrepancies were noted that were thought to reflect the use of a single variety of maize in the simulations. In the case of velvet bean, this applies to a much lesser extent because there is currently a limited phenological diversity among available cultivars.

In the case of Jalisco, regional differences in production agreed with expert opinion, as well as the results on where it would make sense to introduce residue conservation (dry climate, poor soils in the north east of Jalisco). In wet areas, where substantial amounts of soil surface runoff are reduced, the need for residue retention was recognized, but the main interest was clearly set on obtaining short-term gains in maize production.

Stakeholders from both regions indicated that maize production occurs on even more shallow soils than included in the soil scenarios of the case study (20 to 25 cm

Table 9.1a Evaluation of different methodologies for guiding introduction of crops and management practices (targeting) (Honduras).

Method/Approach	Advantages	Disadvantages
Agro-ecological zoning Carceres (1970) SRN (1999)	Classification in very few areas or categories Usually includes some infra-structural administrative (socio-economic) data	Categories too generic for specific management recommendations No distinction of seasons; no indication of minimum and maximum temperature, rainfall distribution. Usually no use of important crop growth determining factors such as soil depth. Usually regional studies, which are difficult to replicate in other regions
Site similarity and crop requirement mapping and zoning (using Hodson et al., 1998)	Can be applied worldwide, very generic results. Method easy to execute and results are easy to interpret Includes detailed climate parameters (min, max, extreme events) and can include (high resolution) soil data Can include seasonal dimensions	Usually based on monthly climate data, monthly indicators of extreme events can be used (e.g., number of frost days) In site similarity no use of crop data; in crop requirement mapping no distinction between varieties Difficult to account for variation in crop management High risk of obtaining incorrect results because of error in site data (location or climate surface data)
GIS data framework (e.g., CIAT Honduras Atlas) Barona et al., 1999	Visualization of many different data sources; provides a general view Land use data – some management is included Rough estimation of crop potential through meteorological parameters and soil taxonomic potential. The application framework is static, difficult to include new data sources	Depends heavily on data quality, and without high confidence, tends to be ignored by decision makers Maps can easily lead to false interpretation Many data sources that have many different amounts of precision or error. Use and interpretation is difficult for non-GIS skilled people
Crop simulation-GIS interface (in which summary results presented in the ACT framework)	Daily climate and soil data (and interaction between these) directly estimate production potential Is responsive to different crops, varieties, and management practices. Can model different cropping seasons and sequences and evaluate trends over time. Many different output variables from which to evaluate biophysical performance Understanding the specific causes of limited crop production in spatial form. Can be linked with other regional administrative data (census)	Crop models use assumptions that can cause an over-estimation of yield. Difficult to include effects of diseases, pests and soil constraints (e.g., P availability, compaction, micro-nutrients) in models. In this specific case, the crop model should be calibrated better to tropical maize varieties. The method is time consuming and can generate very large sets of data that are difficult to interpret.

Table 9.1b Evaluation of different methodologies for guiding introduction of crops and management practices (targeting) (Jalisco).

Method	Application	Advantages	Disadvantages/limitations
Crop requirement GIS based potential	Identification of zones with production potential of several crops	Quick and flexible Analysis is geographically complete (no areas missing)	Requirement mapping not sufficiently precise (different cultivars within a species)
	Guiding introduction of new crops		Qualitative estimation of potential not quantitative
Gonzalez et al. (1991) Medina et al. (1999) Ruiz et al. (1999)	Priority setting through identification of highest potential	No need for detailed information and can adapt to the variables available	Use of climate normals
	Can direct crop improvement	Can be applied to any crop species Relatively easy Immediate and practical use	Very few variables are accounted for Difficult to parameterize Crop requirement information not always available Socio-economic data can not included and can not be integrated
Crop simulation-GIS interface (results presented in the ACT framework)	Prioritize regions for CTCRR not only in terms of production but of soil and water conservation	Can evaluate for various years and possible explore trends	Requires lots of data and data management
	For medium and longer term assessment	Can evaluate more than production potential, also water and nutrient limiting	The models need to be tested, and validated extensively. New models are costly
	Prioritize areas for new varieties and fertilizer recommendations	Other factors besides production can be assessed, soil status	Stakeholders must trust the model
	Can be used also for erosion and plant nutrition studies	Can be used to evaluate cropping systems over multiple seasons not only one crop	Need detailed and precise information
	Ability to evaluate the spatial importance of a technology or management practice	Information can be extrapolated	Laborious
		The GIS database can be used for various other applications Can be used for several crops and varieties Can be used in areas where there are not weather data Errors in daily climate data can be found	Results are not always easy to interpret

Table 9.1b Continued.

Method	Application	Advantages	Disadvantages/limitations
Water balance - GIS	Promote CTCRR	Model reliable for CTCRR	Very simplified climate approach
CIRAD/INIFAP/ CIMMYT	Short-term information available for process understanding	Model is very precise for the region and for the water resource	The model is based on several empirical relations that cannot be extrapolated
Arreola (2000)		Practical to be applied and relatively simple	Only indirect estimate of total production potential, no estimate of yield
		Evaluate agronomic management practices (densities, etc.)	To date, no estimate of soil loss is provided (only surface runoff)
		Not easy to interpret processes	No estimate of soil organic carbon and nitrogen dynamics
Site similarity study	Locate sites similar to known site	Quick flexible and easy to use by anyone	Not very precise, accurate
	Identify crop niches	Results easy to interpret	At this point only climate similarity, not soils
	Worldwide extrapolation		Agronomic management can not be included
created using Hodson et al. (1998)	Wide range of applications possible		The quality of results vary based on input data of varying resolution Results may be geographically incomplete. Gaps can occur in identifying priority regions.

effective depth instead of 40 cm). However, stakeholders agreed that agriculture on extremely shallow soils (< 25 cm) should not be promoted and therefore should remain outside the conditions or scope of an assessment study as such was the focus of this thesis.

Results: Evaluation methodology

An 'evaluation matrix' was created in which the application possibilities, advantages and disadvantages of the various methodologies were highlighted (Tables 9.1a-b). Concerns identified in the workshops, which apply to all methodologies for exploring regional potential of production options, are data quality control and the need for a stronger linkage of biophysical and socio-economic information (labour and input markets). This linkage is feasible in principle (Bouman et al., 1999), however does not yet take place dynamically at the spatially explicit level of cropping systems. Another aspect that was identified, concerns the integration of information on disease incidence. For the specific case study applications this would relate primarily to ear rot (*Stenocarpella maydis*, *S. macrospora*, and *Fusarium moniloforme*) diseases in summer maize for Honduras (Buckles et al., 1998) and grey leaf spot (*Cercospora zea maydis*) disease in residue retention systems of Jalisco (see Nyvall, 1989; Ward et al., 1997). Velvet bean has few diseases or pests (Duke, 1981), other than the sporadic attack of large leaf cutter ants (*Atta spp.*).

In comparison to other methodologies, stakeholders reported that the methodology described in this thesis showed key strengths in being flexible enough for various applications, sufficiently generic for application in different regions, and capable of showing the various dimensions of agricultural systems that are of interest. Many hypotheses can be tested and questions answered using the same approach and information. Major disadvantages of the methodology in this thesis were identified as being laborious, requiring investment in large data sets and analysis methods. The approach is complex, both in content and software to be used by any single person. The results need careful interpretation for which scientists can function as advisor and mediator. The first set of issues may be resolved by further improving integration of the tools, and automating the analysis procedures. The rapid development of computer processing power will additionally favour the methodology. To tackle the second set of issues, the (simplification of the) presentation and communication of results is an area that can be improved.

Results: Personal observations

Stakeholders valued the visualization of regional patterns in production and resource dimensions depending on climate and soil, and as such the presentation greatly assisted the understanding sources of variation within 'target' regions. By including experimental trial sites in the maps, interaction amongst stakeholders led away from traditional discussions on the individual findings from (well-known, experimental) locations to an increased focus on regional issues. In this manner, interaction between stakeholders was facilitated. It is recognized that more iterative forms of interaction on the assessment of agricultural options is needed. Skills for communication between scientists and stakeholders need to be improved to achieve this successfully.

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10.
DISCUSSION AND RECOMMENDATIONS

The design and redesign of agricultural production systems must focus on the efficient use of resources for production and on the location where production takes place. The feasibility of production options is determined in the first place by climate and soil conditions; subsequent probability of success depends on economic viability and social acceptability. The thesis focused on the biophysical assessment of production options in maize production systems at the regional scale. This biophysical targeting is useful in guiding technology introduction by indicating where, when and why production options are suitable taking into account the climate and soil conditions. Biophysical targeting is important because it can prioritize areas for socio-economic adaptation research investment, reduce inappropriate introduction, identify gaps in the production option and consequently, in the underlying knowledge.

This thesis contributed to methodology development in the area of biophysical targeting. The methodology was based on harnessing the potential of two powerful tools, simulation modelling and GIS. Agricultural production systems are evaluated for both production and soil-water dimensions, explicitly accounting for a spatial and temporal variability in climate in interaction with soil, crop characteristics and agronomic management strategies. The methodology was operationalized through inductive use of two specific types of production options: green manure cover crop and reduced tillage with residue management in maize cropping systems in Central America. Expert knowledge and literature sources on agronomic cropping system and management information were collected for the case study practices. Modelling capacities for velvet bean and crop residue mulch were developed and applied regionally. Insight is gained into the regional potential for and the soil and climate conditions under which successful introduction of these production options may be achieved. The transparency of spatially explicit trade-offs between production and conservation dimensions of agricultural production options was increased. Results from this study can help regional stakeholders, involved in agricultural development, technology dissemination and design, in their analysis and discussion, negotiation and decision-making concerning where to implement production systems.

In this chapter, the major findings from previous chapters are discussed in light of broader implications. Limitations of this study are identified and recommendations for future research are provided.

Insights from the case studies

Green manure cover crop – velvet bean in Honduras

Quantitative information on green manure cover crops is scarce. Often the effect of green manures on the following food or cash crop is measured without determining the biomass of the green manure. In this study, time series samplings led to the development of a velvet bean model. Although extensive reviews of velvet bean exist (Carsky et al., 1998), documentation on and understanding of velvet bean phenology is still limited.

In the application of the methodology to Honduras, clear messages can be formulated on where introduction of velvet bean is appropriate and for what reasons (nitrogen fixation, erosion or weed control), and where introduction should be avoided. For those areas where introduction of velvet bean currently should be avoided, crop improvement for wider adaptation or evaluation of alternative green manure cover crops or soil and water conservation measures is recommended. For higher cool environments, red scarlet bean 'Chinapopo' (*Phaseolus coccineous*) has been proposed (CIDICCO, 1997). In developing suitable green manure cover crops for the area, selection must favor species that have high nitrogen fixing potential but low seed nitrogen concentration to optimally utilize the benefit of biological nitrogen fixation (see Yinbo, 1999). In dry areas, the implementation of other soil and water conservation techniques should be explored.

Crop residue retention in Jalisco

For the case of residue systems, substantial benefits were obtained with 33% residue retention, while the 66% and 100% residue retention levels did not increase yield to a large extent in most areas. This finding is consistent with field experiments in the region (Scopel, 1995; Scopel and Chavez, 1997) and was confirmed at the regional scale in this thesis. This is an important finding as crop residue is also valued as livestock feed. Livestock may feed on the land in the fallow season, after which a percentage of residue must be left behind. The burning of residues should be discouraged. Various policy measures may help implement this (Erenstein, 1999). In dry areas of maize biomass production below 1 ton ha^{-1}, alternative sources of fodder, such as from hedges should be promoted.

Crop production in Jalisco is market oriented with substantial use of input such as fertilizer. Also the use of nitrogen fertilizer affects the response to the residue retention practice. The effect of varying nitrogen management was therefore examined. Nitrogen management did not interfere with the response to residue retention. The average farmer nitrogen management level of 150 kg ha^{-1} is beneficial to maize production everywhere in the Jalisco region, but there is not much gain in adding more nitrogen to the amounts of 250 kg ha^{-1}, which confirms findings from the region (Ariel Ruiz Corral, Eric Scopel, Damien Jourdain, pers. communications). Interaction with farmers should convey this principle more clearly to prevent increasing fertilizer use beyond those increasing production. The use of demonstration plots can prove to be successful in this process.

Literature suggests that at low nitrogen application levels systems without residue retention outyield those with residue retention (Erenstein, 1999). As nitrogen application is increased the response curves intersect and subsequently at high nitrogen application levels residue retention systems outyield systems without residue retention. This intersection, or crossover point, occurs at around 80-100 kg N ha^{-1} (Philips et al., 1980; Zea and Bolaños, 1997). In this thesis, results suggest this effect may not occur in areas and on soils where maize production is limited by water availability. Maize grain yield is increased due to water conservation in residue retention systems and this benefit to maize grain yield is larger on soils of low water holding capacities and sloping topography than the negative effect of nitrogen immobilization at the low nitrogen availability level.

In the Jalisco case study, trade-offs were found between focusing on areas where enhancement of maize productivity is largest versus areas where benefits to soil surface runoff reduction are largest. Although the effect of soil loss is not accounted for in crop simulation models, these latter areas of soil surface runoff reduction are hypothesized to be areas of productivity gain in the longer term.

Insights from methodology application

Expanding agronomic models from a point-based application to a spatial application greatly increases the required volume of input and output data. Extensive data requirements must be satisfied, while also ensuring data quality control. From Chapter 2 and during the application of the methodology proposed in this study it became evident that the software tools are available and that interfacing these tools is relatively easy. The availability of quality data and data standards commonly limits the application of the methodology to one-off case studies. In this study, data sources have been documented and ICASA data standards used. The results of the study are available on CD-ROM media. Chapter 3 evaluated interpolation techniques for climate variables of use in agricultural applications. Understanding the accuracy of spatial interpolation techniques is a first step toward identifying sources of error and qualifying results based on sound statistical judgments. The accuracy of the popular interpolation techniques splining and co-kriging can be improved by using more independent co-variables that are strongly correlated with the prediction variable. The investment in creating climate surfaces has additional spin-offs, since they can be used for other applications besides as input to crop or system simulation models, such as for disease mapping, germplasm adaptation mapping (thermal days), or climate change research.

In Chapter 4, weather generators are evaluated for use in GIS-simulation modelling interfaces. In different climatic regions of the world and application it is desirable to repeat the comparison of the weather generators. The procedures described in the chapter are useful. If possible, the effect of prediction error in the generated data should be quantified for the specific application under study. In Chapter 4, it was determined that the error in weather data generated by SIMMETEO did not affect the simulation of maize and beans such that results differed from results obtained using actual weather data. Chapters 5 and 6 contributed to the development of a version of CROPCRO adapted for velvet bean. To estimate impacts of introducing a green manure cover crop, especially those with long growth duration such as velvet bean, a capability enabling the tracking of senesced leaves and stems was necessary. The development of a capacity for simulating crop residue mulch (Chapter 8, Grace et al., 2000) was necessary to allow for evaluation of the effect of mulch on soil and water resources. The process of developing these additional capacities confirmed the need for systematic documentation and storage of data from experiments. The application of the methodology provided (*ex ante*) insight into – the geographical extent of – the regional potential for, and conditions under which, successful introduction of velvet bean and residue retention in maize cropping systems may be achieved. Understanding of the conditions under which successful introduction of and identification of trade-offs between production and conservation dimensions of the production options can improve the analysis and decision-making of stakeholders.

Regional stakeholders in agricultural development

The use of the methodology to evaluate production and soil and water resource dimensions can facilitate discussion among stakeholders and a learning process. This interaction is necessary to improve the transparency of priority setting, implementation and interdisciplinary design of these systems (see also Röling 1994; Leeuwis, 1999; Hammer, 2001), especially towards biophysical dimensions of production and natural resources. In this thesis a first attempt was made to interact with stakeholders interact and discuss of the results of the case study applications as is described in Chapter 9. Clearly, a more iterative interaction would be useful to guide negotiation and decision-making, especially towards the formulation or design of alternatives for further improving maize production systems in the region. As identified in land use planning studies, the need for a 'knowledge broker' (Kok, 2001), preferable highly educated in communication skills, is essential in these interactions. Integration over various tools and scales, such as suggested by Verburg (2000) is desirable. As identified by researchers such as Bouma (1997), an investment in communication skills will be useful to improve our endeavors in this area.

The causes of 'conflicts' among stakeholders, including land users, are often sought solely in divergent objectives of stakeholders. An important issue, that is commonly overlooked, is the absence of a concerted approach to defining problem in the first place. Interaction between stakeholders (and engineers) on the synthesis of problems, before the design of possible solutions hardly takes place, priority setting and communication skills are lacking or priority setting is *ad hoc*. Perhaps before setting the tools to work, researchers may play a role in urging for a synthesis and consorted effort to defining the specific issue or problem at hand.

Although, researchers and end-users meet in useful participatory efforts that are essential to 'technology tailoring', the wide scale dissemination of technologies remains outside of the mandate of researchers and is the area of experts (and linked extension programs) who have set agricultural development priorities within the wider context of society and of the farmers themselves within the communities they live.

Use by extension together with farmers

The results from the applications can also be used at the farm level to illustrate the effects of management practices to farmers. Working together with extension services, farmers can examine the expected effect of the practice in their 'grid cell'. The climate of the grid cell is actual and a wide range of possible soil scenarios has been used, from which they can 'select'. Therefore maps can be used as look-up references. Additionally, the results could have an educational role in showing the longer-term effect of the practice. The use of crop simulation modelling results with farmers has shown potential (Vaughan and Shamudzarira, 2001). For this purpose, investment in the further processing of results of this study would still be needed. Moreover, socio-economic considerations need to be linked to the study. The exchange of information with farmers could be supported by those institutions involved in supplying inputs necessary to the specific management practices (e.g. equipment for planting in residues), or for by seed companies that distribute cultivars that thrive well under conservation tillage (e.g., maize resistant to grey leaf spot disease). The application of the methodology by extension agents and farmers in developing countries themselves is unlikely at this time, but realistic in the future (Matthews et al., 2000).

Use by researchers

Further use of the results and methodology is envisioned for other system approaches and tools. True response to management strategies (nitrogen, plant densities) and processes in time allow for detailed analysis of agronomic variation and trends. The need for trade-off analysis between the various biophysical dimensions of crop production has been identified (e.g. Rossing et al., 1997; Van Ittersum and Rabbinge, 1997; Bouman et al., 1999; De Koning, 1999). Allowing for the identification of deficiencies in available data (e.g., spatial variation in soils and in farmer preference for maize cultivars) and in the models (e.g., incomplete handling of residue impacts on runoff and soil structure), the mapped outputs were found credible and useful by local researchers. The visualizing of the inappropriateness of practices, for instance through identification of geographical gaps, can trigger the creative (re)design of management practices and technologies.

Intermediate products of this study, such as the climate surfaces, are already in use for other applications, i.e., at CIMMYT, such as regional environmental characterization for socioeconomic studies (Ellie Rice, pers. communication).

The application of tools, such as crop models, to a large range of environmental and edaphic conditions increases our knowledge on their flaws and limitations and the possibilities for their improvement.

Setting the scene for future efforts

The simulation of green manure cover crops and residue retention systems within the DSSAT models is still under development. The CROPGRO model for velvet bean needs further development in the area of cultivar evaluation. Quantification of cultivar specific daylength response is essential to the determination of the possibilities for introducing the crop into different environments and in different production systems. The 'residue mulch-module' needs more extensive testing in various environments, for different types of residue that have different decomposition rates. To evaluate the performance of tropical legumes, the simulation of phosphorus is required. A capacity for simulation of phosphorus within DSSAT has been developed (Daroub et al., 1998; Gerakis et al., 1998) and needs to be incorporated into the central DSSAT crop modelling arena. In several countries, experiments have shown that the addition of phosphorus is essential to the success of the green manure (IITA, 1993).

In the current CERES model cooler temperatures delay time to anthesis and maturity. Growth and partitioning of assimilates are affected to a much lesser extent. Therefore, yield increases indefinitely as the growth cycle and grain filling period is extended (see also White et al., 2000). Although this problem is evaded through use of different cultivars for different temperature ranges, care must be taken in applying the model in areas where mean temperatures show substantial variation. The CERES models should be adapted to ensure that grain filling terminates after a prolonged delay or that less partitioning to grains takes place. This need for adaptation has been confirmed for high altitude maize in Mexico (Castelán et al., 2000).

This study benefited greatly from the access to expert knowledge, experimental and on farm information via the PRM (Latin American Maize Network) and through NGOs such as CIDICCO. At the same time, however, it has become evident that volumes of agronomic data on experiments and on-farm research are distributed and fragmented across many experts and institutions and unavailable even for researchers working in similar disciplines or subject areas. The fact that the investment of this type of on-station and on-farm prototyping is decreasing will not help, and unless we capture and synthesize the information, we will loose this valuable farming systems (research) information. The same applies for crop phenological information. Only limited phenological data for modelling are available for tropical maize environments, let alone for green manure cover crops. The investment in maize phenological trials does not match the information or data available for simulation. Previously, the poor capacity to simulate growth of tropical maize materials may have influenced this situation. However, the time is more than due to change the approach for data management and sharing before the information is lost. Information on different varieties and their adaptation to environments is highly necessary for successful regional crop simulation studies. For future applications better access to agronomic management information and experimental data is essential, and there is great potential for international database systems, e.g., the International Cop Information System – ICIS (CIMMYT and IRRI, 2000) for crop data, and the Sustainable Farming Systems Database – SFSD (Lieshout et al., 2001) for cropping systems data. These database systems enable wider use of the information by other parties while ensuring basic quality control, recognition of the data contributor and his/her intellectual property rights. The later issues are common constraints to data sharing and subsequent availability. Besides the need for systematic data storage, data standards – such as proposed by ICASA (Hunt et al., 2001) and data sharing policies (Porter and Callahan, 1994) can further facilitate the exchange and accessibility of data.

In this study few management practices were considered. Farmers may vary cultivars, sowing rates, N applications and other practices according to local conditions or their specific socio-economic situation and expectation for weather conditions. Areas with preferences for certain cultivars may be determined and incorporated in future applications.

In our case, soil information was used on a scenario basis. Detailed spatial soil profile information for use in crop simulation models is hardly available. Even if several soil profile descriptions are available for a region, it is linked to soil taxonomical units maps to obtain a general applicability of the profile. Efforts towards improving the capability to capture this (Lagacherie, 2000) are highly valuable. Another alternative would be to carefully georeference phenoforms instead of genoforms (Bouma and Drogers, 1999), as phenoforms do capture soil characteristics of agronomic importance.

Various long-term processes exist that affect system productivity positively but are not readily modelled by cropping system models. Residue retention saves soil surface runoff but also soil matter. Increased organic matter content has a positive effect on soil structure and microbiology. Worldwide documentation and synthesis of experimental findings is essential to advance in understanding processes affecting the system.

Information on disease and pest (including weeds) incidence can be mapped and monitored through geo-referenced disease survey data (see e.g., Spies et al., 1997; Barbee, 1999; Lee and Black, 2001). Although the effects of diseases on production per se cannot be handled at this stage, linking information on disease and pest incidence to the presented case study information can already be very useful.

Incorporating geo-referenced socio-economic data at the cropping system and farm level is desirable. Socio-economic data from census are currently limited to quite large administrative boundaries and integration of this information with cropping systems data has proven difficult (see Barreto and Hartkamp, 1999; Kok, 2001). Information on factors affecting smallholder adoption of 'productivity enhancing resource conserving technologies' has been analysed at CIMMYT by Erenstein (1999), in CIMMYT regional programs by Sain (pers. communication) and by Zurek (2002). An effort to integrate the results of these studies with the insights into the regional variation of these production systems as presented in this thesis is highly recommended.

The contribution of researchers to designing appropriate production options has traditionally followed a one – way supply oriented approach. Researchers evaluated the issues from their own perspective and information was supplied top-down to decision-makers and stakeholders. Increasingly, we realize that the design of agricultural production options should root from a demand. Interaction with stakeholders and decision-makers has proven essential to achieve agricultural change. Currently, more open interaction and more frequent discussion on the underlying issues, context and possibilities takes place. A more ideal approach to the design, evaluation and implementation of agricultural production options is an iterative interaction between researchers and stakeholders involving at least four interaction moments or stages:

1) Context and issues are discussed and analysed, objectives and goals of agricultural change are defined.
2) Knowledge on current and desirable production options is exchanged or formulated.
3) Desirable production options are assessed and their (biophysical and socio-economic) suitability is analysed; results are discussed.
4) Shortcomings of the production options are identified and alternatives are formulated. Stage 3 can be re-entered and again followed by stage 4, thus the interaction process becomes iterative.

In this thesis, stakeholders were included in the process of defining the agricultural options that need to be assessed and discussing the outcomes of the application of the simulation methodology (steps 2 and 3). Clearly a more iterative interaction on the options for the regions of Honduras and Jalisco is desirable. For a more iterative interaction with stakeholders using the presented methodology, a quicker turn around time is needed. Despite new powerful computers it is still time consuming to run regional dynamic simulations and analyse results if location specific data on management, climate and soil are to be sufficiently precise. A more integrated approach to presenting summary information is desirable. Further investment in the development of software would be helpful in this aspect.

The absence of a concerted effort for agricultural planning is sought too often in contrasting discipline backgrounds and objectives and too seldom in the inability of researchers and stakeholders to communicate. To ensure effective planning and priority setting in agriculture, especially in developing countries, the communication between researchers from different disciplines and researchers with stakeholders can still be improved. Insights in communication research, such as those documented by Röling (1994) and Van Woerkum (2000) can be useful.

This thesis contributed to the development of a methodology that can help identify where, when and why production enhancement and resource conservation may be achieved through the introduction of agricultural production options. Through the identification of biophysical trade-offs, transparency in priority setting and decision-making by agricultural stakeholders is improved. Through this process more appropriate interventions are formulated and mistakes can be avoided. The limitations or shortcomings of production options are identified which can trigger (re)design. The supply of appropriate agricultural production options that improve production and do not threat the resource base for production can herewith be improved.

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SUMMARY

Global society has become conscious that efforts towards securing food production will only be successful if agricultural production increases are obtained through mechanisms that ensure active regeneration of the natural resource base. Despite the growing liberalization of global markets, the bulk of food will need to be produced in current areas of production, and in the places where it is needed, mainly because of socio-economic and political constraints. The design and redesign of agricultural production systems must focus on the efficient use of resources for production and on the location where production takes place. The feasibility of production options can be analysed through a hierarchy where climate and soil conditions are viewed as first order determinants; subsequently, probability of success is revised based on biotic constraints (e.g., diseases and pests), economic viability and social acceptability.

This study focuses on the biophysical assessment of production options in maize-based cropping systems at the regional scale, to facilitate the biophysical targeting. Biophysical targeting is described as the process with which spatially and temporally explicit goal-specific biophysical benefits are identified. This biophysical targeting is useful in guiding technology introduction by indicating where, when and why production options are suitable, taking into account the climate and soil conditions. Biophysical targeting is important because it can prioritize areas for socio-economic adaptation research investment, reduce inappropriate introduction, and identify shortcomings in the production option. The information supplied can help regional stakeholders in their analysis and discussion, negotiation and decision-making. The specific objectives of the thesis were to:

- Develop a methodology to evaluate the biophysical suitability of agricultural production options that can enhance productivity and conserve soil and water resources.
- Explicitly account for the spatial and temporal variability of climate conditions in interaction with soil, crop characteristics and agronomic management strategies in this methodology.
- Operationalize the methodology through inductive use of two case studies of maize-based production systems: green manure cover crop and reduced tillage with residue retention.

The two cases studies of maize-based cropping systems were selected in consultation with regional stakeholders and because of their importance to food production and resource conservation in Latin America. The contrasting nature of the different production environments was considered ideal for developing and testing the methodology. Under the generally wetter conditions of Honduras, fallow season cropping is an option, while in semi-arid Jalisco, Mexico, options are sought to improve fallow management through crop residue retention.

The first part of the thesis (Chapters 2 - 6) provides a technical basis and evaluates the tools used in the proposed methodological framework for regional cropping systems assessment. The second part (Chapters 7 and 8) of the thesis describes the application of the methodology to the case studies for Honduras and Jalisco. Chapter 9 documents on an interaction with stakeholders to discuss and evaluate the results of the case study applications and the methodology *per se*.

Process-based simulation models offer the potential for assessing management practices and production systems for different climate and soil conditions at single sites. Geographical information systems (GIS) facilitate the storage, manipulation, analysis, and visualization of spatial data. Interfacing simulation models to GIS offers the potential to analyse spatial and temporal variation. Expanding agronomic models from a point-based application to a spatial application commonly increases the volume of input and output data. In Chapter 2, strategies for interfacing agronomic models with GIS are reviewed. The choice of the interfacing strategy should depend on the research problem, the application objectives, and the investment the user is able to make. However, more commonly the strategy is determined by the availability of (spatial) data. A major challenge in interfacing GIS to models lies in satisfying extensive data requirements, while ensuring data quality. Eventually, developing interfaces that handle interaction among spatial units will be of increasing interest.

To obtain spatial climate data from meteorological station data, interpolation techniques may be used. In many regions across the world, especially in developing countries, the density of meteorological stations is low, and reliable long-term, continuous data are scarce. When point data are abundant, most interpolation techniques give similar results, but when data are sparse, the choice of interpolation technique becomes more critical, as the underlying assumptions about the variation among sampled points differ. Chapter 3 evaluates interpolation techniques for climate variables of use in agricultural applications. The use of co-variables that are strongly correlated with the prediction variable can improve interpolation results. Taking into account the value of error prediction, assumptions concerning the input data, and computational simplicity, thin-plate smoothing splines are recommended for regional crop growth simulation applications for the selected regions at this time.

Many crop growth simulation models require daily weather data. Interpolated surfaces of weekly or monthly climate variables can be used to generate daily weather from these. Weather generators are available to automate this data generation process. Chapter 4 compares the performance of the weather generators, WGEN, MARKSIM, and SIMMETEO to observed daily weather data. Statistical procedures are used to evaluate the performance of the weather generators in simulating weather phenomena. Furthermore, the impact of using different weather generators for the simulation of maize and bean cropping is evaluated at a range of locations. Considering data requirements, the weather generator SIMMETEO is robust and can be recommended for crop modelling applications at single point locations as well as for applications that use interpolated summary weather data as input. The weather generator MARKSIM creates a high inter-annual variability and long chains of wet days that are not found in observed data, but the generator has use for areas of poor distribution of weather stations or where monthly means are unavailable. The results presented are valid for the subtropical region from which the test locations were selected. For different climatic regions of the world repeating the comparison of the weather generators is desirable. To this end the procedures described in this chapter are useful.

Chapters 5 and 6 describe the development and evaluation of a generic crop growth model for velvet bean (*Mucuna pruriens*). CROPGRO – Soybean is adapted to the phenology, growth and partitioning, and canopy development of velvet bean at three sites in Mexico. Compared to soybean, velvet bean has a much longer growth cycle, allowing very large numbers of nodes to form. Velvet bean has larger, thinner leaves than soybean, resulting in more rapid leaf area development, and larger seeds, which affects both early season growth and pod development. A modification to CROPGRO to permit the tracking of senesced materials to feed into a litter layer is incorporated. The model was evaluated for performance for phenology, growth, senescence and N accumulation at multiple locations that represent a range of environmental and agronomic management scenarios. Overall, the physiological processes underlying growth and development of velvet bean appear similar to other tropically adapted legumes. However, conclusive values for critical daylength and daylength sensitivity for the various cultivars cannot yet be determined. Sensitivity analyses evaluating the ability of the green manure cover crop to provide ground cover and intercept light for soil protection and weed suppression indicate that a mean temperature of over 22 °C and a soil moisture holding capacity of at least 100 mm is required in the growing cycle. The new model, incorporated as part of the DSSAT 3.5 suite of crop growth simulation models, has potential to identify potential regions for introduction of velvet bean as a green manure cover crop.

In Chapter 7, the proposed methodology for regional assessment of cropping systems is described and applied to the case study of maize–velvet bean systems in Honduras. Management practices were synthesized from regional expert information and used as input to the cropping systems simulation model. Gridded climate profile surfaces and a wide range of soil scenarios form the basis of the regional input. The weather generator SIMMETEO is used to generate daily weather from the profiles. Selected cropping systems are simulated for a term of 12 consecutive years. Variables considered in the assessment are those related to crop production, light interception, nitrogen fixation, surface runoff water, organic carbon and organic nitrogen. The assessment considers velvet bean production *per se*, as well as the effects of velvet bean on maize production and soil and water resources. Responses to water and nitrogen conditions at individual locations and for a selection of soil scenarios are analysed to increase the understanding of variation in regional results. Benefits of increased maize production from cropping velvet bean are expected in areas where off-season climate and soil conditions enable velvet bean growth and in nitrogen limiting soils with low nitrogen fertilization management. An increase in maize grain yield of up to 2 ton ha^{-1} is found under illustrated conditions. Increases in soil organic carbon and nitrogen from cropping velvet bean are substantial. Dry climatic regions are identified where soil surface runoff cannot be reduced through introduction of velvet bean. For these areas, the use of alternative soil and water conservation measures such as crop residue retention, vegetative barrier systems may be explored.

In Chapter 8, modified versions of the cropping system models are used to allow for dynamic simulation of crop residue retention via an additional surface mulch layer. The methodology is applied to the case study in Jalisco, Mexico. Systems where crop residues are partially or totally retained are compared to systems with no residue retention. Benefits to maize production from residue retention are found mainly in areas mainly in the northeast of the study region, where precipitation limits maize production. Benefits of soil surface runoff reduction from residue retention are evident in high rainfall areas in the central east of the study area. Trade-offs exist between focusing on areas where maize production is increased versus areas where soil surface runoff is reduced due to residue retention. Although the effect of soil loss is not accounted for in crop growth simulation models, these latter areas of soil surface runoff reduction are hypothesized to be areas of productivity gain in the long term.

The applications provide insight into – the geographical extent of – the regional potential for, and the soil and climate conditions under which, successful introduction of velvet bean and residue retention in maize-cropping systems may be achieved. Chapter 9 documents on an interaction with stakeholders to discuss and evaluate results from the case studies and the methodology *per se*. The methodology is valued by stakeholders for its capability of showing dynamic responses to management as a function of variable soil and climate conditions. Stakeholders value the visualization of regional patterns in production and resource dimensions, and report that the presentation greatly assisted their understanding of sources of variation within 'target' regions. The transparency of spatially explicit trade-offs between production and conservation dimensions is increased. This can help regional stakeholders, involved in agricultural development, technology dissemination and design, in their analysis and discussion, negotiation and decision-making concerning where to implement production systems that enhance productivity and conserve resources. Chapter 10 provides recommendations to operationalize the methodology for future applications.

SAMENVATTING

Steeds meer realiseert de wereldgemeenschap zich dat een verhoging van de wereldvoedselproductie alleen is veilig te stellen, indien netjes en efficiënt met de natuurlijke hulpbronnen wordt omgegaan. Ondanks de toenemende liberalisatie van de wereldmarkt zal veruit het grootste deel van het voedsel toch geproduceerd moeten worden in de huidige productiegebieden om zowel biofysische, sociaal-economische als politieke redenen. Het (her)ontwerpen van agrarische productiesystemen zal dan ook vooral gericht moeten zijn op het doelmatig gebruik van de natuurlijke hulpbronnen ter plekke. De uitvoerbaarheid van productiesystemen kan volgens een hiërarchische benadering worden geanalyseerd, waarbij klimaat en bodem als eerst bepalende factoren worden beschouwd en vervolgens wordt nagegaan welke groeibeperkende factoren zoals plantenvoedingsstoffen en onkruiden en kortingen door ziekten en plagen een rol spelen. De economische perspectieven en sociale acceptatie zijn uiteindelijk doorslaggevend voor het inzetten van (nieuwe) productiesystemen.

In deze studie is gewerkt aan de biofysische evaluatie van door maïs gedomineerde productiesystemen op regionaal niveau. In deze evaluatie werden productiesystemen geëvalueerd in afhankelijkheid van de ruimtelijke en tijdsgebonden variabiliteit van klimaat in interactie met bodemeigenschappen, gewaseigenschappen en teeltstrategieën. Dit doelgericht onderzoek is belangrijk omdat dan prioriteitsgebieden voor sociaal-economisch onderzoek in kaart gebracht kunnen worden, ongeschikte introductie kan worden voorkomen en witte vlekken in de agrotechnieken of de daaraan ten grondslag liggende kennis geïdentificeerd kunnen worden. De resultaten zijn bruikbaar op regionaal niveau, waarbij plaatsgebonden afwegingen tussen de effecten van productiesystemen op productie en bodem- en waterconservering dimensies zichtbaar worden. Deze informatie kan de basis vormen voor analyse, discussie en besluitvorming van regionale belanghebbenden over de geschiktheid van productiesystemen. De specifieke doelstellingen van het onderzoek waren:

- Het ontwikkelen van een methodologie die het mogelijk maakt de geschiktheid te beoordelen van productiesystemen om zowel de productie te verhogen als het gebruik van hulpbronnen te verbeteren;
- Hierbij expliciet rekening te houden met de heterogeniteit van klimaatcondities in ruimte en tijd in interactie met bodemeigenschappen, gewaseigenschappen en agronomische aspecten van het management;
- De methodologie operationeel te maken door inductief gebruik bij toepassingen voor twee categorieën productiesystemen: bodembedekkende groenbemesters en systemen waarbij gewasresten op het veld worden behouden.

Ter adstructie van de methodologie werd deze toegepast in twee voorbeeldstudies. Deze voorbeeldstudies werden gekozen in samenspraak met belanghebbenden op grond van het belang van deze systemen voor voedselproductie en bodem- en waterconservering in Latijns America. Ook werd het tegengestelde karakter van de productieomgeving van deze gebieden als ideaal gezien voor het toetsen van de methodologie. Onder de, over het algemeen, nattere klimaatcondities van Honduras is een tweede teelt tijdens het braakseizoen mogelijk, terwijl men in het meer semi-aride gebied Jalisco, Mexico, zoekt naar mogelijkheden om met behoud van gewasresten het beheer van de braakperiode te verbeteren.

Het eerste deel van dit proefschrift (Hoofdstukken 2 - 6) voorziet in de technische basis en evaluatie van het gereedschap dat in de voorgestelde methodologie wordt gebruikt. Het tweede deel van het proefschrift (Hoofdstukken 7 en 8) beschrijft de toepassing van de methodologie en de resultaten voor de twee onafhankelijke voorbeeldstudies voor Honduras en Jalisco. Hoofdstuk 9 beschrijft de resultaten van het contact met regionale belanghebbenden waarbij de resultaten van de toepassingen en de gebruikte methodologie worden geëvalueerd.

Het gebruik van dynamische simulatiemodellen gebaseerd op kennis en inzicht van processen biedt mogelijkheden voor evaluatie van teelttechnieken en teeltsystemen voor verschillende klimatologische en bodemkundige condities op puntlocaties. Geografische Informatie Systemen (GIS) vergemakkelijken opslag, manipulatie, analyse en visualisatie van ruimtelijk vastgestelde gegevens. Het creëren van een koppeling ('interface') tussen simulatiemodellen en GIS biedt mogelijkheden voor het opvangen van zowel ruimtelijke als tijdsgebonden variatie. Het verruimen van het gebruik van landbouwkundige simulatiemodellen voor puntsimulaties naar een regionale toepassing vergroot de hoeveelheid aan benodigde invoer- en gegenereerde uitvoergegevens sterk. In Hoofdstuk 2 wordt een overzicht gegeven van de verschillende strategieën voor het koppelen van landbouwkundige simulatiemodellen en GIS. De keuze van de strategie zou vastgesteld moeten worden op basis van het te onderzoeken probleem en de doelstelling van de toepassing. Echter, vaak wordt de strategie bepaald door de beschikbare data (zowel type als hoeveelheid). Een van de grote uitdagingen van het creëren en gebruik van koppelingen ('interfaces') tussen simulatiemodellen en GIS ligt in het bijeenbrengen van zeer veel data en het tegelijkertijd waarborgen van de kwaliteit ervan. Het ontwikkelen van koppelingen welke de interactie tussen ruimtelijke eenheden aankunnen, zal in de toekomst van toenemend belang zijn.

Voor het verkrijgen van ruimtelijke weersgegevens van meteorologische stations, kunnen interpolatie technieken worden gebruikt. In vele gebieden in de wereld, vooral in ontwikkelingslanden, is de dichtheid van meteorologische stations laag en zijn betrouwbare, ononderbroken lange termijngegevens schaars. Wanneer gegevens voor veel locaties aanwezig zijn, geven interpolatie technieken hetzelfde resultaat. Echter als er slechts voor weinig locaties gegevens beschikbaar zijn, wordt de keuze van de interpolatietechniek belangrijker. Dit omdat de verschillende aan de techniek ten grondslag liggende aannames over de ruimtelijke variatie tussen punten doorwerken in de resultaten van interpolatie. In Hoofdstuk 3 worden interpolatietechnieken voor klimaatgegevens, die onder andere voor landbouwkundige toepassingen gebruikt kunnen worden, geëvalueerd. Het gebruik van onafhankelijke co-variabelen voor interpolatie leidt tot betere resultaten. Gezien het belang van het kwantificeren van voorspellingsfouten, de aannames ten aanzien van de gegevens, en rekenkundige eenvoud, wordt op dit moment het gebruik van twee-dimensionale 'splines' aangeraden voor regionale toepassingen van gewasgroei simulatiemodellen.

Veel gewasgroei simulatiemodellen hebben dagelijkse weersgegevens nodig. Geïnterpoleerde oppervlaktekaarten met wekelijkse of maandelijkse klimaatgegevens kunnen gebruikt worden om de dagelijkse weersgegevens te genereren. Hiertoe zijn weer-generatoren beschikbaar. In Hoofdstuk 4 worden de gegenereerde gegevens van drie verschillende weer-generatoren vergeleken met waargenomen gegevens. Statistische procedures worden gebruikt om de weer-generatoren te evalueren op hun vermogen om verschillende weerfenomenen te kunnen nabootsen. Verder wordt gekeken naar de effecten van het gebruik van verschillende weer-generatoren voor het simuleren van maïs- en boonteeltsystemen op negen sterk verschillende locaties binnen het (sub)tropisch studiegebied. Gezien de benodigde gegevens, kan de weer-generator SIMMETEO worden aangeraden voor zowel puntlocatie toepassingen als toepassingen op regionale schaal. De weer-generator MARKSIM genereert een grotere variatie tussen jaren en langere reeksen van opeenvolgende natte dagen dan wordt gevonden in waargenomen gegevens van het studiegebied. De uitspraken zijn geldig voor het bestudeerde gebied. In andere klimatologische delen van de wereld is het wenselijk de exercitie te herhalen. De procedures die in het hoofdstuk gepresenteerd worden, kunnen daarbij worden benut.

Hoofdstukken 5 en 6 beschrijven het ontwikkelen en evalueren van een generiek gewasgroeimodel voor de bodembekkende groenbemester fluweeljeukboon (*Mucuna pruriens*). In Hoofdstuk 5 wordt CROPGRO-Soja aangepast aan fenologie, groei, drogestofverdeling en gewasontwikkeling van de fluweeljeukboon voor drie locaties in Mexico. Vergeleken met soja heeft de fluweeljeukboon een veel langere groeicyclus, wat in een groot aantal knopen resulteert. De fluweeljeukboon heeft grotere en dunnere bladeren dan soja, wat zich uit in een snellere bladoppervlakte ontwikkeling. Een aanpassing van CROPGRO maakt het mogelijk na te gaan hoeveel materiaal er gedurende het seizoen afsterft en afvalt, wat voor een juiste simulatie van een laag met gewasresten nodig is. Het model werd op verschillende locaties over de gehele wereld geëvalueerd. Over het algemeen kwamen de fysiologische processen welke ten grondslag liggen aan de simulatie van groei en ontwikkeling van de fluweeljeukboon overeen met die van andere tropische bonen met kortere groeicycli (soja, gewone boon, kekererwt). Er kan echter nog geen uitsluitsel worden gegeven over de daglengtegevoeligheid voor de bloei van de verschillende variëteiten. Een gevoeligheidsanalyse is uitgevoerd teneinde het vermogen van deze groenbemester om de grond te bedekken en licht te onderscheppen, voor een verscheidenheid aan omgevingscondities te bepalen. De resultaten wijzen erop dat voor voldoende groei, bodembescherming en onkruidonderdrukking, een gemiddelde temperatuur van tenminste 22 °C gedurende het groeiseizoen nodig is, en een watervasthoudend vermogen van de bodem van tenminste 100 mm. Het nieuwe model CROPGRO-fluweeljeukboon als onderdeel van het geheel aan gewasgroei modellen georganiseerd binnen het softwarepakket DSSAT 3.5, biedt mogelijkheden voor het evalueren van teeltstrategieën voor specifieke klimaat- en bodemcondities. Potentiële gebieden waar de fluweeljeukboon geïntroduceerd kan worden als bodembedekkende groenbemester kunnen met het model worden geïdentificeerd.

Hoofdstuk 7 beschrijft de voorgestelde methodologie als leidraad voor het doelgericht inzetten van maïs-fluweeljeukboon teeltsystemen in Honduras. Veel voorkomende teelttechnieken werden samengevat en gebruikt als invoer voor het simulatiemodel. Verschillende systemen werden over een periode van twaalf achtereenvolgende jaren gesimuleerd. Klimaatprofielinformatie, een samenvatting van gemiddelde waardes en stochastische parameters opgeslagen in grid-cell formaat, en een verscheidenheid aan bodemscenario's werd als basisinvoer gebruikt voor de regionale gegevensbank. De weer-generator SIMMETEO werd gebruikt om dagelijkse weersgegevens te genereren van deze profielen. In de evaluatie worden effecten op gewasproductie, lichtonderschepping, stikstoffixatie, oppervlaktewater afstroming, organische koolstof en -stikstof opgenomen. Er is eerst gekeken naar de gunstige condities voor de teelt van fluweeljeukboon, waarna de effecten op maïsopbrengst en andere bodem- en watereigenschappen zijn beoordeeld. Verhoogde maïsopbrengsten ten gevolge van fluweeljeukboon worden verwacht in gebieden waar condities voor de groei van fluweeljeukboon goed zijn en vooral onder condities van lage stikstofbeschikbaarheid. Het voordeel kan oplopen tot 2 ton ha^{-1} maïsopbrengst. Ten aanzien van bodemorganische koolstof en bodemorganische stikstof zijn er duidelijke voordelen verbonden aan de teelt van fluweeljeukboon. Er werden droge klimaatgebieden geïdentificeerd waar de afstroming van het oppervlaktewater niet kan worden verminderd door de teelt van fluweeljeukboon. Voor deze gebieden zullen alternatieve bodem- en waterconserverende maatregelen verkend moeten worden, zoals het gebruik van gewasresten en vegetatieve grasbarrières.

In Hoofdstuk 8 worden aangepaste gewassysteemmodellen gebruikt die de gevolgen van het gebruik van gewasresten kunnen simuleren. De in dit proefschrift voorgestelde methodologie wordt toegepast voor Jalisco, Mexico. Verschillende maïsbraaksystemen waarbij gewasresten geheel of gedeeltelijk in het veld worden behouden, werden geëvalueerd. Voordelen van het behoud van gewasresten werden vooral gevonden in het noordoosten van het studiegebied, daar waar regenval de groei van maïs limiteert. In gebieden met hoge regenval werden de grootste voordelen van een reductie in afstroming van oppervlaktewater behaald. Er bestaat een afweging betreffende doelgerichte aandacht voor gebieden waar de grootste productievoordelen in maïsopbrengst te behalen zijn, of voor gebieden waar de grootste voordelen van waterconservering en een daaruit volgende bodemconservering te behalen zijn. Daar het effect van bodemverlies (erosie) niet is opgenomen in de gewasgroei-simulatiemodellen, kan worden verondersteld dat in de laatstgenoemde gebieden ook op langere termijn voordelen ten aanzien van opbrengst behaald kunnen worden.

Toepassing van de voorgestelde methodologie verschaft inzicht in de grootte van regionale voordelen van nieuwe systemen op het gebied van productie en bodem- en waterconservering onder verschillende bodem- en klimaatcondities. Daarmee wordt duidelijk waar en wanneer succesvolle introductie van de fluweeljeukboon in Honduras en het behoud van gewasresten in Jalisco kan plaatsvinden. Hoofdstuk 9 beschrijft het contact met regionale belanghebbenden waarbij de resultaten van de toepassingen en de methodologie geëvalueerd worden. Belanghebbenden hadden vooral waardering voor het feit dat de gebruikte methodologie de analyse van dynamische respons van teeltstrategieën onder een grote variabiliteit aan bodem- en klimaatcondities vereenvoudigt. Daarnaast vonden zij de visualisatie van de effecten van de voorgestelde productiesystemen op de verschillende aspecten nuttig, en de presentatie verhoogt hun begrip voor regionale variatie in deze effecten. De transparantie ten aanzien van de afwegingen tussen de effecten van productie-technieken op productie en bodem- en waterconservering werd vergroot. De informatie kan worden gebruikt ter ondersteuning van de analyse, onderhandeling en besluitvorming omtrent het vinden van productietechnieken die gunstig zijn voor voedselproductie en het goed omgaan met natuurlijke hulpbronnen. Hoofdstuk 10 sluit af met een discussie over de perspectieven van de ontwikkelde methodologie en beschrijft aanbevelingen voor toekomstige toepassingen.

Appendix 1.1 Case study areas and practices

Honduras

Honduras is the second largest country in Central America with an area of 112,492 km^2, an estimated population of 5.3 million people (1994), and one of the highest population growth rates in the Americas (3.3%) Around 87% of the landscape consists of hillsides and is subject to physical and human degradation due to erosion and deforestation (SECPLAN-FNUAP, 1994). It is estimated that in 1993, 64% of all rural households in Honduras were below the poverty line, and an alarming 46% are considered indigent. In rural communities, maize plays an essential role in human nutrition. Over 80% of the farmers cultivate maize on farms less than 20 ha, and contribute to 61% of the total maize production. Average maize yield levels in these farms are around 1 ton indicating a low level of inputs and technology for maize production (SECPLAN, 1994a; SECPLAN, 1994b).

The Atlantic coast of Honduras is wet, moving to the south the climate gets dryer. Annual precipitation ranges from 300 mm to 2800 mm (Fig. A1.1). The main growing season is from May or June to November. The second growing season is from December to April. Annual average maximum temperature is around 30 °C and annual average minimum temperature is around 18 °C (Table A1.1). Major soils include: Acrisols, Cambisols, Luvisols, Rendzinas, Regosols and Andosols.

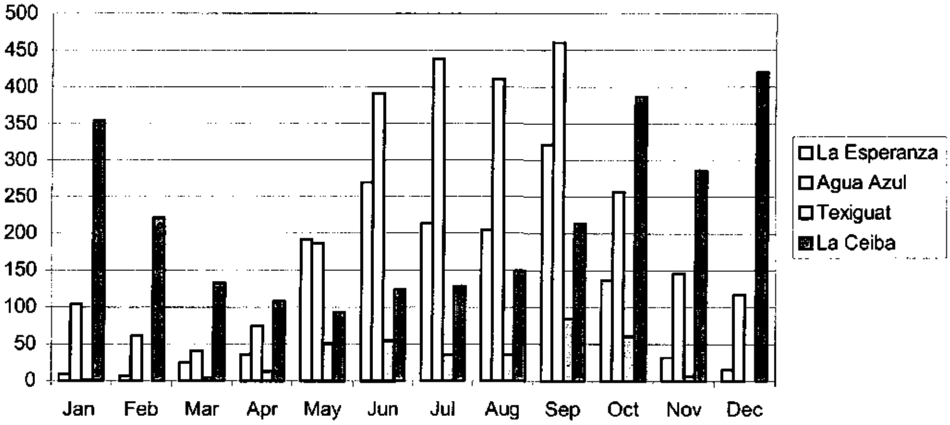

Figure A1.1 Long term averages for precipitation in mm for stations La Esperanza (1980 m), Agua Azul (1650 m), Texiguat (330 m) and La Ceiba (7 m).

Table A1.1 Long term maximum and minimum temperature in °C and standard deviation (stdev.) for Honduras derived from Jones, 1996.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmax	27.3	28.5	30.9	31.9	31.7	31.7	30.2	29.7	29.5	28.1	27.6	26.8
Stdev.	2.8	2.7	2.4	2.4	2.4	2.4	2.5	2.6	2.6	2.7	2.9	3.0
Tmin	15.6	15.7	16.8	18.2	19.1	19.2	18.9	18.3	18.8	18.3	17.2	16.2
Stdev.	2.8	2.7	2.6	2.5	2.5	2.5	2.6	2.5	2.5	2.5	2.7	2.9

Estimates based on the 1993 agricultural census indicate that annually over 400,000 ha is planted to maize, resulting in a production of over 500 thousand ton. Alternative crops are beans (98,000 ha), maicillo-unimproved sorghum (66,000 ha), rice (21,000 ha), and sugar cane (42,000 ha) (Barreto, 1995). Perennial crops include banana (+/- 28,000 ha) and coffee (150,000 ha) (FAO, 1993). The country has averaged net imports of maize in the order of 52,000 tons equivalent to about 37,000 ha at average productivity levels of 1.4 t ha^{-1}. Maize is grown throughout the country from the low altitude valleys to the mountains in the south-western part of the country at altitudes above 1500m. The main intercrops with maize are unimproved sorghum and common bean (Barreto and Hartkamp, 1999).

Jalisco – Mexico

The state of Jalisco lies in the western part of Mexico and includes highland areas that are part of the 'Sierra Madre Occidental', a mountain range, as well as pacific coastal areas. It covers an area of 78,890 km^2. Population is around 6 million, of which 1.7 million live in Guadalajara, the second largest city in Mexico (INEGI, 1981, 1994). Altitude ranges up to 4020 m (GTOPO30; USGS, 1997). Jalisco is a semi-arid region with mono-modal precipitation distribution. Annual precipitation ranges from 600 to 2000 mm (Figure A1.2). The rainy season starts in May-June and ends in November. Annual average maximum temperature is around 29 °C and annual average minimum temperature is around 16 °C (Table A1.2). Major soils in the area include: Cambisols, Andosols, Rendzinas and Regosols, Chernozems, Feozems and Vertisols.

Jalisco is the largest maize producing state of Mexico, accounting for 15% of the national maize production (INEGI, 1994; SAGAR, 1997). Maize production in 1991, was an estimated 1,082,000 tons. Of the total area sown to agriculture, 61% was sown to maize (557,000 ha). Alternative crops include sorghum (67,000 ha), sugar cane (57,000 ha) and common bean (56,000 ha) (INEGI, 1994). Livestock is of importance but is mainly confined to rocky, mountainous areas considered unsuitable for crop production. For this study, a square area of approximately 200,000 km^2 has been selected to cover the state of Jalisco and its surrounding area. In 1994, maize production increased to 2,368,000 ton with only slight increase in land utilization

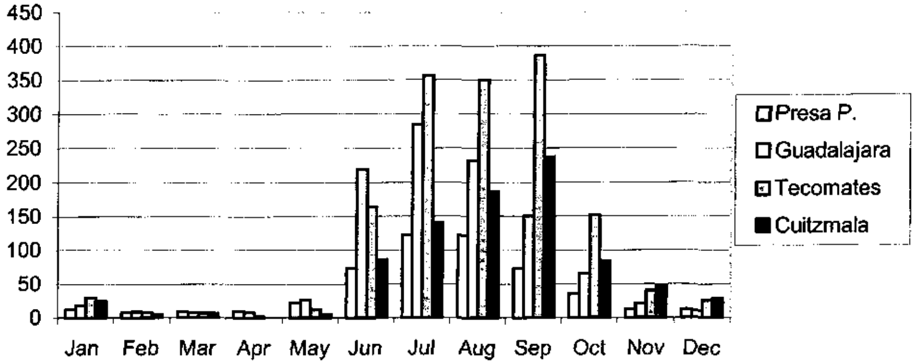

Figure A1.2 Long-term averages for precipitation in mm for stations Presa Portrerillo (2090 m), Guadalajara (1583 m), Tecomates (350 m) and Cuitzmala (30 m).

Table A1.2 Long-term average minimum and maximum temperature in °C and standard deviation (stdev.) for over 150 stations in Jalisco, (1960 → 1980, derived from IMTA, 1996).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmax	25.9	27.2	29.4	31.5	32.5	30.8	28.6	28.4	28.2	28.4	27.7	26.3
Stdev.	4.1	4.0	3.6	3.4	3.2	3.5	3.7	3.6	3.6	3.8	3.9	4.1
Tmin	11.5	12.1	13.4	15.5	17.7	19.6	19.2	19.0	18.9	17.1	14.2	12.6
Stdev.	4.8	4.6	4.1	3.9	3.7	3.8	3.8	3.8	4.0	4.6	5.1	4.9

(665,000); 1995 saw a slight drop in production to 2,100,000 ton while the area slightly increased to 689,000 ha. Importation of maize has increased over the last years to a figure of 2,634,000 tons for 1995 (SAGAR, 1997). Major agricultural problem in the region include: erosion (caused by deforestation, overgrazing, leaving soil bare and natural phenomena such as slope, weather), and contamination of soil, water and aquifers (INIFAP, 1996).

Case study practices

Green manure cover crops

Use of green manures is an age-old practice, utilized by the Chinese almost three thousand years ago (Woodward, 1982). Green manuring is the farming practice in which undecomposed green plant material is incorporated into the soil to increase its productivity. Many of the species used in green manuring are herbaceous legumes, which are valued for their ability to fix atmospheric nitrogen.

To provide the greatest system benefits, a green manure cover crop should show the following features:

- Have rapid growth
- Produce large amount of biomass
- Have deep roots
- Tolerate different climatic conditions
- Resist pests and diseases.
- Return more nutrients to the soil than it has removed (e.g., through nitrogen fixation)
- Require little cultivation or weeding
- Decompose rapidly after incorporation

(Davy, 1925)

Besides potential addition to soil nitrogen, green manures are valued for their soil cover. Cover reduces soil erosion and therewith also conserves soil fertility and moisture. They are also valued as sources of forage and food. The advantages of using cover crops in tropical agriculture have been widely recognized and documented (Giller and Wilson, 1991; Skerman et al., 1988; Wade and Sanchez, 1983).

Velvet bean or *Mucuna pruriens* (L.) DC cv. group *utilis* (syn. *Mucuna deeringiana* [Bort] Small, *Stizolobium deeringianum* Bort.) is one of the most widely used green manure cover crops in maize production systems of Meso America, West and South Africa. While in more arid parts Africa it is used to improve soil fertility and structure, in the humid parts of Meso America it's main advantage is through weed and erosion control (Waddington et al., 1998; Vissoh et al., 1997; Kumwenda et al., 1996; Thurston et al., 1994).

Velvet bean shows a cycle of 150 to 300 days (depending on cultivar and planting date)[1] and aboveground dry matter biomass production can be as high 12 ton ha^{-1} (Buckles et al., 1998; Triomphe, 1996; Duke, 1981). Effects on soil fertility and soil improvement have been reported by Triomphe (1996) and Waddinton et al. (1998). Because velvet bean contains L-dopa it is reported to have few diseases (Duke, 1981; Buckles and Perales, 1995; Skerman et al., 1988; Davy, 1925). Although it is used to control root-knot and cyst nematodes in soybean systems of the south-eastern United States (Weaver et al., 1997), it is said to have problems with root knot nematodes in Zimbabwe (Vaughan et al., 1996). Velvet bean has been used in soil regeneration projects in Indonesia (Hariah, 1992). It has been successful in controlling Imperata cylindrica and other notorious weeds in Asia and Latin America (Buckles et al., 1998; Buckles and Perales, 1995; Hariah, 1992; Van Eijk-Bos, 1987).

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[1] Velvet bean is daylength sensitive, showing a short daylength response.

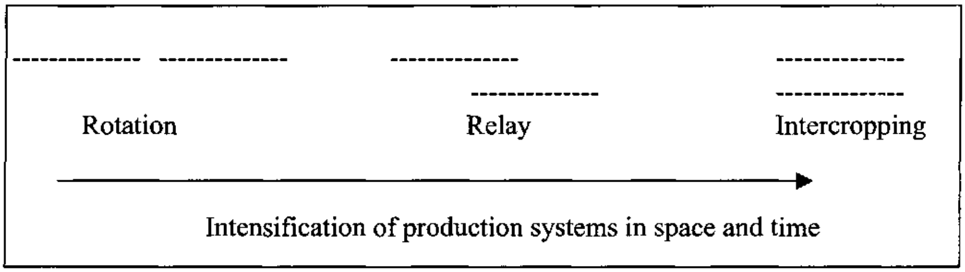

Figure A1.3 Strategies for intensifying production systems in space and time (based on Buckles and Barreto, 1996).

Velvet bean can be introduced in production systems in several temporal and spatial arrangements: rotation, relay, intercropping (Figure A1.3, Buckles and Barreto, 1996). In intercropping systems, velvet bean growth can become quite aggressive (Gilbert, 1998; Skerman et al., 1988). Velvet bean is usually planted as relay crop 30-40 days after maize, or used as a rotation crop in improved fallow systems.

Green manures are attractive where fertilizer is expensive, where weed control is a major cost factor, and where farmers have little access to off-farm employment and place a low opportunity cost on family labor (Soule, 1997). Green manure use declined when cheap inorganic nitrogen sources became available and pressures on farmers space time and energy have increased (Buckles et al., 1998; Meelu, 1994).

Velvet bean was probably introduced from the US into Meso America around the 1920s to serve as forage crop in banana plantation systems. In the US, velvet bean was intercropped with summer season maize (Buckles et al., 1998). In Guatemala a different strategy was developed, where velvet bean was rotated with winter season maize. This system also moved to Honduras, where it slowly began to replace traditional slash-and-burn agriculture. The ability of velvet bean to control weeds and to improve soil fertility was recognized. A field of velvet bean became known as 'abonera' or 'fertilized field'. The maize-velvet bean cropping system reduces labour costs by controlling weeds and increases maize productivity by supplying nutrients when they are most needed (Buckles et al., 1998).

The maize-velvet bean cropping system represented a departure from traditional slash and burn systems characteristic of the humid tropics, which require long fallow periods. However, population growth lead to increasing land pressure and intensification of cropping calendar. Without external inputs, intensive cropping systems using the slash and burn techniques lead to soil fertility decline, increase in weed invasion and soil erosion. This undermines the productivity and sustainability of the shifting cultivation system (Buckles et al., 1998; Thurston et al., 1994).

The reverse of the 'abonera' cropping system, in which maize is grown in the summer season and velvet bean in the winter season is still found in limited amount in Veracruz, Mexico. However, less advantage of the GMCC is experienced because of its limited growth in the drier winter season.

Another option used to intensify maize production systems is to relay crop velvet bean 30-40 days after maize. This system is found in Mexico, Guatemala and Honduras (Eilittä, 1998; Soule, 1997; CIDICCO, 1997; Jerome Fournier pers. communication). The benefit of this system is that it can replace 50 to 100% of the fertilizer normally. Evidence suggests that fertilizer substitution rates in maize of 60 to 80 kg N ha^{-1} can be attained (Lobo-Burle et al., 1992; Moscoso and Raun, 1991). Weed populations can be reduced to up to two thirds in Veracruz (Buckles and Perales, 1995). Experiments with velvet bean relay cropping systems in Mexico suggest that soil erosion can be is reduced from 50 ton ha^{-1} y^{-1} to 4 ton ha^{-1} y^{-1} (Lopez, 1993). The amount of erosion the cover crop can control depends on the rainfall and soil characteristics.

Conservation tillage with crop residue retention (CTCRR)
The Soil Conservation Society of America (1976, as cited by Violic et al., 1989) defined 'conservation tillage' as any system that reduces soil and water losses relative to conventional tillage. The terminology used in the definition has caused confusion. The words 'tillage' and 'conservation' are unclear and subjective. Many practices are related to tillage and it is unclear whether conservation relates to soil, water or other factors (Erenstein, 1996, 1997). More narrowly, the United States Conservation Tillage Information Center (CTIC, 1994) defined conservation tillage as any system in which at least 30% of the soil surface is covered by crop residues after planting to reduce soil erosion by water. We must recognize two requirements for conservation tillage: that of reduced tillage and residue use.

In the tropics the success of conservation tillage has been most pronounced in Brazil and Argentina. In Brazil the success has been rather recent, while beginning 1990s there was less than 1 million ha under no-tillage (NT) systems, by 1998 the area under NT is around 10 million ha (Derpsh, 1998; Amado and Reinert, 1998; Hebblethwaite, 1998). In Mexico, national agricultural research networks have generally established trials evaluating CTCRR with 30, 60 or 100% residue retention (INIFAP, Scopel et al., 1998). The relation between amount of residues, cover and relative erosion has been determined by several sources (see Scopel, 1998 ; Glo and Martin, 1995; Shaxon et al., 1989). Reducing tillage conserves soil moisture and reduces production costs. Leaving residues in the field further conserves moisture both by reducing runoff and evaporation from the soil surface. In a socio-economic context, residues are often seen as a valuable source of animal feed, either by the farmer or by pastoralists, who may possess rights to graze livestock (Erenstein, 1996). However, usually enough residues are available after grazing of livestock on the field. Campaigns in Mexico to promote conservation tillage have emphasized no burning of residues, as this is one of the major factors that prevent adoption. Another constraint is the availability of direct seeding equipment.

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Appendix 3.1 Description of applying the linear model of co-regionalization[2]

The linear model of co-regionalization is a model that ensures that estimates derived from co-kriging have positive or zero variance. For example there is the following model:

$$\Gamma(h)=\begin{bmatrix}\gamma_{11}(h) & \gamma_{12}(h)\\ \gamma_{21}(h) & \gamma_{22}(h)\end{bmatrix}=\begin{bmatrix}b_{11}^{0} & b_{12}^{0}\\ b_{21}^{0} & b_{22}^{0}\end{bmatrix}*g_0(h)+\begin{bmatrix}b_{11}^{1} & b_{12}^{1}\\ b_{21}^{1} & b_{22}^{1}\end{bmatrix}*g_1(h)$$

where:

$\Gamma(h)$ = the semi-variogram matrix, and

$g_l(h)$ = basic variogram model in the linear model of co-regionalization.

So the basic variogram models are the same for every variogram, or cross-variogram. In this case, $g_0(h)$ is the nugget model and $g_1(h)$ is the sill model.

For a linear model of co-regionalization, all of the co-regionalization matrices (B_l) should be positive definite. A symmetric matrix is positive semi-definite if its determinants and all its principal minor determinants are non-negative. If $N_v = 2$, as in the example or with the precipitation data:

$b_{11}^{1} \geq 0$ and $b_{22}^{1} \geq 0$

$b_{11}^{1}b_{22}^{1} - b_{12}^{1}b_{12}^{1} \geq 0 \rightarrow b_{12}^{1} \leq \sqrt{b_{11}^{1}b_{22}^{1}}$.

Thus, when fitting the basic structure $g_l(h)$ in the linear model of co-regionalization, these four general rules should be taken into account:

$b_{ij}^{l} \neq 0 \rightarrow b_{ii}^{l} \neq 0$ and $b_{jj}^{l} \neq 0$

$b_{ii}^{l} = 0 \rightarrow b_{ij}^{l} = 0 \ \ \forall j$

b_{ij}^{l} may be equal to zero

$b_{ii}^{l} \neq 0$ and $b_{jj}^{l} \neq 0 \rightarrow b_{ij}^{l} = 0$ or $b_{ij}^{l} \neq 0$.

To fit a linear model of co-regionalization:

- Take the smallest set of semi-variogram models $g_l(h)$ that captures the major features of all N_v.
- Estimate the sill and the slope of the semi-variogram models $g_l(h)$ while taking care that the co-regionalization matrices are positive definite.
- Evaluate the ‘goodness’ of fit of all models. When a compromise is necessary, then the priority lies in fitting a model to the variogram of the variable to be predicted, as opposed to the variogram of the co-variable or cross-variogram.

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[2] As described by Goulard and Voltz, 1992.

Appendix 3.2 Data set comparison for precipitation

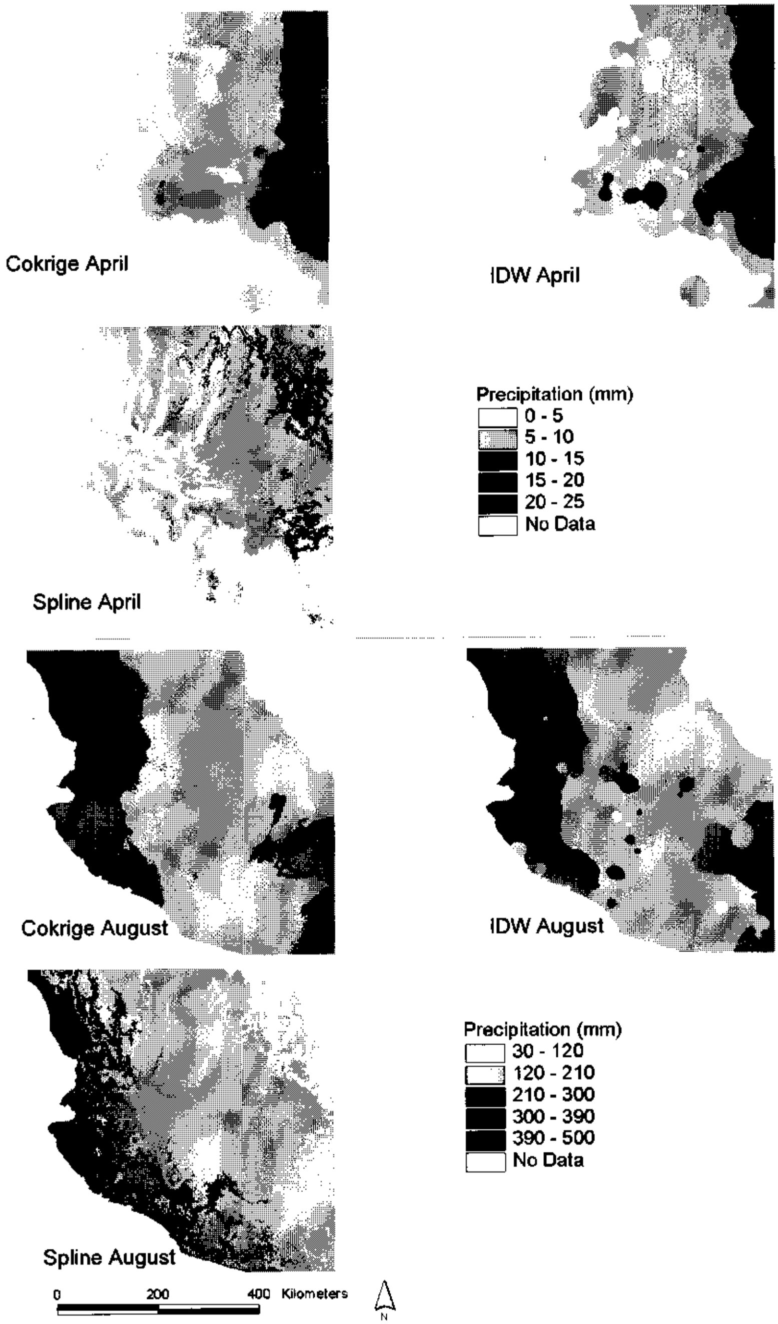
Comparison between the data set with 320 points and the data set with 194 points.

	Variable	Model	Nugget	Sill	Range	ssd/sst	Nugget diff.[1]	Rel. nugget diff. (%)[2]
198	January	Exponential	0.0254	0.073	1.36	0.086	0.0071	21.8
320	January	Exponential	0.0325	0.079	4.06	0.025		
198	February	Spherical	0.0099	0.027	1.07	0.155	0.0021	17.8
320	February	Spherical	0.0120	0.018	1.10	0.236		
198	March	Gaussian	0.0226	0.068	9.47	0.487	–0.0019	–9.2
320	March	Gaussian	0.0207	0.004	2.65	0.631		
198	April	Gaussian	0.0175	0.192	9.47	0.073	–0.0014	–8.7
320	April	Gaussian	0.0161	0.243	9.47	0.039		
198	May	Spherical	0.0786	3.410	9.47	0.055	0.0174	–0.3
320	May	Spherical	0.0594	0.322	9.47	0.066		
198	June	Spherical	0.4340	5.400	5.33	0.019	0.1210	21.8
320	June	Spherical	0.5550	5.090	6.09	0.014		
198	July	Spherical	0.9930	8.940	6.00	0.022	0.4520	36.7
320	July	Spherical	1.2300	6.470	6.00	0.034		
198	August	Spherical	0.7780	13.70	7.00	0.063	0.2920	27.3
320	August	Spherical	1.0700	10.30	7.00	0.094		
198	September	Gaussian	1.8500	20.50	3.58	0.061	0.0200	1.1
320	September	Gaussian	1.8700	95.30	9.47	0.050		
198	October	Gaussian	0.4750	4.980	5.98	0.017	–0.0520	–12.3
320	October	Gaussian	0.4230	10.20	8.95	0.025		
198	November	Exponential	0.0129	0.170	1.38	0.038	0.0162	55.7
320	November	Exponential	0.0291	0.428	7.00	0.037		
198	December	Spherical	0.0058	0.179	9.47	0.019	0.0015	20.5
320	December	Spherical	0.0073	0.139	9.47	0.075		

[1] Nugget difference = nugget of the big data set – nugget of the small data set.

[2] Relative nugget difference is: $\left(\frac{nugget320 - nugget194}{nugget320}\right) * 100\%$

Appendix 3.3 Interpolated monthly precipitation surfaces from IDWA, splining and co-kriging for April, and August



Appendix 3.4 Basic surface characteristics

Station values and DEM surface values for elevation.

Elevation	Measured (m)	DEM (m)
Minimum	27	1
Maximum	2361	4019
Mean	1396	1455

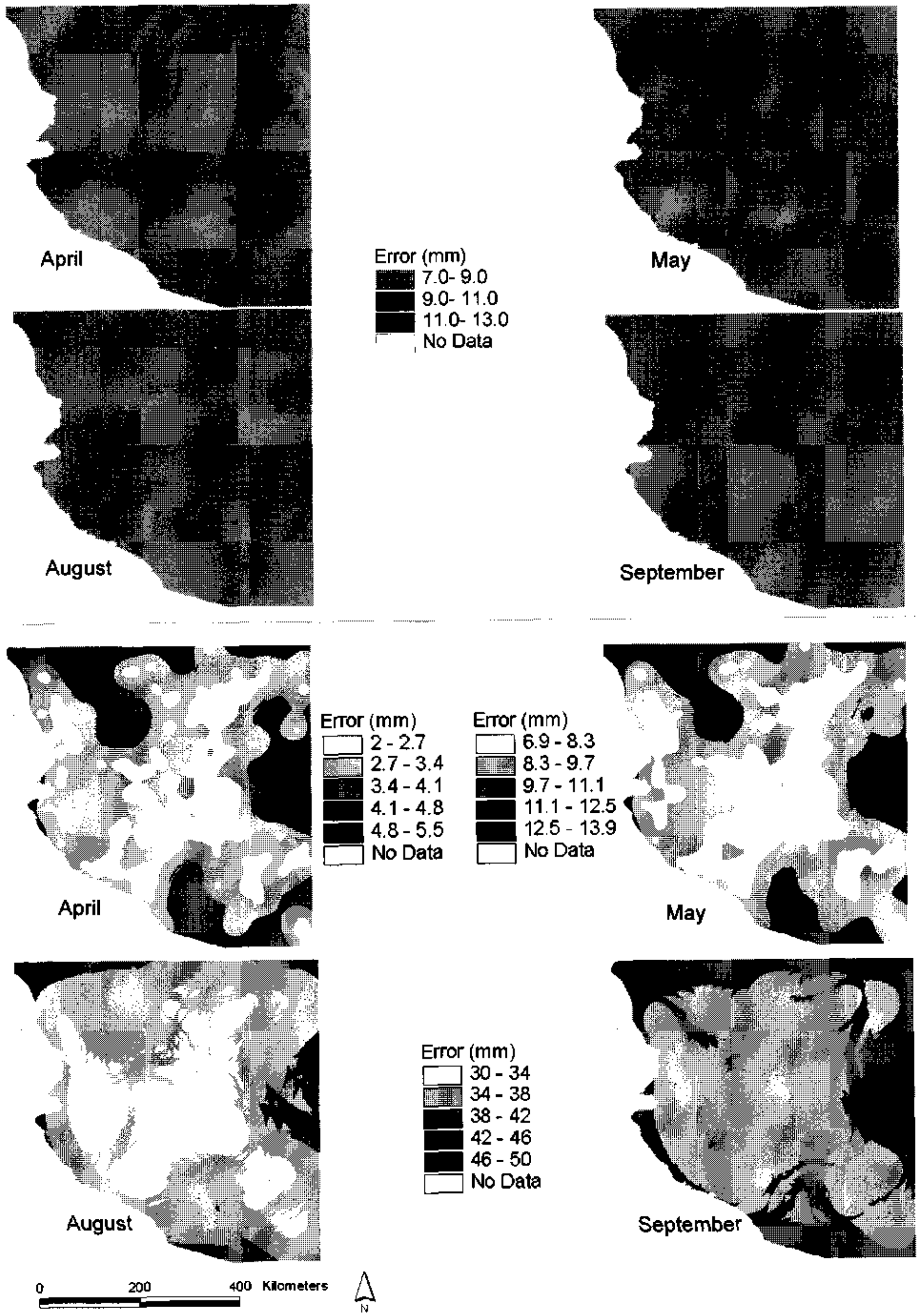
Measured values and interpolated surface values for precipitation.

April	Measured (mm)	IDW (mm)	Spline (mm)	Co-krige (mm)
Minimum	0.0	0.0	−1.4	−1.5
Maximum	20.3	24.9	15.6	20.4
Mean	5.9	5.2	284.7	6.2
May	Measured (mm)	IDW (mm)	Spline (mm)	Co-krige (mm)
Minimum	3.8	3.7	−11.0	1.3
Maximum	60.8	75.1	57.1	57.1
Mean	27.2	22.6	24.0	24.9
August	Measured (mm)	IDW (mm)	Spline (mm)	Co-krige (mm)
Minimum	76.8	47.0	55.7	38.0
Maximum	426.8	495.7	317.3	423.1
Mean	197.6	216.7	175.4	198.3
September	Measured (mm)	IDW (mm)	Spline (mm)	Co-krige (mm)
Minimum	95.8	44.0	28.9	44.5
Maximum	429.6	472.4	280.0	382.8
Mean	166.4	186.7	143.6	164.4

Measured values and interpolated surfaces for maximum temperature (°C).

April	Measured °C	IDWA °C	Spline °C	Co-krige °C
Minimum	25.4	24.7	14.9	27.5
Maximum	40.1	40.9	40.0	38.8
Mean	31.9	32.0	31.0	32.0
May	Measured °C	IDWA °C	Spline °C	Co-krige °C
Minimum	26.9	25.4	15.7	28.0
Maximum	41.2	41.2	41.2	40.1
Mean	32.9	33.0	31.9	33.2
August	Measured °C	IDWA °C	Spline °C	Co-krige °C
Minimum	21.3	20.9	12.3	22.6
Maximum	35.2	35.5	36.0	34.7
Mean	28.3	29.4	28.1	28.8
September	Measured °C	IDWA °C	Spline °C	Co-krige °C
Minimum	21.3	21.3	12.1	22.5
Maximum	35.5	35.1	35.6	35.4
Mean	28.2	29.1	27.8	28.7

Appendix 3.5 Prediction error surfaces for precipitation interpolated by splining and by co-kriging



Appendix 7.1 Synthesis of cropping systems information

Using expert knowledge and existing literature sources agronomic cropping system and management information was collected on the most important maize production systems for Honduras. System 1 is a summer maize winter fallow system that occurs over all of Honduras. System 2 and 3 are alternatives, namely cropping either common bean or velvet bean in the winter season. System 4 is a traditional bush fallow system where maize is cropped in both summer and winter seasons, and consequently a four-year fallow period follows. System 5 is a continuous maize cropping system. Systems 4 and 5 are only possible in wetter regions of Honduras where second season rainfall is allows double maize cropping. System 6 is a continuous maize system with a fallow once every fifth cropping season. System 7 is a continuous maize system without fallow. Systems 8 and 9 are alternatives to continuous maize cropping, in areas where summer maize is less viable due to high disease pressure (ear rots high humidity). System 10 was a maize fallow system in a 2020 climate change scenario (Hennessy, 1998) In the simulation study, an equal level of inputs for the individual crop management is assumed to facilitate comparison between these systems.

Cropping systems calendar for maize cropping systems in Honduras.

× 3

Rotation number	Year 1		Year 2		Year 3		Year 4	
	summer	winter	summer	winter	summer	winter	summer	winter
1	Maize	Fallow	M	F	M	F	M	F
2	Maize	V. bean	M	V. bean	M	V. bean	M	V. bean
3	Maize	C. bean	M	C. bean	M	C. bean	M	C. bean
4	Maize	Maize	M	M	F	F	F	F
5	Maize	Maize	M	M	V. bean	M	M	M
6	Maize	Maize	M	M	F	M	M	M
7	Maize	Maize	M	M	M	M	M	M
8	V. bean	Maize	V. bean	M	V. bean	M	V. bean	M
9	C. bean	Maize	C. bean	M	C. bean	M	C. bean	M
10	MaizeCC	FallowCC	M-CC	F-CC	M-CC	F-CC	M-CC	F-CC

M = Maize; F = Fallow; V. bean = Velvet bean; C. bean= Common bean

CC = Assuming climate change year 2020 model, grid covering Honduras (Hennessy, 1998)

Crop	Cultivar	Population pl m^{-2}	Row width cm	N fertilizer rate kg ha^{-1}
Maize	HB83	4	80	23
V. bean	Veracruz black	3.5	80	-
C. bean	Rabia de Gato	15	70	9

(Banegas et al., 1975; SRN, 1978; CATIE, 1979; Valle Moreno et al., 1982; Amaya, 1987; Rivera, 1987; Zea et al., 1991; Zea, 1992; Barreto et al., 1992; Gordon et al., 1993; Lopez et al., 1993; Brizuela and Barreto, 1996; CIDICCO, 1997; Fournier and Lopez, 1997; Gordon et al., 1997; Larios et al., 1997; Buckles et al., 1998; Eilittä, 1998; S. Beebe, pers. communication, 2000).

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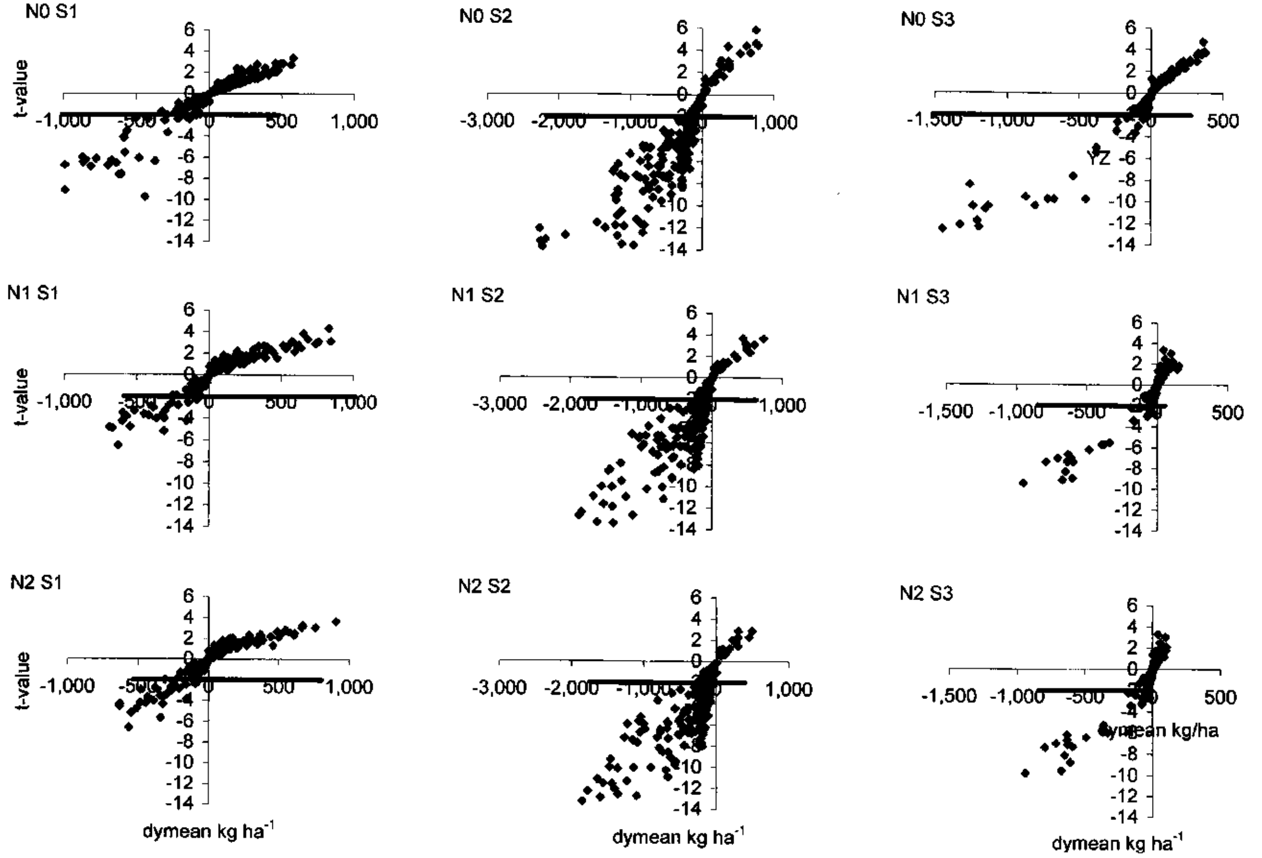
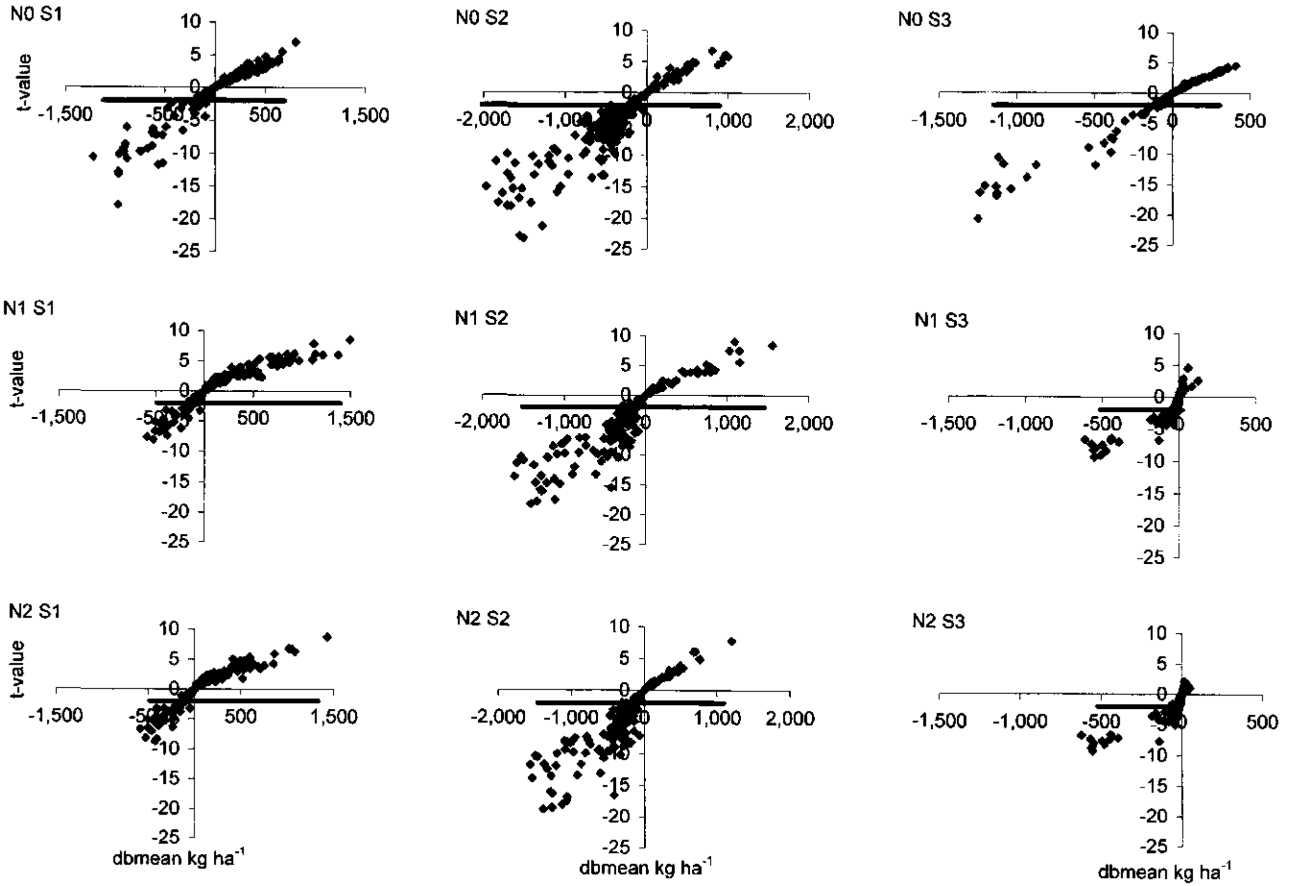
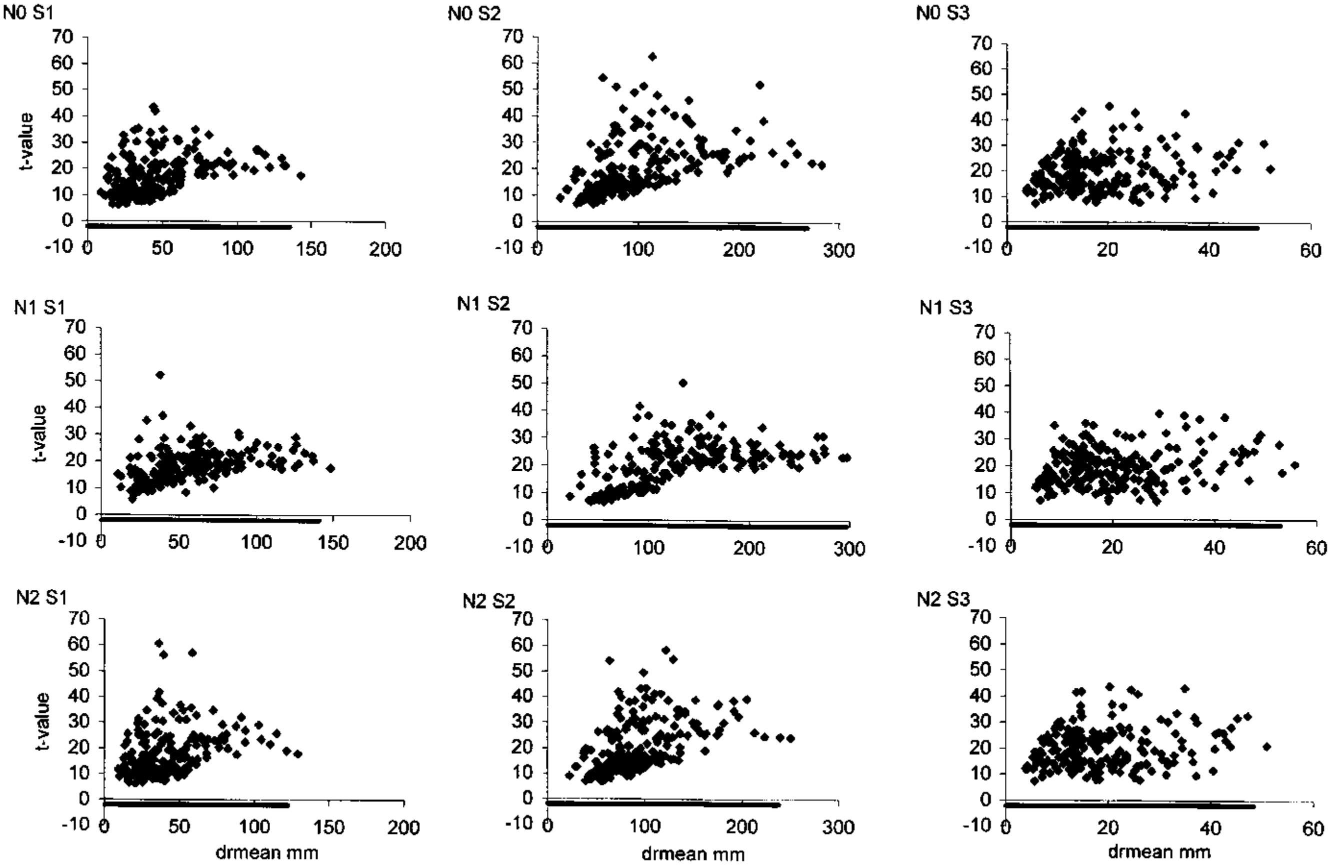
Appendix 8.1 Student *t*- values for delta performance variables (0 - 100% residue retention) for three soil scenarios and three nitrogen management levels (N0=0 ; N1=150; N2=250 kg ha^{-1}). (dy = maize grain yield)



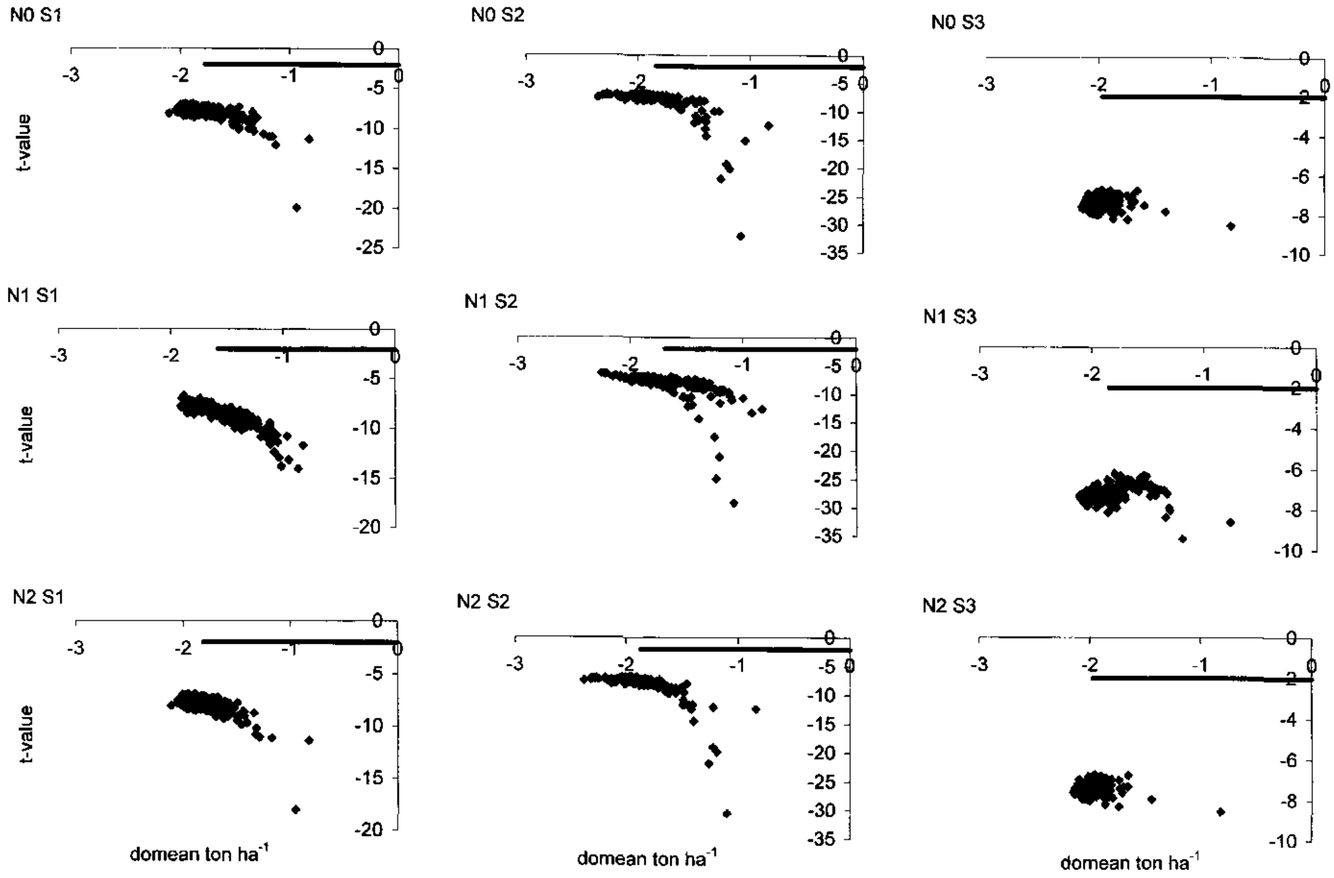
Appendix 8.1 Continued. (db = maize biomass)



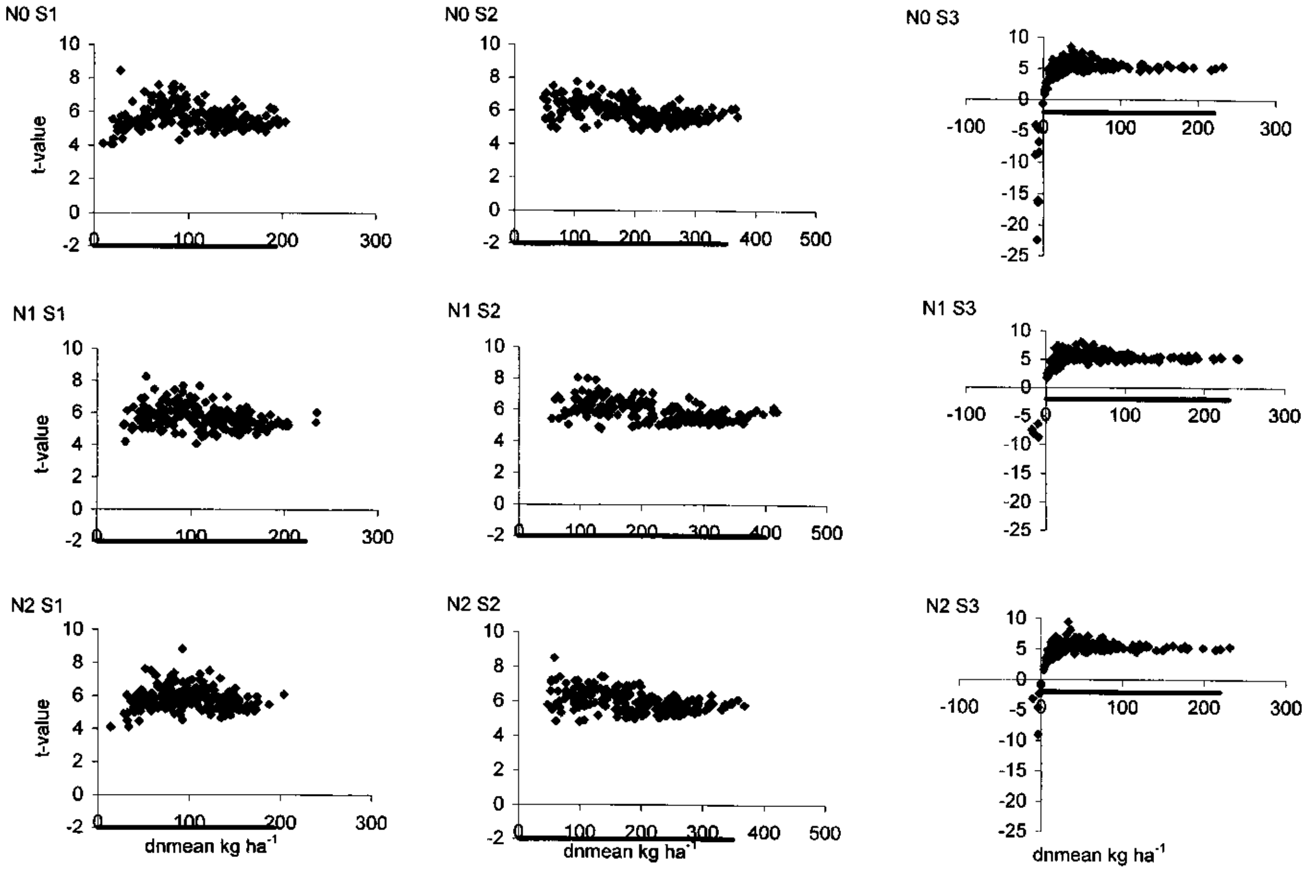
Appendix 8.1 Continued. (dr = runoff)



Appendix 8.1 Continued. (do = soil organic carbon)



Appendix 8.1 Continued. (dn = soil organic nitrogen)



Appendix 8.2 Cannonical correlation analysis between delta performance variables and seasonal climate variables for three soil scenarios and for the medium farmer nitrogen management level (N1=150 kg ha^{-1}).

S1 Shallow silty clay on non sloping topography

					Canonical Correlation Analysis Eigenvalues of INV(E) × H = CanRsq/(1−CanRsq)				Test of H0: The canonical correlations in the current row and all that follow are zero				
	Canonical Correlation	Adjusted Canonical Correlation	Approx Standard Error	Squared Canonical Correlation	Eigenvalue	Difference	Proportion	Cumulative	Likelihood Ratio	Approx F	Num DF	Den DF	Pr > F
1	0.875101	0.862950	0.01660	0.765801	3.2699	0.7821	0.4297	0.4297	0.0162950	29.465	42	880.56	1E-04
2	0.844561	0.841077	0.02033	0.713283	2.4878	1.4952	0.3269	0.7566	0.0695777	23.803	30	754	1E-04
3	0.705789	0.692415	0.03558	0.498137	0.9926	0.4493	0.1304	0.8871	0.2426702	16.717	20	627.792	1E-04
4	0.593316	0.585214	0.04593	0.352024	0.5433	0.3533	0.0714	0.9585	0.4835392	13.247	12	502.984	1E-04
5	0.399589	0.373443	0.05957	0.159671	0.1900	0.0639	0.0250	0.9834	0.7462305	10.034	6	382	1E-04
6	0.334631	.	0.06295	0.111978	0.1261	.	0.0166	1	0.8880221	12.105	2	192	1E-04

Multivariate Statistics and F Approximations

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.01629503	29.4657	42	880.5598	0.0001
Pillai's Trace	2.60089491	20.9875	42	1152	0.0001
Hotelling-Lawley Trace	7.60958537	33.5788	42	1112	0.0001
Roy's Greatest Root	3.26987206	89.6879	7	192	0.0001

Correlations Between the performance variables and the Canonical Variables of the environment

	ENV1	ENV2	ENV3	ENV4	ENV5	ENV6
ΔYield	0.4829	0.0018	0.3296	-0.1730	-0.2466	0.0360
ΔstdYield	-0.3797	0.3335	-0.3781	0.0857	0.2041	0.0987
ΔBiomass	0.4679	-0.1743	0.4602	-0.2481	-0.1061	0.0098
ΔRunoff	0.7935	-0.2031	0.2327	-0.0025	-0.0074	0.0350
ΔOC	0.2424	-0.5894	-0.0096	-0.3056	-0.1183	0.0965
ΔON	-0.0149	-0.4704	0.5120	0.1933	-0.0519	0.0672

Correlations Between the environment and the Canonical Variables of the performance variables

	PERF1	PERF2	PERF3	PERF4	PERF5	PERF6
GS Precipitation	0.6261	0.4683	0.0355	-0.1052	0.0512	0.1207
GS Mean Temperature	-0.1665	0.7536	-0.2780	0.0260	-0.0271	0.0215
GS Max. Temeprature	-0.2776	0.6946	-0.2554	0.0329	-0.0081	0.0991
GS. Min. Temperature	-0.0375	0.7516	-0.2798	0.0138	-0.0470	-0.0609
GS Temperature difference	-0.4192	-0.0401	0.0460	0.0745	0.0563	0.2855
GS Number of rainy days	0.4456	0.3175	0.4594	-0.2259	-0.0125	0.0559
GS Solar radiation	0.3213	0.0536	0.1570	0.2743	0.2553	-0.0965

Appendix 8.2 Continued.

S2 Shallow silty clay on sloping topography

					Canonical Correlation Analysis Eigenvalues of INV(E) × H = CanRsq/(1−CanRsq)				Test of H0: The canonical correlations in the current row and all that follow are zero				
	Canonical Correlation	Adjusted Canonical Correlation	Approx Standard Error	Squared Canonical Correlation	Eigenvalue	Difference	Proportion	Cumulative	Likelihood Ratio	Approx F	Num DF	Den DF	Pr > F
1	0.923661	0.918818	0.01041	0.853150	5.8097	3.7697	0.5873	0.5873	0.0121477	32.724	42	880.56	1E-04
2	0.819177	0.805576	0.02332	0.671051	2.0400	0.5377	0.2062	0.7935	0.0827217	21.731	30	754	1E-04
3	0.774828	0.773440	0.02833	0.600359	1.5022	1.0742	0.1519	0.9454	0.2514726	16.203	20	627.792	1E-04
4	0.547497	0.535002	0.04964	0.299753	0.4281	0.3254	0.0433	0.9887	0.6292462	8.02	12	502.984	1E-04
5	0.305184	0.288884	0.06429	0.093137	0.1027	0.0935	0.0104	0.9991	0.8986060	3.495	6	382	0.002
6	0.095418	0.076475	0.07024	0.009105	0.0092	.	0.0009	1	0.9908955	0.882	2	192	0.416

Multivariate Statistics and F Approximations

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.01214766	32.7247	42	880.5598	0.0001
Pillai's Trace	2.52655496	19.9513	42	1152	0.0001
Hotelling-Lawley Trace	9.89186798	43.6498	42	1112	0.0001
Roy's Greatest Root	5.80968029	159.351	7	192	0.0001

Correlations Between the performance variables and the Canonical Variables of the environment

	ENV1	ENV2	ENV3	ENV4	ENV5	ENV6
ΔYield	0.4547	0.2569	-0.2938	-0.1464	0.1979	-0.0147
ΔstdYield	-0.2645	0.4793	-0.1418	0.2930	-0.1016	0.0363
ΔBiomass	0.6438	0.0026	0.1966	-0.2872	0.1176	0.0154
ΔRunoff	0.6619	-0.4375	0.2799	-0.0734	0.0579	0.0123
ΔOC	-0.0517	-0.1986	-0.3691	-0.3363	0.1500	0.0290
ΔON	-0.1498	-0.1064	0.6267	0.1052	0.1473	0.0173

Correlations Between the environment and the Canonical Variables of the performance variables

	PERF1	PERF2	PERF3	PERF4	PERF5	PERF6
GS Precipitation	0.8576	0.2476	-0.1373	0.0025	-0.0111	0.0102
GS Mean Temperature	0.0321	0.6353	-0.3951	0.1864	0.0270	-0.0102
GS Max. Temeprature	-0.0469	0.6730	-0.3776	0.1333	0.0066	0.0113
GS. Min. Temperature	0.1106	0.5433	-0.3823	0.2248	0.0484	-0.0312
GS Temperature difference	-0.2635	0.2670	0.0070	-0.1181	-0.0621	0.0769
GS Number of rainy days	0.7187	0.2779	0.3683	-0.1178	0.0064	-0.0059
GS Solar radiation	0.3078	-0.2516	0.1323	0.3567	-0.1550	0.0062

Appendix 8.2 Continued.

S3 Deep sandy loam on non-sloping topography

					Canonical Correlation Analysis Eigenvalues of INV(E) × H = CanRsq/(1−CanRsq)				Test of H0: The canonical correlations in the current row and all that follow are zero				
	Canonical Correlation	Adjusted Canonical Correlation	Approx Standard Error	Squared Canonical Correlation	Eigenvalue	Difference	Proportion	Cumulative	Likelihood Ratio	Approx F	Num DF	Den DF	Pr > F
1	0.938442	0.93438	0.00846	0.880673	7.3804	3.5578	0.5821	0.5821	0.0080576	37.635	42	880.56	1E-04
2	0.890305	0.886197	0.0147	0.792643	3.8226	2.8854	0.3015	0.8836	0.0675256	24.17	30	754	1E-04
3	0.695557	0.681511	0.03659	0.483799	0.9372	0.5062	0.0739	0.9576	0.3256485	12.635	20	627.792	1E-04
4	0.548833	0.538426	0.04954	0.301217	0.4311	0.3314	0.034	0.9916	0.6308561	7.972	12	502.984	1E-04
5	0.300988	0.28468	0.06447	0.090594	0.0996	0.0923	0.0079	0.9994	0.9027927	3.34	6	382	0.003
6	0.085277	0.062526	0.07037	0.007272	0.0073	.	0.0006	1	0.9927279	0.703	2	192	0.496

Multivariate Statistics and F Approximations

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.00805761	37.6357	42	880.5598	0.0001
Pillai's Trace	2.55619826	20.3591	42	1152	0.0001
Hotelling-Lawley Trace	12.6781787	55.945	42	1112	0.0001
Roy's Greatest Root	7.38035114	202.433	7	192	0.0001

Correlations Between the performance variables and the Canonical Variables of the environment

	ENV1	ENV2	ENV3	ENV4	ENV5	ENV6
ΔYield	-0.0873	0.7055	0.2044	0.1345	0.1402	0.0002
ΔstdYield	-0.0129	-0.4749	-0.1497	-0.0358	-0.0984	-0.0637
ΔBiomass	-0.0094	0.7220	0.3647	0.1301	0.0242	0.0058
ΔRunoff	0.8143	0.4270	0	0.0688	-0.0097	0.0016
ΔOC	0.1309	-0.1914	0.5401	-0.2445	0.1054	0.0087
ΔON	-0.2008	-0.6991	-0.0199	0.2927	0.0166	-0.0189

Correlations Between the environment and the Canonical Variables of the performance variables

	PERF1	PERF2	PERF3	PERF4	PERF5	PERF6
GS Precipitation	0.5888	0.6549	0.0834	-0.0102	-0.0184	0.0162
GS Mean Temperature	-0.1635	0.5313	-0.3697	-0.2608	-0.0414	0.0203
GS Max. Temeprature	-0.1947	0.4357	-0.3148	-0.2570	-0.0399	0.0407
GS. Min. Temperature	-0.1170	0.5864	-0.3954	-0.2466	-0.0386	-0.0023
GS Temperature difference	-0.1499	-0.2126	0.0969	-0.0090	0.0106	0.0782
GS Number of rainy days	0.1869	0.6554	0.4271	0.0965	0.0301	-0.0011
GS Solar radiation	0.1961	0.1615	-0.1925	0.4232	-0.1191	-0.0039

Appendix 8.3 R-squared between delta performance variables (no residue retention-residue retention) and seasonal climate independent variables for three soil scenarios and three nitrogen management levels (N0=0; N1=150; N2=250 kg ha^{-1}).

	Soil scenario[1]	N Level	Season[2]	Ind. variables	Method	Δ yield	Δ biomass	Ind. variables	Method	Δ runoff	Δ ocmean	Δ onmean	Δ octrend	Δ ontrend
S1	shallow silty clay non-s. t.	N0	in	precip	single	0.29	0.28	precip, nrd, tmeanannual	single	0.73	0.59	0.45	0.53	0.49
S1	shallow silty clay non-s. t.	N0	off	precip	single	0.29	0.30	precip, nrd, tmeanannual	single	0.55	0.66	0.51	0.56	0.54
S1	shallow silty clay non-s. t.	N0	year	precip	single	0.32	0.31	precip, nrd, tmeanannual	single	0.76	0.59	0.47	0.53	0.51
S1	shallow silty clay non-s. t.	N0	in	precip, nrd*	step	0.60	0.61	precip, nrd, tmeanannual*	step	0.76	0.71	0.52	0.66	0.55
S1	shallow silty clay non-s. t.	N0	off	precip, nrd*	step	0.37	0.37	precip, nrd, tmeanannual*	step	0.59	0.73	0.55	0.63	0.57
S1	shallow silty clay non-s. t.	N1	in	precip	single	0.14	0.08	precip, nrd, tmeanannual	single	0.63	0.26	0.40	0.17	0.45
S1	shallow silty clay non-s. t.	N1	off	precip	single	0.22	0.20	precip, nrd, tmeanannual	single	0.57	0.34	0.43	0.24	0.45
S1	shallow silty clay non-s. t.	N1	year	precip	single	0.16	0.10	precip, nrd, tmeanannual	single	0.65	0.27	0.44	0.18	0.47
S1	shallow silty clay non-s. t.	N1	in	precip, nrd*	step	0.43	0.42	precip, nrd, tmeanannual*	step	0.68	0.49	0.45	0.37	0.48
S1	shallow silty clay non-s. t.	N1	off	precip, nrd*	step	0.29	0.33	precip, nrd, tmeanannual*	step	0.59	0.48	0.46	0.34	0.48
S1	shallow silty clay non-s. t.	N2	in	precip	single	0.17	0.13	precip, nrd, tmeanannual	single	0.63	0.19	0.33	0.12	0.38
S1	shallow silty clay non-s. t.	N2	off	precip	single	0.23	0.21	precip, nrd, tmeanannual	single	0.53	0.25	0.35	0.17	0.39
S1	shallow silty clay non-s. t.	N2	year	precip	single	0.19	0.15	precip, nrd, tmeanannual	single	0.66	0.20	0.34	0.13	0.39
S1	shallow silty clay non-s. t.	N2	in	precip, nrd*	step	0.43	0.46	precip, nrd, tmeanannual*	step	0.69	0.44	0.36	0.32	0.40
S1	shallow silty clay non-s. t.	N2	off	precip, nrd*	step	0.27	0.29	precip, nrd, tmeanannual*	step	0.56	0.37	0.37	0.25	0.41
S2	shallow silty clay slope t.	N0	in	precip	single	0.36	0.50	precip, nrd, tmeanannual	single	0.74	0.14	0.17	0.38	0.41
S2	shallow silty clay slope t.	N0	off	precip	single	0.25	0.45	precip, nrd, tmeanannual	single	0.59	0.28	0.33	0.23	0.26
S2	shallow silty clay slope t.	N0	year	precip	single	0.38	0.54	precip, nrd, tmeanannual	single	0.75	0.15	0.189	0.37	0.40
S2	shallow silty clay slope t.	N0	in	precip, nrd*	step	0.63	0.72	precip, nrd, tmeanannual*	step	0.77	0.53	0.53	0.50	0.51
S2	shallow silty clay slope t.	N0	off	precip, nrd*	step	0.46	0.53	precip, nrd, tmeanannual*	step	0.62	0.45	0.46	0.30	0.32
S2	shallow silty clay slope t.	N1	in	precip	single	0.29	0.31	precip, nrd, tmeanannual	single	0.66	0.08	0.07	0.33	0.35
S2	shallow silty clay slope t.	N1	off	precip	single	0.05	0.32	precip, nrd, tmeanannual	single	0.54	0.06	0.08	0.16	0.18
S2	shallow silty clay slope t.	N1	year	precip	single	0.30	0.34	precip, nrd, tmeanannual	single	0.66	0.09	0.09	0.31	0.33
S2	shallow silty clay slope t.	N1	in	precip, nrd*	step	0.57	0.61	precip, nrd, tmeanannual*	step	0.70	0.05	0.44	0.43	0.45
S2	shallow silty clay slope t.	N1	off	precip, nrd*	step	0.35	0.37	precip, nrd, tmeanannual*	step	0.56	0.22	0.21	0.21	0.24

Appendix 8.3 Continued.

	Soil scenario[1]	N Level	Season[2]	Ind. variables	Method	Δ yield	Δ biomass	Ind. variables	Method	Δ runoff	Δ ocmean	Δ onmean	Δ octrend	Δ ontrend
S2	shallow silty clay slope t.	N2	in	precip	single	0.29	0.40	precip, nrd, tmeanannual	single	0.69	0.13	0.12	0.29	0.31
S2	shallow silty clay slope t.	N2	off	precip	single	0.15	0.32	precip, nrd, tmeanannual	single	0.48	0.05	0.07	0.10	0.13
S2	shallow silty clay slope t.	N2	year	precip	single	0.30	0.43	precip, nrd, tmeanannual	single	0.68	0.14	0.13	0.27	0.29
S2	shallow silty clay slope t.	N2	in	precip, nrd*	step	0.55	0.69	precip, nrd, tmeanannual*	step	0.71	0.53	0.49	0.39	0.41
S2	shallow silty clay slope t.	N2	off	precip, nrd*	step	0.37	0.38	precip, nrd, tmeanannual*	step	0.53	0.18	0.18	0.17	0.19
S3	deep sandy loam non-s. t.	N0	in	precip	single	0.30	0.34	precip, nrd, tmeanannual	single	0.83	0.43	0.32	0.66	0.68
S3	deep sandy loam non-s. t.	N0	off	precip	single	0.17	0.23	precip, nrd, tmeanannual	single	0.65	0.43	0.32	0.56	0.55
S3	deep sandy loam non-s. t.	N0	year	precip	single	0.31	0.35	precip, nrd, tmeanannual	single	0.87	0.43	0.33	0.65	0.66
S3	deep sandy loam non-s. t.	N0	in	precip, nrd*	step	0.72	0.81	precip, nrd, tmeanannual*	step	0.85	0.50	0.37	0.78	0.79
S3	deep sandy loam non-s. t.	N0	off	precip, nrd*	step	0.25	0.30	precip, nrd, tmeanannual*	step	0.66	0.49	0.35	0.62	0.61
S3	deep sandy loam non-s. t.	N1	in	precip	single	0.22	0.32	precip, nrd, tmeanannual	single	0.80	0.09	0.03	0.58	0.59
S3	deep sandy loam non-s. t.	N1	off	precip	single	0.04	0.08	precip, nrd, tmeanannual	single	0.69	0.06	0.01	0.54	0.54
S3	deep sandy loam non-s. t.	N1	year	precip	single	0.22	0.32	precip, nrd, tmeanannual	single	0.86	0.08	0.03	0.58	0.59
S3	deep sandy loam non-s. t.	N1	in	precip, nrd*	step	0.66	0.87	precip, nrd, tmeanannual*	step	0.84	0.20	0.08	0.71	0.72
S3	deep sandy loam non-s. t.	N1	off	precip, nrd*	step	0.14	0.18	precip, nrd, tmeanannual*	step	0.70	0.11	0.07	0.61	0.61
S3	deep sandy loam non-s. t.	N2	in	precip	single	0.22	0.32	precip, nrd, tmeanannual	single	0.81	0.08	0.03	0.56	0.58
S3	deep sandy loam non-s. t.	N2	off	precip	single	0.04	0.07	precip, nrd, tmeanannual	single	0.68	0.05	0.01	0.50	0.51
S3	deep sandy loam non-s. t.	N2	year	precip	single	0.22	0.32	precip, nrd, tmeanannual	single	0.86	0.07	0.02	0.55	0.57
S3	deep sandy loam non-s. t.	N2	in	precip, nrd*	step	0.66	0.87	precip, nrd, tmeanannual*	step	0.84	0.18	0.07	0.71	0.72
S3	deep sandy loam non-s. t.	N2	off	precip, nrd*	step	0.14	0.18	precip, nrd, tmeanannual*	step	0.7	0.09	0.07	0.58	0.58

[1] slope t. = sloping topography; non-s. t. = non-sloping topography.

[2] in season = June - October ; off season= November-May.

ACTIVITIES WITHIN THE PE&RC EDUCATIONAL PROGRAMME

C.T. de Wit Graduate School for Production Ecology and Resource Conservation

Term at CIMMYT Mexico:	Aug. 1996 - Aug. 2000
Term at Plant Production Systems Group Wageningen	Sept. 2000 - June 2001

Presentations of literature reviews and preparing project proposals

Besides writing the Ph.D. proposal presenting a plan on the thesis work, an Ecoregional proposal was prepared in which the Ph.D. project was incorporated and linked to several other activities at CIMMYT such as database management, soil science activities and socio-economic studies etc. Also some of the subjects – literature reviews on interpolation methods, interfacing GIS and modelling etc. – in this thesis have been presented to a wider scientific public, i.e. at CIMMYT on several occasions.

PE&RC Post-Graduate Courses workshops

During the term in Wageningen the author followed the post-graduate course:

- Operational tools for regional land use analysis, organized by dr. ir. Stoorvogel (and dr. ir. C. van de Vijver), 2001.

PE&RC PhD discussion groups

During the term in Wageningen the author took part in two discussion groups:

- Nr. 7) Sustainable land-use and resource management with a focus on the tropics, lead by prof. dr. ir. L. Stroosnijder, prof. dr. ir. H. van Keulen, dr. ir. J. Stoorvogel, and dr. ir. H. Olff.
- Nr. 9) Statistics, maths and modelling in Production Ecology and Resource Conservation, lead by prof. dr. ir. J. Grasman, prof. dr. ir. G. van Straten, prof. dr. ir. A. Stein, prof. dr. ir. A. Bregt.

Annual meeting of the PE&RC Graduate School

In 2000 the author presented a poster at the annual meeting of the graduate school:

- Genetically Modified Organisms: Benefits and risks, desirable or redundant

Seminars organized by PE&RC Graduate School

The author took part in several PE&RC seminars and seminar series:

- Models in Action (1996); Production Ecology: the bridge between theory and practice (1996); Water and Nitrogen: Prospects for improving the water and nitrogen use efficiency of crops (2000); Improving Water and Land Resource Management for Food, Livelihoods and Nature (2001) and was co-author for a presentation and paper in the seminar series on Spatial Statistics for Production Ecology (1999).

International symposia and conferences

At international symposia and conferences the author presented – intermediate – results of her work:

- Annual Agronomy meetings, ASA/SA/SSA (USA), 1997
- Latin America Regional Maize Agronomy Meetings, PRM (Panama), 1997
- Annual Agronomy meetings, ASA/SA/SSA (USA), 1998
- Annual Agronomy meetings, ASA/SA/SSA. (USA), 1999
- DSSAT modelling workshop, CIMMYT/IFDC (Mexico), 1999
- DSSAT modelling workshop, CIMMYT/IFDC (Mexico), 2000
- PE&RC workshop, CIMMYT/IICA (Mexico), 2000

Laboratory training and working visits

The author underwent training courses during the Ph.D. term e.g.:

- GIS Larenstein (The Netherlands), GIS (ArcView, IDRISI, ILWIS), 1996
- IFDC (International Fertilizer Development Institute; USA), Decision support systems for Agrotechnology Transfer, 1997

General courses

Minor language brush-up courses were followed:

- NIOW (The Netherlands), Spanish (3 weeks), 1996
- Cuernavaca Language School (Mexico) Spanish (2 weeks), 1996
- NIOW (The Netherlands), English writing (individual 3 days), 1997
- NIOW (The Netherlands), English writing (individual 3 days), 1998

Teaching obligations

Within the lecture course Agroecological characterization (F 350-241) of the Group of Plant Production Systems, Wageningen University (The Netherlands), the author prepared and presented a lecture in 2001.

PUBLICATION LIST

Refereed papers

Hartkamp, A.D., G. Hoogenboom, J.W. White. 2001. Adaptation of the CROPGRO growth model to velvet bean as a green manure cover crop: I. Model development. Field Crops Research (accepted).

Hartkamp, A.D., G. Hoogenboom, R. Gilbert, T. Benson, S.A. Tarawali, A. Gijsman, W. Bowen, J.W. White. 2001. Adaptation of the CROPGRO growth model to velvet bean as a green manure cover crop: II. Model evaluation and testing. Field Crops Research (accepted).

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Hartkamp, A.D., J.W. White, A. Rodriguez. 1999. Global maize production environments. A GIS-based approach. Agronomy Abstracts vol. 65. ASA/CSSA/SSSA. Madison, WI. {Annual Meeting, 91; Salt Lake City, USA; 31 Oct. - 4 Nov., 1999}

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EPILOGUE AND ACKNOWLEDGEMENTS

After graduating from Wageningen Agricultural University, I thought – slightly indoctrinated by the general mood concerning the poor job market at that time – that it would be impossible to find a challenging and scientifically rigorous job in international agriculture. However, when I set my eyes on the position of Associate Scientist in crop simulation modelling and GIS at CIMMYT, as advertized by the Dutch Ministry of Foreign Affairs, I was pleasantly surprised. This was exactly what I was looking for! During my time at CIMMYT, I realized that an international scientist must continue to advance in scientific knowledge and education. I started looking for options to present the work as Ph.D. research...

This thesis would not have been possible without the valuable effort of many scientists around the world. The support and encouragement of family and friends is greatly acknowledged.

Jeff White, The Great White Chief, you helped me with the formulation of ideas in this work. Without your scientific insight and rigour, your continuous encouragement, this work would not have resulted in this thesis. Numerous times you edited my work so that it would be more digestible for the general pubic. In this area I still can learn.

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Dewi Hartkamp

Utrecht, April 2002

ABOUT THE AUTHOR

Agnes Dewi Hartkamp was born on the 7th of December 1971 in Jakarta, Indonesia. After completing primary school in Egypt and England, she entered the Dutch school system in 1983. In 1989, she obtained her VWO diploma from the Menso Alting College in Hoogeveen. In September of that same year she started her MSc. studies in Tropical Land Use, with specialization in crop science, at Wageningen Agricultural University. In 1992 she conducted her practical training in the Eastern Hills of Nepal, surveying the taxonomic variation, cultivation and marketing of cardamom, an important cash crop. In 1993, she did her first major thesis work for the department of Agronomy on the variability in rice growth, at individual plant level in the greenhouses in Wageningen, as well as at the field level at WARDA (West African Rice Research Center) in Ivory Coast. Her next thesis was conducted in 1994 for the department of Theoretical Production Ecology, at AB-DLO (Dutch Research Institute for Agrobiology and Soil Fertility) in Wageningen, on improving the modeling interface (ROTAT-RW) between wheat and rice models of puddled rice-wheat systems of the Indo-Gangetic plains. She completed a third thesis at CIP (International Potato Center) in Ecuador in 1995, on the simulation of potential potato production as limited by light interception in mountainous terrain for the department of Theoretical Production Ecology and the department of Agronomy.

After graduating in August 1995, she worked on the simulation of individual apple fruit growth at the Research Station for Fruit Growth, The Netherlands.

In June 1996, she was appointed Associate Expert in Simulation Modelling and Geographic Information Systems for the Natural Resources Group at CIMMYT (The International Maize and Wheat Improvement Center), in Mexico. Besides contributing to the set up of a GIS and simulation modelling capacity at CIMMYT, her activities focused on applying these tools to evaluate soil and water conserving technologies for maize production systems of Meso America. In September 2000, she returned to The Netherlands for a study leave at the department of Plant Sciences, Plant Production Systems Group of Wageningen University. During this time she continued research on this subject, which resulted in this thesis. As from July 2001, she is employed at the Product Board for Cereals, Seeds and Pulses in The Hague.

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