Quantitative understanding of the performance of upland rice – cover legume cropping systems in West Africa

Promotor: Prof. dr. M.J. Kropff
Hoogleraar in de Gewas- en onkruidecologie

Co-promotor: Dr. ir. L. Bastiaans
Universitair docent, leerstoelgroep Gewas- en onkruidecologie

Samenstelling promotiecommissie:
Prof. dr. ir. A.H.C. van Bruggen (Wageningen Universiteit)
Prof. dr. K.E. Giller (Wageningen Universiteit)
Prof. dr. ir. H. van Keulen (Wageningen Universiteit)
Prof. dr. M. Becker (University Bonn, Germany)

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René K. Akanvou

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Propositions

1. The choice of the sowing date of the legumes in upland rice–legume relay intercropping systems should be based on the yield loss in rice that the farmers are willing to tolerate.
   (this thesis)

2. Upland rice–legume relay intercropping systems require fast-growing drought-tolerant legumes.
   (this thesis)

3. In simulation models for plant–plant competition, procedures to simulate morphological responses to environmental conditions and competitive stress are still inadequate.

4. As the positive influence of cover crops on soil fertility only becomes substantial in the long run, short-term benefits, such as food, feed or forage production, are crucial for adoption of this technology by farmers.

5. Food security should be a concern for everyone.

6. Criticizing is an art.

Propositions belonging to the PhD thesis of René K. Akanvou:
Quantitative understanding of the performance of upland rice – cover legume cropping systems in West Africa.

Wageningen, 16 November 2001.

Abstract

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Reducing the long fallow period by replacing the natural fallow with fast growing legume species to improve soil fertility, control weeds or to grow additional forage necessitates selection of suitable species for those objectives. In three agro-ecological zones in West Africa, rice grain yield increased by 20 to 30% following legume fallow compared to a natural fallow. Within an agro-ecological zone, yield differed significantly depending on the management of the cover crop residues. Burning of the residues had a positive effect on yield in the derived savanna zone as well as the Guinea savanna zone. Residue incorporation was superior to farmers' practice of removing the residues. In contrast to the savanna zones, farmers' practice of residue burning in the forest zone, produced the highest yield. Basic information on morphology and growth characteristics was collected to compare productivity and competitiveness of six legume cover crop species (*Crotalaria juncea, Cajanus cajan, Mucuna pruriens* var. *cochinchinensis, Calopogonium mucunoides, Aeschynomene histrix* and *Stylosanthes hamata*) in monoculture. The most competitive species were identified as the most productive. On average N accumulation was *ca* 70 kg ha^{-1}, except for *S. hamata* and *A. histrix*, which only produced *ca* 25 kg ha^{-1}. In the savanna zone of West Africa with a prolonged dry season, the successful growth of legume species as short-season fallow necessitates relay establishment of the cover crop into the preceding food crop. To understand interactions between the components of a relay cropping system, two contrasting species *C. cajan* (highly competitive) and *S. hamata* (less competitive) were intercropped with two rice cultivars, WAB56-50 and WAB450-24-3-2-P18-HB syn. V4, that differed in competitiveness. Rice biomass and grain yield were significantly ($p<0.001$) reduced when legumes were established between 0 and 28 days after rice sowing (DARS). The derived yield loss–legume biomass relationship showed that *C. cajan* was the most suitable legume species for a relay intercropping system with upland rice, as it produced reasonable amounts of biomass at low levels of rice grain yield loss. Further analysis of the results by dynamic modelling of the cropping system revealed that the inferior performance of *S. hamata* was indirectly caused by its weak competitiveness, which required a relatively early introduction of this legume. The combination of early introduction and short growth duration of this species prevented a rapid leaf canopy development after rice harvest, resulting in a relatively poor biomass production.

It was concluded that options to improve legume biomass production in upland rice–legume intercropping systems in the savanna zone of West Africa should strongly focus on maximization of legume biomass production in the period following rice maturity, when residual soil moisture still allows for additional growth.

Keywords: Upland rice, West Africa, relay intercropping, modelling, cover crops, improved fallow.

Preface

Diagnosis of production constraints in tropical and sub-tropical zones of Africa and the development and the testing of appropriate technologies to increase food crop production is a priority research objective for research centres. For rice production, the West Africa Rice Development Association (WARDA) co-ordinated a joint regional task force, which started in 1995, to tackle the many problems of rice production in West Africa. My involvement in production systems research activities gave me the ambition to improve my knowledge on a new area in application of systems approaches in agriculture, which eventually led to this study in Wageningen.

The thesis work started in 1996 under a so-called 'Sandwich programme' which involved Wageningen University, WARDA and my research institute Centre National de Recherche Agronomique (CNRA). As I complete this exciting experience, I would like to acknowledge all the Institutions above-mentioned, the Government of Norway for financial support of the field work and all the persons who at every level took part in the completion of this work in one way or another. I am particularly grateful to my promotor Professor Martin J. Kropff for his permanent motivation and advice not only during the three-time visit to my experimental trials, but also for constantly guiding the writing of the thesis. I am also thankful to Dr. Lammert Bastiaans my co-promotor for his everyday guidance and more particularly for providing keen critics and suggestions in modelling physiological processes in plants. In spite of the long hours of intensive work supported by countless cups of coffee, he was always available until the alarm of the building went on. Thanks to you and your family for your friendship.

Experiments were conducted at WARDA (Mbé, Ivory Coast) under the supervision of the principal Agronomist Prof. M. Becker now a staff at the University of Bonn. His personal involvement and interest in my topic was a real source of motivation for conducting the experiments. The Centre National de Recherche Agronomique is highly acknowledged. I particularly express my gratitude to Dr. Koffi Goli, DG of the former IDESSA under whom this study started in 1996. I am also grateful to the administration of the new Institute directed by Dr. Sié Koffi, and Dr. Yo Tiemoko for their continuous encouragement. Special thanks to CNRA staff at Korhogo for their endless support to my family and myself.

I had a good relationship with workers at WARDA, principally with technicians and field workers. I will always remember the support and collaboration of Kouame Sylvain, my field assistant, Kouame Romeo, Agui Oscar, Toure Amadou, Abdoulaye Sow, and many others that I can not personally name here.

During my stay in Wageningen, I had support from Professor J. Goudriaan for reviewing some of the chapters and from a wonderful Gon van Laar for editing and improving the booklet to its final version. I wish to thank them for their technical support. Students of the Crop and Weed Ecology discussion group of the C.T. de Wit Graduate School for Production Ecology and Resource Conservation are also acknowledged for their constructive comments on draft versions of some of my chapters. There are many persons who showed friendship and support to me that I cannot mention personally here. However, I would like to express my deep appreciation to Daniel Baumann, Nick den Hollander, Martina Mayus, Ruben Muasya, Woldeamlak and Sergio Cerretta with whom I had unforgettable moments. Thanks are also extended to the secretaries Hilde Holleman and Leonie van Scherrenburg, to Paula Westerman, Maja Slingerland, Peter Leffelaar, Cor Langeveld, Anne-Marie van Dam, Tjeerd-Jan Stomph, Henriette Drenth, Arnout van Delden, Loualidi, Mahamoud Otroshy, and Admasu Tsegaye for their friendship and support which at some points were important to keep the work going.

Finally, I thank my brothers and sisters, relatives and parents in law for their great deal of concern. To my wife Louise, and kids Linda-Ann, Ghislain-Yves and Renée-Marie-Louise. I would like to praise their courage as they felt abandoned during the year 2001 which was marked by weeks of instability in my country while I was completing this work. For their love, patience and endless support to me, I dedicate this thesis to them with pride and honour.

God bless you all!

René Akanvou

Contents

CHAPTER 1

General introduction

CHAPTER 1

General introduction

Rice is the most important food crop of the world with 150 million hectares of cultivated area. While about 90% of the world's rice is produced and consumed in Asia, rice production is gaining importance in Africa as well. Current production in West Africa occupies 4.3 million hectares with an average yield of 1.5 t ha^{-1} of paddy rice, which is low compared to the average world rice production of 3 t ha^{-1}. Between 1983 and 1992, total rice production increased in many West African countries, mainly as a result of expansion of the cultivated area (WARDA, 1996). The increase in production however, was not sufficient to meet the growing demand due to a population growth of 2.9% per year and an increase in rice consumption because of a gradual shift in consumer's preference towards rice (IRRI, 1997). Consumption of traditional cereals such as sorghum and millet is relatively decreasing while the share of rice in cereals consumed has grown from 15 to 25% during the same period. Since 1980, the annual growth rate in rice demand has been 4.7% and that figure is likely to be maintained. As a consequence, the gap between regional demand and supply is met by regular imports of about 2.6 millions tons per year in West Africa, at a cost of $800 million in foreign exchange (IRRI, 1997).

In West Africa, rice has become a staple food for rural population across a large zone stretching from the Gambia to Ivory Coast as well as among the urban population throughout Sub-Saharan Africa (Table 1.1). At present, only 64% of the region's rice consumption is produced locally. To ensure food production for the growing population, domestic rice production must continue to increase.

Rice situation in West Africa

Rice production environments

Due to its wide adaptability, rice is produced in different agro-ecological zones and in various ecologies ranging from irrigated or submerged conditions in the coastal mangrove swamps and inland valleys, over seasonally flooded plains, to strictly rainfed uplands (Buddenhagen, 1978; IRRI, 1997). Three major production environments can be distinguished in West Africa. These are upland rice, rainfed lowland rice and irrigated rice. The upland ecosystem is one of the major rice production environments with 39% share of the total rice growing area (Fig. 1.1). Rainfed lowland rice represents 38% of the

Table 1.1 Major food crops balance in West Africa (source FAOSTAT).

	Africa Developing		Western Africa[1]		Ivory Coast	
	1996	1997	1996	1997	1996	1997
Maize production (Mt)	33.0	30.8	8.9	8.9	0.57	0.58
Maize imports (Mt)	5.7	7.5	0.15	0.23	0.019	0.017
Rice (milled equivalent) production (Mt)	10.4	11.4	4.3	4.8	0.56	0.86
Rice (milled equivalent) imports (Mt)	3.4	3.8	2.5	2.8	0.35	0.52
Rice (paddy equivalent) production (Mt)	15.6	17.0	6.4	7.3	0.83	1.3
Rice (paddy equivalent) imports (Mt)	5.0	5.6	3.8	4.2	0.52	0.78

[1] Benin, Burkina Faso, Ivory Coast, Gambia, Ghana, Guinea, Guinee-Bissau, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo.

production area and is expanding rapidly. The remaining 23% of the rice growing area is covered by deepwater rice, mangrove and irrigated lowland rice. Given its importance in terms of area (1.8 million ha) and regional production (1.6 million t), upland rice warrants special attention.

Production constraints of rainfed rice

Upland rice-based cropping systems

Climate, land profile and available resources determine the cropping systems, which vary

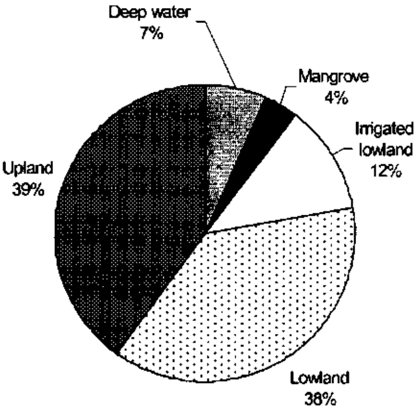

Fig. 1.1 Rice production areas in West Africa (Source: WARDA, 1996).

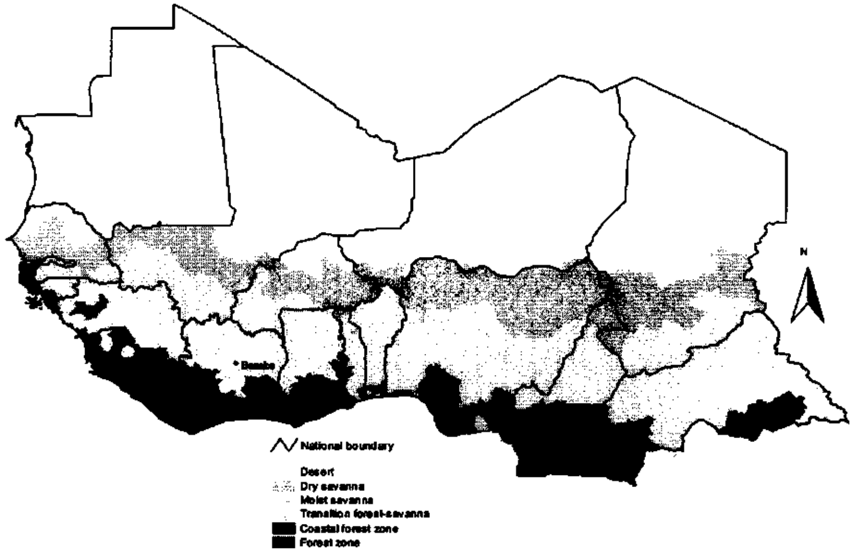

Fig. 1.2 West Africa ecological zones and rice production areas.

as a function of the biophysical and sociological environment. Upland rice cropping systems are mainly dominated by fallow rotation systems. Within an agro-ecological zone (Fig. 1.2), the rotation system varies. Rice is planted either as a sole crop in rotation with other crops or as an intercrop. In the forest zone, common intercropping systems are rice–cassava or rice–maize while in the savanna area, rice–yam or rice–maize prevails. Cotton is becoming the principal crop in the savanna zone of Ivory Coast, and it is widely grown in rotation with upland rice. Often grain legumes such as groundnut, cowpea or soybean are sown before the land is abandoned for natural regrowth. When land is left fallow, farmers will start cropping another available piece of fallow land. Until recently, traditional shifting cultivation was the dominant production system. Shifting cultivation is a system in which short periods of cultivation are followed by relatively long periods of fallow where land is abandoned for natural regrowth (Willen, 1990). Due to yield decline because of reduced fertility, and increased weed infestation, farmers are forced to move from one location to another. However, this system cannot be sustained if population pressure is high (Ruthenberg, 1980). Over time, shifting cultivation systems have evolved towards fallow rotations in which the fallow length has been reduced considerably due to demographic growth and emerging land shortages. Fallow length declined from about 12-15 years in the 1980s to 3-8 years to date (mainly in the forest zone). This has resulted in an average upland rice yield reduction of about 25% (Becker and Assigbe, 1995). Factors responsible for this yield decline comprise reduced organic matter and N resources, accelerated soil nutrient leaching, increased weed pressure, soil erosion and degradation. Despite the increased pressure on the land resource base, farmers have not adapted their cropping practices especially due to lack of resources to purchase inputs. As a result, upland rice yields in West Africa are estimated to be less than 1 t ha^{-1}.

Major constraints to sustainable rice production

Upland rice-based cropping systems still rely on periods of bush fallow to restore fertility and to prevent the build-up of insect pests and weeds (Nye and Greenland, 1960; Willen, 1990). Recent surveys indicate that in shifting cultivation the fallow lengths have decreased so much that the fallow period does not lead to restoration of soil fertility anymore (Becker and Assigbe, 1995; Becker and Johnson, 1999). Significant yield reduction as well as nutrient depletion along with persistent weeds and pests make this system no longer sustainable. In the savanna zone of Ivory Coast, 40% of total labour invested in rice is devoted to hand weeding (Ouattara, 1994). In cash crop production, systems subsidized herbicides and fertilizers may be available to control weed growth and to avoid nutrient deficiencies. However, they are rarely used in upland rice, which predominantly is a subsistence crop. Current levels of land use intensification induce rice yield losses of about 20% in the moist or Guinea savanna zone, of about 30% in the forest-savannah transition or derived savanna zone, and of about 41% in the forest zone (Becker and Johnson, 1998). In low-input production systems, permanent upland cultivation results in a severe decline in soil productivity and, as a consequence, in poor crop yields (IRRI, 1997). This degradation is mainly due to nutrient losses as the result of inappropriate management and nutrient depletion (Oldeman *et al.*, 1991), leading to a fertility decline that is dependent on soil type (Sanchez, 1976; Gigou, 1992).

Given the current intensity of land use, the fragility of many upland soils and the lack of resources by smallholder farmers, low-input but sustainable land use systems must be developed. However, studies clearly indicate that long-term upland rice productivity is not likely to be achieved under current traditional practices (Becker and Johnson, 1998). To meet the growing food demand, rice production systems must be intensified in a way that conserves the resource base and allows for sustainable productivity increases. To ensure adoption, new technological options must be affordable by smallholders and meet the needs and management skills of West African rice farmers without ignoring their perceptions and production objectives (Richards, 1985).

Role of legumes in improving production systems

A promising alternative to existing short-fallow rotations involves the improvement of the quality of short fallows. This may be achieved by introducing annual leguminous cover crops into the system (Yost and Evans, 1988; Balasubramanian and Blaise, 1993; Hoefsloot *et al.*, 1993). The use of cover crops in farming systems is not a new technology. Burkill, cited by Kiff *et al.* (1996) reported that in Java, Bali and Sumatra, *Mucuna* spp. has been used since the 17th century for the recuperation of degraded soil. Nitrogen-fixing leguminous species that belong to the family of Leguminoseae or Fabacaea are more often used as cover crops. The Leguminoseae family is composed of three sub-families: the Cesalpinioideae, the Mimosoideae and the Papillionoideae (Polhill and Raven, 1981; Kretschmer, 1985). Most of the herbaceous forage legumes are Papillionoideae, which comprise about 440 genera and 12,000 species.

The introduction of legumes into a cropping system has several advantages. Once a legume is established, generally the biomass is cut, slashed, burnt or incorporated. Residue incorporation into the soil before the seeding of a subsequent crop of rice can improve soil chemical and physical properties (McVay *et al.*, 1989; Mulongoy *et al.*, 1993) and consequently increase grain yields (Osei-Bonsu and Asibuo, 1997; Buckles *et al.*, 1998b). The biologically fixed N released during residue decomposition may reduce fertilizer-N requirements of a subsequent crop (Hesterman *et al.*, 1992; Holderbaum *et al.*, 1990). In minimum and no-till systems, cover crops can conserve soil water during the following cropping season (Blevins *et al.*, 1971; Sullivan *et al.*, 1991; Seguy *et al.*, 1998). The ability of cover crops to control weeds has also been reported (Akobundo, 1983; Nguimbo and Balasubramanian, 1992; Becker and Johnson, 1998). *Mucuna*, for example, has been effective in suppressing the perennial grass *Imperata cylindrica* in maize-based systems in northern Benin (Versteeg and Koudopon, 1990) and *Rottboellia cochincinensis* in northern Honduras (Triomphe, 1996). In the Guinea savanna zone where soil erosion poses a serious threat to the sustainability (Pieri, 1992), cover crops can reduce the negative site effects of heavy rainfall on surface erosion (El-Swaify *et al.*, 1985; Bourgoing, 1990). Furthermore, cover crops can serve as fodder banks for cattle (Tarawali and Ogunbile, 1995). Finally and most importantly, cover crops have been shown to substantially increase grain yield of subsequent cereal crops (Becker and Johnson, 1998). Thus legume species can be used to replace the natural fallow vegetation in different environments. To determine which of the many potentially useful legume species and genotypes can be used in any given situation has been studied by various authors (Becker and Johnson, 1998; Kiff *et al.*, 1996) and decision tool expert systems have been developed (Weber *et al.*, 1997). However basic insight in growth pattern and the most optimal cropping system for a specific environment is still lacking. In addition, management options for using the residues need further investigation.

Establishment of cover crop fallow

The savanna zone in West Africa has a rainy season of six months followed by a dry period from November to March. In general, the cropping season that starts in June or July lasts until October, leaving a short-time span between the harvest of the main crop and the beginning of the dry period. The growing of a cover crop for fallow improvement can be realized by sole cropping them sequentially with the main crop or by relay-planting them as an undersown in the main crop. Sole cropping cover crops in rotation with the main crop is most widely spread. As a sole crop, the cover crop occupies the land for at least a cropping season and for a longer period at the time when other crops could be grown. Large amount of biomass is expected to be produced in this situations which could be beneficial to succeeding crops. However due to labour and land scarcity increases, rejection of growing sole legume cover crops or green manure as fallow by smallholders has been reported in southern Africa (Kumwenda *et al.*, 1996).

As conditions may vary within the same region, cover crops can be planted in mixture with the rice crop (Torres, 1979; Schulz *et al.*, 2000). Under the savanna zone conditions, the planting time of a post rice crop–cover legume must be carefully selected to match the weather conditions and cropping systems. To provide a good ground cover during the dry season, an improved fallow legume that is well established before the onset of the dry season is required. Establishing these legumes after rice harvest in savanna environments will not allow for sufficient growth of the cover crop. In fact successful establishment of fallow legumes in upland rice-based systems can only be achieved through a relay system wherein the legume overlaps with part of the rice-growing period. The choice of species and the timing of establishment are crucial factors for optimizing beneficial effects of a relay cropping system (Aggarwal and Garrity, 1989; Becker and Johnson, 1999). An early establishment in rice cropping systems will permit the legume to benefit from soil nutrients and water resources available during the rainy season, allow a good establishment before the beginning of the dry season, and contribute to weed suppression. However, when intercropped, the cover legume will also compete for space, water, light, and nutrients with the rice plant resulting in a substantial reduction in grain yield (Kropff and van Laar, 1993). In that respect, integrating cover legumes as an intercrop into a rice system would require a balance between optimal legume establishment for short-fallow improvement and minimal legume competition with the rice crop. The extent of this competition will depend on growth characteristics of both the legume and the rice, and their relative time of establishment. The number of possible combinations and the complexity of interactions call for a systems approach, using eco-physiological competition models to support analysis of experimental data.

Objective and approach

The objective of this study was to evaluate the role of cover crops as short improved fallows on upland rice production and to analyse the underlying mechanism of establishing the cover crops as relay crop into the rice. Main focuses were to evaluate the after-effects of the improved fallow and to explore conditions for minimizing competition effects on upland rice when the legumes are established as intercrop. For this purpose experiments and simulation were combined to:

- Assess growth of a various legume species in different agro-ecological zones and to evaluate effects of residue management on a succeeding rice crop.
- Characterize growth traits and competitive ability of legume species.
- Study the competitive relations between rice varieties and cover crops in a relay cropping system with a variable introduction time of the legume.
- Adapt a mechanistic eco-physiological model of the intercrop components.
- Use the developed model to analyse upland rice–cover crop system and identify the main determinants of a successful system.

To achieve this goal, field experiments of pure and mixed stand rice crop and cover crop species were conducted on research station under non water-limiting conditions and at key experimental sites in the savanna, derived savanna and forest zone. An integrated approach, which combines experiments and analysis of experiments using descriptive and mechanistic models, was used interactively. First, a testing of different legume species in combination with different residue management options in three agro-ecological zones in the region was carried out to determine the importance of crop residue management and nitrogen contribution to subsequent rice yield. Secondly, a screening was conducted to identify and classify the diversity of cover crop species with respect to productivity, N-accumulation and competitiveness, all being important attributes when cover crops are used as relay cover crop. Exploration of the relay intercropping system was conducted using all combinations of two rice cultivars of different competitive ability and two very contrasting cover crop species *Cajanus cajan* and *Stylosanthes hamata*. An eco-physiological model for interplant competition was applied to further analyse the data and obtain a better understanding of the complex rice–cover crop intercropping systems.

The research was carried out as a collaborative research programme between the Group Crop and Weed Ecology of Wageningen University, the West African Rice Development Association (WARDA) and the Centre National de Recherche Agronomique (CNRA) in Ivory Coast, West Africa.

Outline of the thesis

The structure of this thesis is represented in Fig. 1.3. Chapter 2 follows this general introduction. It provides a comparative analysis of selected cover crops, tested in three agro-ecological zones including the effects of different fallow residue management options on rice yield. Chapter 3 gives a description of morphological and physiological characteristics of six different legumes species for growth and development under non water-limited conditions, with additionally a focus on competitiveness related to their potential use in upland rice cropping systems. In Chapter 4, competitive relationships in relay cropping systems of all combination of two contrasting cover crops and two rice cultivars were analysed. Yield loss in rice as a consequence of legume introduction at different times was determined and additionally the relation between rice yield loss and produced legume biomass was established. For analysis of the mechanisms involved in the competition between the component crops of the relay cropping systems, the INTERCOM model was parameterized, calibrated and validated for growth and development of the two cover legume species (Chapter 5). A similar parameterization was conducted for rice in monoculture, after which the two models were combined (Chapter 6). The chapter further summarizes the outcome of the simulation by using a descriptive model. General discussion of all the results, remarks and conclusions are presented in Chapter 7.

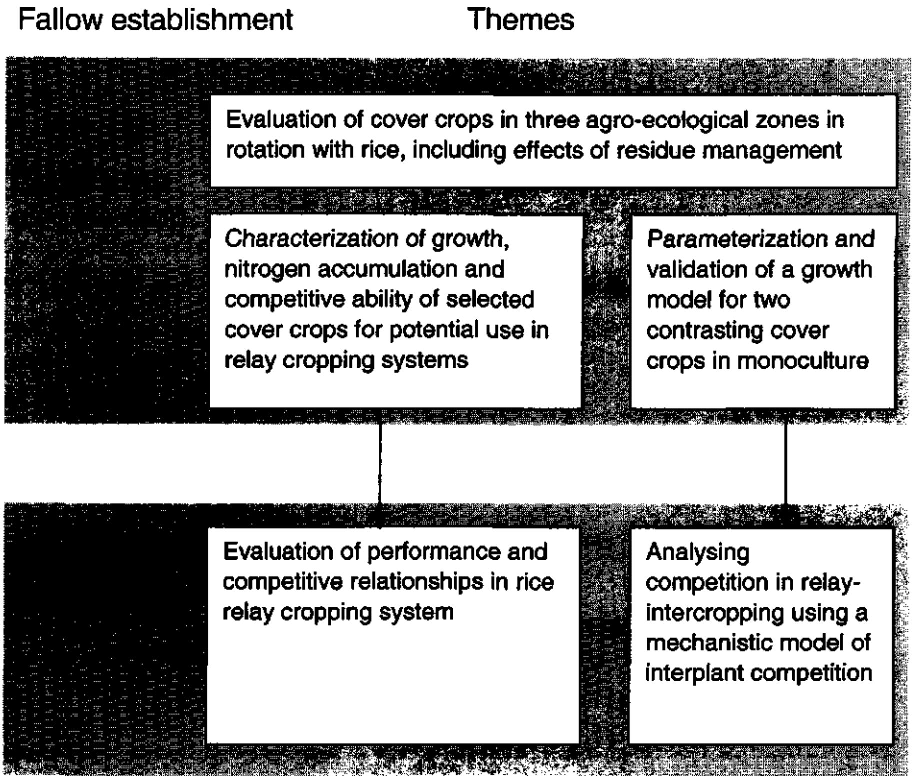

Fig. 1.3 Outline of the thesis.

CHAPTER 2

Cover crops evaluation and fallow residue management effects on upland rice in three agro-ecological zones of West Africa

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CHAPTER 2

Cover crops evaluation and fallow residue management effects on upland rice in three agro-ecological zones of West Africa

Abstract

Improving fallow quality in upland rice–fallow rotations in West Africa through the site-specific use of leguminous cover crops has been shown to sustain the productivity of such systems. We studied the effects of a range of residue management practices (removal, burning, mulching and incorporation) on fallow biomass and N accumulation, on weed biomass and yield response of upland rice and on changes in soil physical and chemical characteristics in 2-year field trials conducted in three agro-ecological zones of Ivory Coast. Across fallow management treatments and agro-ecological zones, rice yields were on average 20-30% higher in legume cultivated than in natural fallow plots. Weed biomass was highest in the savanna zone and lowest in the bimodal forest zone and tended to be less following a legume fallow. Regardless of the type of fallow vegetation and agro-ecological zone, biomass removal resulted in the lowest rice yields that varied from 0.5 t ha^{-1} in the derived savanna zone to 1.5 t ha^{-1} in the Guinea savanna zone. Burning of the fallow vegetation significantly increased yield over residue removal in the derived savanna (0.27 t ha^{-1}, $p<0.05$) and bimodal forest zones (0.27 t ha^{-1}, $p<0.01$), but not in the Guinea savanna. In both savanna environments, residue incorporation was superior to farmers' practice of residue removal and rice yield increases were related to the amount of fallow N returned to the soil ($r^2=0.803$, $p<0.01$). In the forest zone, the farmers' practice of residue burning produced the highest yield (1.43 t ha^{-1} in case of legumes) and resulted in the lowest weed biomass (0.02 t ha^{-1}). Regardless of the site, improving the quality of the fallow or of its management had no significant effects on either soil physical or soil chemical characteristics after two fallow cycles. We conclude that incorporation of legume residue is a desirable practice for rice-based fallow rotation systems of the savanna environments. No promising residue management alternatives to slash-and-burn were apparent for the forest zone. Determining the possible effects on soil productivity will require long-term experiments.

Keywords: Legumes, Nitrogen fixation, *Oryza sativa*, Soil fertility, Weeds, Ivory Coast

Introduction

Upland rice in West Africa is mainly cultivated in rotation with extended periods of natural fallow. Demographic pressure and land shortage are leading to increasingly shorter fallow periods which, in turn, result in declining soil fertility (Juo and Lal, 1977; Pieri, 1992) increased weed infestation (de Rouw, 1995) and low yields (Agboola, 1994; Becker and Johnson, 1999). In addition, the fallow vegetation is usually cleared by slashing and burning (forest zone) or biomass removal (savanna zone), resulting in substantial nutrient losses from the system (Sanchez, 1976; Oldeman *et al.*, 1991). A promising option for stabilizing such land-use systems involves the improvement of the quality of the fallow vegetation through using N-fixing leguminous cover crops (Lathwell, 1980; Balasubramanian and Blaise, 1993; Buckles *et al.*, 1998a). The choice of legume species varies by agro-ecological zone and farmers' resource base and production system. The use of site-specifically adapted legumes has been shown to maintain productivity under shortened fallow management by sustaining soil fertility, adding organic matter and N and suppressing weed growth in rice (Becker and Johnson, 1998). Such improved fallow systems are recommended by extension services in several countries of the sub-region and have recently started to be used by farmers (Buckles *et al.*, 1998b).

In a further step, alternative residue management practices that retain the organic matter and nutrients accumulated by the fallow vegetation *in situ* is required in order to maximize the beneficial effects of improved fallows. Such alternatives to slash-and-burn or residue removal may include the mulching or incorporation of the biomass (Sanchez *et al.*, 1989; Tonye *et al.*, 1997). Previous work has mainly focused on the effects of management of one type of residue in one environment on soil physical and chemical characteristics (Steiner, 1994; Adetunji, 1997; Wylie, 1997). However, most appropriate residue management practices are likely to vary with residue quality and agro-ecological zone. Furthermore, residue management effects on weed biomass and species composition have not yet been evaluated. Two-year field experiments were conducted in three agro-ecological zones of Ivory Coast, West Africa. The effects of different legumes and the natural fallow and of a range of residue management practices on fallow biomass, N accumulation, on weed biomass and yield response of upland rice and on changes in soil physical and chemical parameters were evaluated.

Materials and methods

Experiments were conducted between 1994 and 1996 on agricultural research stations at three sites in Ivory Coast, representing the major upland rice-growing environments of West Africa. The sites were situated in the Guinea savanna (Ferkéssédougou), the derived savanna (Bouaké), and the humid forest zone with bimodal rainfall distribution (Gagnoa). A description of the sites (geographic location, climate and soil) and of the production systems is given in Table 2.1. All sites received a basal blanket application of 15 kg P ha^{-1} as triple superphosphate after harvest of a preceding homogeneity crop of upland rice.

Four to five legumes per site were selected based on preliminary legume screening trials (Becker and Johnson, 1998). The main selection criteria were (1) N accumulation and (2) weed suppression in the fallow and, additionally at the Guinea savanna site, (3) dry season survival.

Legumes included the creeping species *Calopogonium mucunoides, Canavalia*

Table 2.1 Description of the experimental sites.

	Guinea savanna	Derived savanna	Humid forest
Location			
Village	Ferkéssédougou	Mbé	Guéménédou
Longitude (°)	5.1 W	5.0 W	6.1 W
Latitude (°)	9.4 N	7.8 N	6.1 N
Climate			
Growing period (days)	210	250	270
Annual rainfall (mm)	1200	1000	1100
Rainfall distribution	Monomodal	Bimodal	Bimodal
Soil			
Soil class	Alfisol	Alfisol	Alfisol
Parent material	Schist	Gneiss	Shist
Texture class	Sandy loam	Sandy clay loam	Loamy sand
pH (KCl)	4.9	6.1	5.4
Organic C (%)	0.70	0.54	2.16
Total N (%)	0.07	0.09	0.21

ensiformis, Centrosema pubescens, Mucuna pruriens var. *cochinchinensis* and *Pueraria phaseoloides* in the forest and derived savanna sites and *Cajanus cajan, Crotalaria juncea, Mucuna pruriens* var. *cochinchinensis* and *Tephrosia villosa* at the Guinea savanna site. Legumes were dibble-seeded into the 25 cm inter-row spaces after harvest of a preceding upland rice crop. The intra-row spacing was 25 cm for small- and medium-seeded plants and 40 cm for large-seeded legumes. Main plots of 100-120 m^2 were arranged in a randomized block design with three replications (about 2000 m^2 total experimental area per site). The fallow vegetation (legumes and the natural fallow control) was left to grow for 8 months during the dry season in the derived savanna or for 20 months at the forest and Guinea savanna sites. The cropping pattern in relation to the rainfall distribution is represented for each site in Fig. 2.1.

With the onset of the rainy season, main plots (fallow species) were divided into four sub-plots (strip-plot design), where the fallow vegetation was either (1) cut and removed (traditional practice in savanna systems), (2) cut, allow to dry and burnt (traditional practice in forest systems), (3) cut and mulched or (4) incorporated by hand hoe. An improved medium statured, 115-day upland rice variety (*Oryza sativa cv.* WAB56-50) was dibble-seeded at a 25 cm × 25 cm spacing. Plots were clean-weeded and dry weed biomass was determined at 28 and 56 days after seeding (DAS) based on 2 m^2 quadrants, except at the forest site where weed biomass was taken only at 56 DAS. Rice yield was harvested in August (bimodal forest site), and November (monomodal Guinea savanna and derived savanna sites). Grain yield was based on 6 m^2 harvest areas and was corrected for 14% grain moisture. At the beginning and the end of the experiment, soil auger samples (0-20 cm) were taken along a diagonal in each field (composites of eight sub-samples per plot). Soil chemical [pH(H_2O), organic C, total N, extractable Bray-I P], and soil physical (texture analysis, bulk density, penetrometer resistance, infiltration characteristics) were done using standard methods (Page *et al.*, 1982; Klute, 1986).

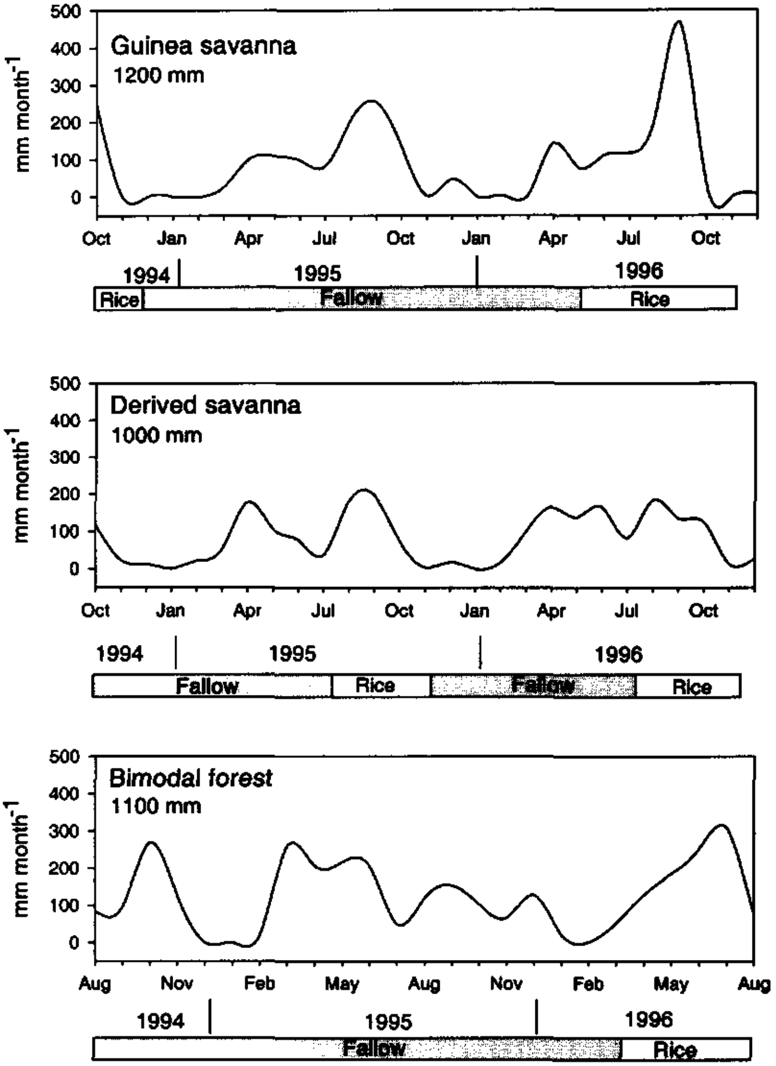

Fig. 2.1 Rainfall distribution in relation to cropping patterns at the study sites in three agro-ecological zones of Ivory Coast.

Results and discussion

Fallow vegetation

A range of different legume species was compared to the natural weed growth for assessing the quality of fallow vegetation between two crops of rice. At the savanna sites, grasses (e.g., *Andropogon* spp.) dominated the natural fallow, while *Chromolaena odorata* and woody regrowth dominated at the forest site. The dry biomass and N accumulation in 20-month-old fallow vegetation were higher in the forest than in the Guinea savanna zone and were significantly more in legume plots than in the natural fallow (Table 2.2). Legume biomass accumulation was negatively correlated with weed biomass in the fallow ($r^2 = 0.619^{***}$, data not shown). The highest fallow N accumulation was observed with *P. phaseoloides* (227 kg N ha^{-1}) in the forest zone and with *C. cajan* (167 kg N ha^{-1}) in the Guinea savanna zone. N accumulation was less in the derived savanna zone where fallow growth duration was only 8 months. There, the natural fallow vegetation was dominated of *Digitaria horizontalis*, *Tridax procumbes* and *Boerhavia* spp. with a mean biomass accumulation of about 2 t ha^{-1}, corresponding to 22 kg N ha^{-1} per year. *Centrosema pubescens* produced largest fallow biomass (data not

Table 2.2 N accumulation (kg ha^{-1}) at the end of the dry season by natural and legume fallow vegetation at the derived savanna site (8 months growth), and the bimodal forest and Guinea savanna sites (20 months growth) in Ivory Coast.

	Derived savanna		Bimodal forest	Guinea savanna
Treatment	1995	1996		
Natural fallow	26	17	65	48
Calopogonium mucunoides	64	76	114	nd*
Canavalia ensiformis	99	82	99	nd
Centrosema pubescens	63	51	130	nd
Mucuna pruriens	61	53	84	35
Pueraria phaseoloides	54	60	227	nd
Crotalaria juncea	nd	nd	nd	58
Tephrosia villosa	nd	nd	nd	102
Cajanus cajan	nd	nd	nd	167
Legumes mean	68	64	131	91
LSD 0.05	*17*	*19*	*20*	*33*

* not determined.

shown) and the highest N was determined in *Canavalia ensiformis* and *Calopogonium mucunoides*, both in 1995 (64-99 kg N ha^{-1}) and 1996 (76-82 kg N ha^{-1}). The fact that legume fallows outperformed the natural fallow in terms of biomass production and N accumulation has been reported in humid forest zones of Asia, South America and Africa (Magbanua *et al.*, 1988; Balasubramania and Blaise, 1993; Buckles *et al.*, 1998a). Similar to the present study, *P. phaseoloides* and *C. ensiformis* showed the highest N accumulation in humid environments of South America (Luna-Orea and Wagger, 1996). Positive effects of legumes on weed control in the fallow in various agro-ecological zones have been reported (Becker and Johnson, 1998). Thus, the use of site-specifically adapted legumes can improve fallow quality.

Rice and weed response to improved fallow

Across fallow management treatments and agro-ecological zones, upland rice yields were on average 20-30% higher in legume than in natural fallow plots (Table 2.3) as has been discussed above. Rice yields were higher in the Guinea savanna zone (average 1.7 t ha^{-1}) than in the forest (about 1 t ha^{-1}) or the derived savanna zone (0.8 t ha^{-1}). The biomass of weeds in association with upland rice was highest in the savanna zone, where it was dominated by annual grasses and sedges, and was lowest in the bimodal forest, where it was composed nearly exclusively of *Chromolaena odorata*. The derived savanna fields had a cumulative weed biomass of about 0.25 t ha^{-1}, which was dominated by *Euphorbia heterophylla* and other short-cycled annual weeds. Regardless of the site, the weed biomass associated with upland rice tended to be less following a legume fallow, though these differences were in most instances not significant (Table 2.3). It may be concluded that improved legume fallows increased yield of upland rice in all three agro-ecological zones and tended to reduce weed growth.

Fallow management effects on yield and weeds

The extent of yield and weed effects of fallow legumes was studied differentially for four residue management practices. Regardless of fallow quality and agro-ecological zone, biomass removal resulted in lowest rice yields that varied from 0.5 t ha^{-1} in the derived savanna zone to 1.5 t ha^{-1} in the Guinea savanna zone (Fig. 2.2). In this treatment, nutrients accumulated in the biomass were fully removed from the field. Thus, Magbanua *et al.* (1988) were able to relate low upland rice yields after residue removal in the Philippines to soil N and K depletion. Burning of the fallow vegetation resulted in significant yield increases over residue removal in the derived savanna and bimodal forest zones, but not in the Guinea savanna. A positive effect of burning over mulching on cereal grain yield has also been reported from humid forest environments in South Asia (Beri *et al.*, 1995), Southeast Asia (Roder *et al.*, 1998) and South America

Table 2.3 Effect of fallow and residue management (a) on rice yield and (b) on associated weed biomass in three agro-ecological zones of Ivory Coast.

	Residues removed			Residues burnt			Residues mulched			Residues incorporated			Treatment mean	
Agro-ecological zone	Natural fallow	Legume fallow	*LSD 0.05*	Natural fallow	Legume fallow	*LSD 0.05*	Natural fallow	Legume fallow	*LSD 0.05*	Natural fallow	Legume fallow	*LSD 0.05*	Natural fallow	Legume fallow
(a) Rice yield (t ha^{-1})														
Guinea savanna	1.51	1.67	*ns*	1.43	1.92	*0.49*	1.40	1.88	*ns*	1.26	2.04	*0.61*	1.40	1.88
Derived savanna	0.27	0.73	*0.2*	0.40	1.00	*0.39*	0.24	0.92	*0.38*	0.36	1.11	*0.44*	0.32	0.94
Bimodal forest	0.72	0.80	*ns*	0.78	1.43	*0.69*	1.07	1.05	*ns*	0.99	1.05	*ns*	0.89	1.08
(b) Weed mass (t ha^{-1})														
Guinea savanna	0.48	0.46	*ns*	0.38	0.40	*ns*	nd	nd	-	0.48	0.44	*ns*	0.45	0.43
Derived savanna	0.22	0.19	*ns*	0.33	0.27	*0.06*	0.28	0.23	*0.05*	0.26	0.25	*ns*	0.27	0.24
Bimodal forest	0.11	0.06	*0.02*	0.02	0.02	*ns*	0.06	0.05	*ns*	0.14	0.17	*ns*	0.08	0.07

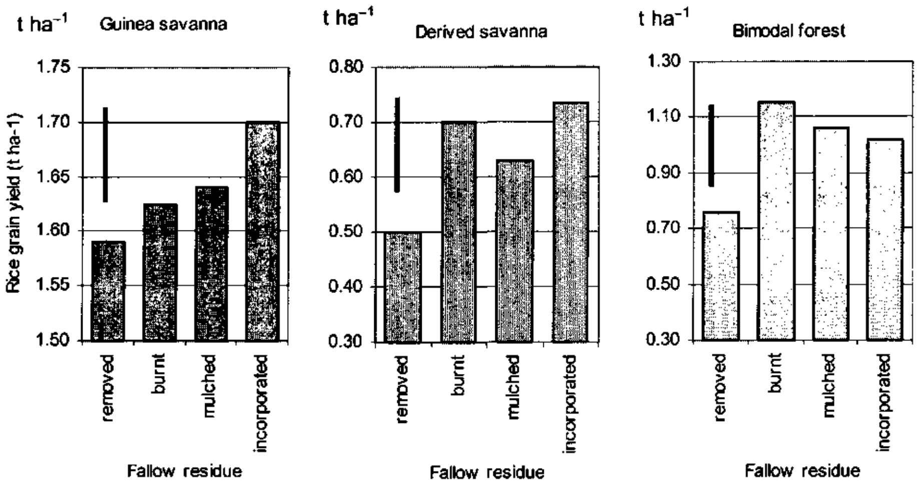

Fig. 2.2 Rice yield response to fallow residue management (natural and legume fallows confounded) in three agro-ecological zones of Ivory Coast.

(Luna-Orea and Wagger, 1996). In the process of burning, much of the N (and S) in the biomass is loss to the atmosphere (60-85%; Sanchez, 1976) but most of the P and cations are returned to the soil in the form of ahs (van Reuler and Janssen, 1996). Also, many of the weed seeds in the top soil layer are no longer viable after a 'hot burn' (de Rouw, 1995). Fallow management studies by Tonye *et al.* (1997) concluded that residue burning appears to be the best management strategy for forest environments in Central Africa.

In the Guinea savanna environment, residue incorporation into the soil produced a significant yield advantage over the farmers' practice of residue removal. A similar effect of incorporation was observed in the derived savanna, but not in the forest zone. Residue mulching occupied an intermediate position with significant yield increases over biomass removal only in the forest zone. In contrast to maize-based systems (Mulongoy *et al.*, 1993), rice seeding into the mulch was difficult and germination rates were lower than in other residue treatments. Furthermore, residue mulching resulted in up to 20% plant loss due to termite damage in the two savanna environments (data not shown). Thus, the incorporation of fallow biomass was generally advantageous in savanna environments, while the farmers' practice of burning appears the most appropriate type of residue management in the forest zone. These trends and the extent of management effects can be clearly differentiated between different fallow qualities (Fig. 2.3). Residue management practices had little or no effect on rice yield in the case of the natural weedy fallow, while an average 30% yield increase was observed with burning, mulching and incorporation of fallow residues. In addition, weed control effects tended to be more in

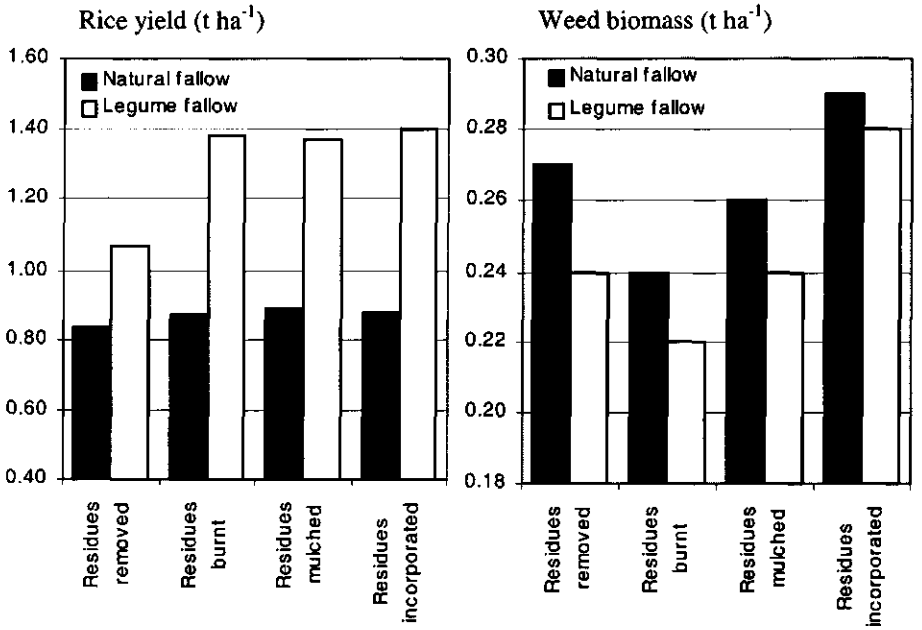

Fig. 2.3 Effect of fallow quality and residue management (mean effects across sites) on rice grain yield (left graph) and associated weed biomass (right graph).

improved than in natural fallow, regardless of residue management. However, burning resulted in significantly less weed biomass than residue incorporation (Fig 2.3).

The relationship between fallow N accumulation and rice yield response is shown in Fig. 2.4 for the derived savanna site. Rice responded linearly to incorporated residue N, with an N-use efficiency of about 10 kg rice grain per kg N applied. Similar trends were observed in the cases of mulching and burning, but at lower N use efficiency and significance levels (data not shown). No such relationship was apparent in case of residue removal. A positive relationship between legume N accumulation and upland rice yield has been shown before in cases where fallow legumes were incorporated (and thus all the N accumulated in the biomass returned to the soil) soil but not where these residues have been burnt and an important share of the N in the fallow biomass has been lost to the atmosphere (Becker and Johnson, 1998). It may be concluded that in savanna environments, residue incorporation was superior to farmers' practice of residue removal, while in the forest zone, farmers' practice of residue burning produced highest yield and resulted in lowest weed biomass.

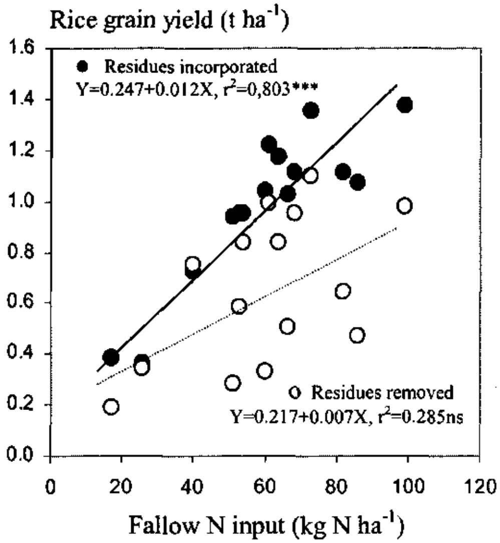

Fig. 2.4 Relationship between fallow N accumulation and rice grain yield as a function of residue management (Ivory Coast, derived savanna zone, 1994-1996).

Fallow management effects on soil parameters

Regardless of the site, improving the quality of the fallow (legumes) or of its management (biomass and nutrient return through mulching or incorporating) had no measurable effects on either soil physical or soil chemical characteristics. The effects of natural and improved fallow at various residue management treatments are presented for the example of the derived savanna site (Table 2.4). While no significant differences were apparent between improved and natural fallow after two cropping cycles, residue burning tended to increase soil pH, and residue mulching showed highest organic C and total N contents. Similarly, no residue management effects after one fallow cycle on soil chemical parameters were reported from two fallow legume trials in the Amazon forest (Luna-Orea and Wagger, 1996). Significant effects on soil pH (increases of up to three units) and available cations (K, Ca, Mg) have been shown after burning of long fallow forest vegetation in Ivory Coast (Slaats, 1995; van Reuler and Janssen, 1996) and of short-fallow vegetation in Nigeria (Adetunji, 1997) but these were only of short duration. Studies from Australia (Thomas *et al.*, 1990) indicate a positive effect of residue incorporation over residue removal on soil organic matter and soil water-holding capacity after seven fallow cycles, but showed again no significant changes in soil chemical parameters.

A residual effect on the yield of an unfertilized rice crop in India was attributed to increased soil organic matter content with incorporation instead of burning of rice and wheat straw (Beri *et al.*, 1995). The present results as well as most other published studies indicate no lasting effects of improved fallow management on soil characteristics.

Table 2.4 Effect of 2-years cultivation with different fallow management on changes in soil chemical and physical parameters (Ivory Coast, derived savanna zone 1994-1996); *nd* not determined, *ns* not significant.

	pH (H_2O)	organic C (%)	total N (%)	C:N ratio	Bray-I P (mg kg^{-1})	Bulk density (g cm^{-3})	Infiltration (cm h^{-1})	Penetration resistance (kg cm^{-2})
Initial values	6.11	1.77	0.07	29	7.4*	1.81	4.0	80
Natural fallow								
Removed	6.20	1.69	0.06	27	12.53	1.54	nd	57
Burnt	6.53	1.73	0.07	25	15.10	1.57	nd	55
Mulched	6.27	1.83	0.07	26	12.50	1.42	7.0	56
Incorporated	6.43	1.79	0.06	28	15.47	1.57	8.0	57
Legume fallow								
Removed	6.20	1.76	0.06	27	9.99	1.59	nd	59
Burnt	6.49	1.77	0.06	29	10.37	1.57	nd	59
Mulched	6.15	1.81	0.07	25	14.21	1.54	3.7	59
Incorporated	6.21	1.74	0.06	29	12.97	1.53	3.6	59
LSD (0.05)	ns	ns	ns	ns	(ns)	ns	ns	ns

* Sample taken before basal P application.

However, all reported studies considered 'total pool' (e.g., total organic C, total N) which are apparently not very sensitive to short-term management interventions. It is possible that measurable changes may have occurred in the 'available pool' (e.g., labile C, N supplying capacity). Their use as indicators of land management may warrant increased research attention in the future.

Conclusions

Replacing the natural fallow regrowth in short-fallow rotation systems of West Africa increased yield of upland rice in forest as well as in savanna agro-ecological zones and tended to reduce weed growth. In the savanna environments, residue incorporation was superior to farmers' practice of residue removal. Increases in rice yield were related to the amount of fallow N returned to the soil. In the forest zone, farmers' practice of residue burning not only produced highest yields but also resulted in lowest weed biomass. Residue mulching generally hindered rice crop establishment and tended to increase termite damage to rice roots. No short-term effects of fallow species or residue management on soil parameters were apparent. The economics of alternative residue management and possible long-term effects on soil productivity require further investigations.

CHAPTER 3

Characterization of growth, N accumulation and competitive ability of six tropical legumes for potential use in intercropping systems

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CHAPTER 3

Characterization of growth, N accumulation and competitive ability of six tropical legumes for potential use in intercropping systems

Abstract
Legume cover crops can be successfully used as intercrop or relay crops in low-input farming systems. To select appropriate species for intercropping, experiments were conducted in the savanna zone of Ivory Coast during the wet season of 1997 and 1998 to determine growth and nitrogen (N) accumulation of six cover legumes as well as characteristics indicative of competitive ability. The species included the erect growing *Crotalaria juncea* and *Cajanus cajan*, the creeping species *Mucuna pruriens* var. *cochinchinensis* and *Calopogonium mucunoides* and the bushy herbaceous species *Aeschynomene histrix* and *Stylosanthes hamata*. Marked differences in phenology were observed as *S. hamata* and *C. juncea* flowered around 45-55 days after sowing (DAS) and the other species at around 80-95 DAS. *C. juncea* and *C. cajan* produced close to 9 ton dry matter ha^{-1}, whereas the other species produced less than half this amount. Average estimated amount of accumulated N, based on leaf material, was around 70 kg ha^{-1} for all species except *S. hamata* and *A. histrix*, which only produced around 25 kg ha^{-1}. Based on morphological characteristics, *C. juncea*, *C. cajan* and the short-lived *M. pruriens* were identified as potentially most competitive, indicating that productivity and competitive ability are strongly linked. The implications of these findings for intercropping systems in upland rice production are discussed.

Keywords: Cover crops, Dry matter production, Growth rates, Phenology

Introduction

Research on leguminous cover crops in Africa (Hartmans, 1981; Tarawali and Ogunbile, 1995), Asia (Yost and Evans, 1988; Carangal *et al.*, 1994) and in Latin America (Lathwell, 1980; Lobo-Burle *et al.*, 1992) has contributed to promote cover crops utilization for improvement of forage quality and soil productivity, and for combating weed-infested land. In principle, leguminous cover crops can be introduced in cropping systems either as a component of a rotation system or through intercropping. In the latter case, interspecific competition between intercropped species will occur, and apart from productivity and nitrogen fixing ability, competitive ability becomes another obvious characteristic determining the suitability of a leguminous species as a cover crop. Tall and vigorously growing legumes with relatively large leaves and rapid leaf expansion might be detrimental to the associated crop, whereas poorly competing species will be out-competed and will therefore contribute little to improving soil fertility. Consequently, the success of this kinds of crop – cover crop systems is largely determined by the selection of the most appropriate species and additionally by the design of an optimal management strategy for the intercrop. In this respect, Mulongoy and Akobundo (1990) proposed the use of growth retardants to reduce growth of the associated legumes in maize. Shifting the relative sowing dates of the various intercropped components is yet another means to ensure a better use of available resources and to minimize yield loss of the main crop (Midmore, 1993).

Thus, to facilitate the selection of the most appropriate legume for the development of rice–legume intercropping systems for short fallow improvement (Morris *et al.*, 1990; Becker and Johnson, 1999), detailed knowledge on growth and morphological characteristics is required. Total biomass production and nitrogen fixation are the main factors determining the suitability of leguminous species for improving soil fertility, but if used as a component crop in intercropping systems, competitive ability is another obvious criterion. Morphological growth characteristics such as early relative growth rate of leaf area and earliness of height development have been identified to determine competition in intercropping systems (Kropff and van Laar, 1993). For rice, in addition to the above parameters, maximum height (Bastiaans *et al.*, 1997), specific leaf area (SLA), tillering ability and duration of the crop (Dingkuhn *et al.*, 1999) have been reported as other important factors. Furthermore, some winding legume species were found to be more competitive than erect types (Ofori and Stern, 1987).

This study was conducted to determine the biomass production and N accumulation of six different cover legumes in monoculture. In addition, various physiological, morphological and phenological characteristics that would indicate their potential competitive ability were determined. The main objective of the current research was to find out whether productivity and competitive ability were functionally related.

Materials and methods

Field experiments were conducted during the rainy seasons (June-October) of 1997 and 1998 at the main research centre of the West Africa Rice Development Association (WARDA) in Mbé, central Ivory Coast (7°52′ N, 5°06′ W and altitude 376 m). The experimental site was located in the derived savanna zone characterized by a bimodal rainfall distribution pattern. Weather conditions during the two years of the experiment are presented in Fig. 3.1. The soil was classified as an Alfisol according to the USDA soil classification system or as a Rhodi-humic Acrysols according to the FAO system (Hakkeling *et al.*, 1989).

Six species were selected from the cover legume germplasm collection of WARDA based on a previous adaptability screening trial (Becker and Johnson, 1998). The selected legumes comprised two creeping species: *Mucuna pruriens* var. *cochinchinensis* and *Calopogonium mucunoides*, two semi-erect shrubby-type species *Stylosanthes hamata* and *Aeschynomene histrix*, and two woody erect-growing species *Cajanus cajan* and

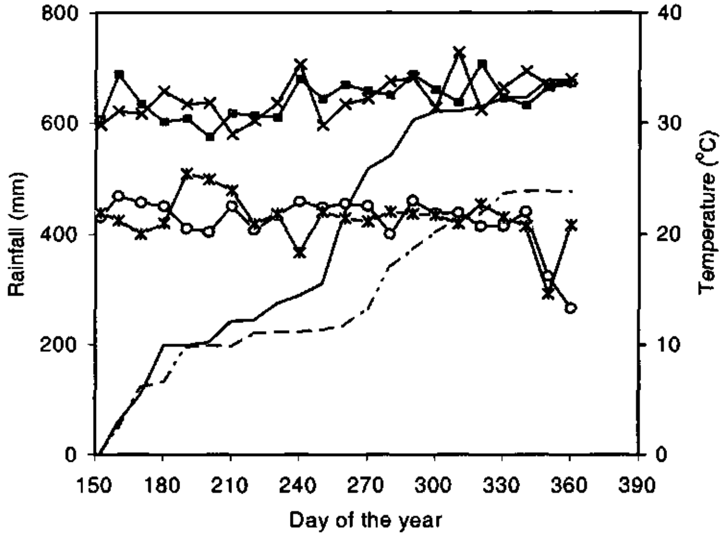

Fig. 3.1 Daily cumulative rainfall (------ 1997, —— 1998) and daily maximum (□ 1997, × 1998) and minimum (○ 1997, ✱ 1998) temperature during the growing period at WARDA research station.

Crotalaria juncea. Legume seeds were sown manually on 15 July 1997 and 2 July 1998 without rhizobial inoculation given the widespread abundance of a range of non-cultivated legumes at the site. Seeds of *S. hamata* and *A. histrix* were scarified for two hours in concentrated solution of sulphuric acid, mixed with fine white sand and dibble-seeded at 80 hills per m^2 (12.5 × 10 cm). Three weeks after emergence, seedlings were thinned to two plants per hill, resulting in 160 plant m^{-2}. The other four species were dry-dibble-seeded using three seeds per hole at 20 hills per m^2 (25 × 20 cm). Two weeks after sowing, *C. cajan* and *C. juncea* were thinned back to two plants per hill (40 plants m^{-2}), whereas *M. pruriens* and *C. mucunoides* were thinned to one plant per hill (20 plants m^{-2}).

Individual plot size was 24 m^2 (6 m × 4 m). The plots were laid out in a randomized complete block design with three replications. A basal application of only 30 kg N ha^{-1} (urea) was given to avoid suppression of nodule formation. Phosphorus as triple super-phosphate (30 kg P ha^{-1}) and potassium as KCl (34 kg K ha^{-1}) were also applied basally and incorporated into the soil during land preparation. Plots were kept weed free by hoeing. Additional water was provided by weekly overhead-boom irrigation.

In 1997, measurements started three to four weeks after sowing, depending on the size of the growing plants while in 1998 observations started one week earlier. Thereafter, measurements were taken every two weeks until final harvest in November. In 1997, height was determined in the laboratory where plant were stretched along a ruler, but in 1998, canopy height was recorded in the field to have a more realistic estimate of effective plant height. At each harvest, two areas of 0.50 × 0.40 m (0.40 m^2) were sampled per plot for destructive measurement of leaf area and total biomass. Leaf was separated from the stem material and leaf area was determined using a LiCor LI-3000 (Lincoln, Nebraska), after which leaf and stem material was oven-dried at 70 °C for 48 hours. Leaf N content was determined by chemical analysis using a standard colorimetric method (Anderson and Ingram, 1993).

Regular field observations were made to determine day of emergence and day of first flowering. Dry matter accumulation over time was described using a logistic equation:

$$Y(TS_s) = Y_{max}/(1 + B_w \times \exp(-R_w \times TS_s)) \qquad (1)$$

Where $Y(TS_s)$ is the shoot dry weight at time TS_s; Y_{max} (g m^{-2}) is the maximum shoot biomass, B_w (-) a coefficient describing the shape of the logistic function and R_w the relative weight increase $(°Cd)^{-1}$. For a better comparison between years time was expressed as the accumulated degree-days since sowing (TS_s; °Cd), using a base temperature of 8 °C. For equation (1), the inflection point M_w (°Cd) is defined as $\ln(B_w)/R_w$. The first derivative of equation (1) was used to derive the growth rate in the inflection point M, which for the logistic function is by definition the maximum growth rate C_m (g m^{-2} $(°Cd)^{-1}$):

$$C_m = Y_{max} \times R_w/4 \qquad (2)$$

Mean comparisons for dry matter production were determined by ANOVA, using the Genstat statistical package (Genstat, 1998).

Observations on early leaf area development (LAI<1) were fitted using an exponential function against temperature sum after emergence:

$$\mathrm{LAI}(TS_e) = \mathrm{LAI}(0) \times \exp(\mathrm{RGRL} \times TS_e) \qquad (3)$$

Where LAI(0) (m^2 m^{-2}) is the leaf area index at emergence, RGR ($(°Cd)^{-1}$) is the relative growth rate of leaf area and TS_e (°Cd) refers to the accumulated temperature sum after emergence.

Parameters describing the height development were derived from a best fit of the data using a logistic equation as a function of TS_s, similar to equation 1, using $H(TS_s)$ as the crop height at time TS_s; H_{max} (cm) as the maximum crop height, B_h (-) as the coefficient describing the shape of the logistic function and R_h as the relative height increase $(°Cd)^{-1}$. All functions were fitted using the non-linear regression option of the Genstat statistical package (Genstat, 1998).

Results

Weather conditions during the two years of experiments are presented in Fig. 3.1. The cropping season lasted from July to November during which daily minimum temperatures varied between 19 and 25 °C and daily maximum temperature fluctuated between 29 and 37 °C. While rainfall pattern looked similar in both years, exceptionally high rainfall was registered in September 1998. Total rainfall during the cropping period (June to November) was 477 mm in 1997 and 645 mm in 1998. A rainfall deficit was observed in 1997 from mid-August until the end of the year.

Phenology

Legumes were grown during the main cropping season and were, thus, exposed to long-day conditions with daylength varying between 13.7 h in June and 12.4 h in September. Differences in time of emergence and in duration of the vegetative growth phase were observed among the species (Table 3.1). *C. juncea* and *M. pruriens* were the two species to emerge first after only three days. The other species emerged within a week after those species, except for *A. histrix*, which emerged only at 13 days after sowing. Flowering in *S. hamata* occurred so early, that in 1997 the date of first flowering was not recorded.

In 1998, first flowering was observed at 600 °Cd after emergence and typically for this species flowering occurred more than once, as growth continued and new branches were formed. In both years, *C. juncea* was the second species to flower, at about 900 °Cd. First flowering for the other four species was observed between 1300 and 1600 °Cd after emergence, corresponding to around three months after sowing.

Table 3.1 Emergence dates, time to flowering and N accumulation by the six legume species during the growing seasons of 1997 and 1998.

	Day of emergence (day of year)		TS_s at flowering (°Cd)		N accumulation (kg ha^{-1})	
Treatments	1997	1998	1997	1998	1997	1998
C. cajan	203	188	1470	1517	67.5	71.8
C. juncea	200	185	925	875	71.6	73.9
M. pruriens	200	185	1425	1482	97.3	57.7
C. mucunoides	207	192	1303	1585	68.0	58.1
S. hamata	207	192	-	624	20.9	35.0
A. histrix	210	195	1481	1465	19.0	29.6
Legumes mean	-	-	-	-	57.4	54.4
LSD 0.05					33.8	28.6

Biomass and nitrogen accumulation

The time course of dry matter (DM) production could be reasonably well described by the logistic function (Fig. 3.2). Observed data were homogeneously distributed around the fitted curves and R^2-values varied from 0.94-0.98. In most situations, the estimated Y_{max} value was already obtained at final harvest. Exceptions were *A. histrix*, which at final harvest still showed a steady increase in total biomass and *M. pruriens* in 1998,

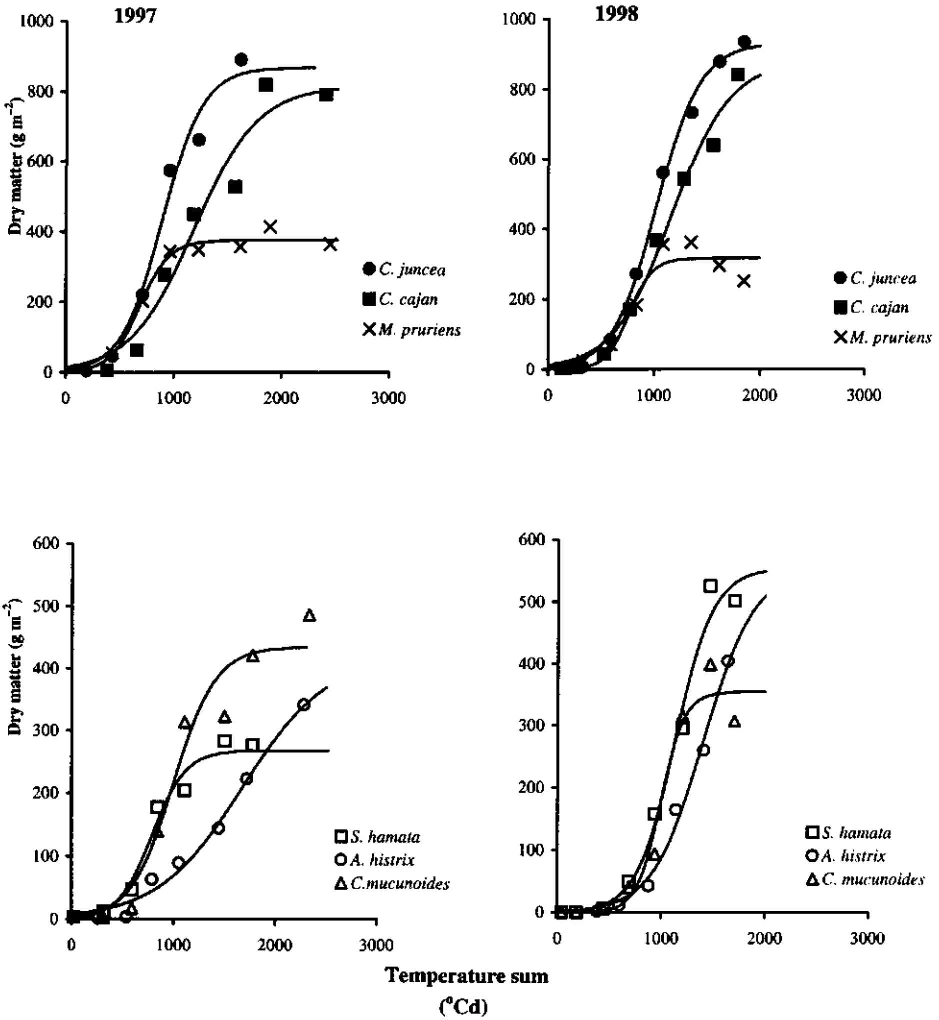

Fig. 3.2 Dry matter accumulation of fast-growing species *C. juncea, M. pruriens* and *C. cajan* and slow-growing *A. histrix, C. mucunoides* and *S. hamata* as fitted by a logistic equation in 1997 and 1998.

which already reached its maximum around 1200 °Cd, and then gradually died of. Most of the species had similar performance in biomass accumulation from year to year. The exception was *S. hamata*, which almost doubled its production in 1998 compared to 1997. Maximum accumulated dry biomass averaged over both years was highest for *C. juncea* and *C. cajan* with over 8.5 t ha^{-1}, followed by *C. mucunoides* and *S. hamata* slightly over 4 t ha^{-1} and *A. histrix* and *M. pruriens* with between 3.5 and 4.0 t ha^{-1}.

The initial relative growth rate R_w $[(°Cd)^{-1}]$ differed among species and between years (Table 3.2). In both years, *M. pruriens* was found to have the highest R_w, whereas the lowest values were observed for *A. histrix* and *C. cajan*. Differences in R_w, together with differences in time of germination are responsible for differences in dry matter accumulation during the initial growth phase. Clear differences were observed in these early stages, for instance in 1998, where after 12 days *M. pruriens* had already produced 44 kg DM ha^{-1}, while *S. hamata* and *C. mucunoides* had accumulated 1.8 and 3.9 kg DM ha^{-1}, respectively, and *A. histrix* had barely germinated. Growth duration is reflected in M_w, the moment to reach 50% of the maximum obtainable biomass. For both years, M_w of *M. pruriens* was estimated at around 700 °Cd, indicating the short growth duration of this species. For *C. juncea*, *C. mucunoides* and *S. hamata* an average value over both years of around 1000 °Cd was observed, with again very different values for *S. hamata* in both years. For *C. cajan*, a slightly higher M_w-value of close to 1200 °Cd was found and clearly the highest values in both years were observed for *A. histrix* with an average of 1500 °Cd. In 1997, the maximum growth rate ($C_{m,w}$) was least for *S. hamata* and *A. histrix* (0.41 and 0.25 g m^{-2} $(°Cd)^{-1}$), intermediate for *C. cajan*, *M. pruriens* and *C. mucunoides* (0.69, 0.68 and 0.52 g m^{-2} $(°Cd)^{-1}$, respectively) and highest for *C. juncea* (1.15 g m^{-2} $(°Cd)^{-1}$; Table 3.2). The same pattern was observed in 1998, however with growth rates nearly doubled for *A. histrix* and *S. hamata* and with slightly higher values for most other species.

Clear differences in maximum N-accumulation in the foliage were observed between *M. pruriens*, *C. juncea*, *C. cajan* and *C. mucunoides* on the one hand and *S. hamata* and *A. histrix* on the other (Table 3.1). For the first group the average N accumulation over both years was around 70 kg N ha^{-1}, whereas for the second group this was only 25 kg N ha^{-1}. A high variability of maximum N accumulation in the leaves at the individual plot level was observed in both years for all species.

Species characteristics related to competitive ability

Together with plant density, the initial per plant leaf area at emergence (LA0) and relative growth rate of leaf area (RGRL) determine the leaf area development early in the season. Early leaf area development differed among the species and between years. RGRL was not determined in 1997 for *C. juncea* and *M. pruriens* because the first

Table 3.2 Parameter values for the logistic growth equation $Y(TS_s) = Y_{max} / (1+B_w \times \exp(-R_w \times TS_s))$ describing dry matter production and growth rate of the six cover legumes.

	C. cajan	*C. juncea*	*M. pruriens*	*C. mucunoides*	*S. hamata*	*A. histrix*
1997						
Y_{max} (g m^{-2})*	815.2	867.8	375	434.2	267.5	423.2
Std error	*89.8*	*77.1*	*12.9*	*40.6*	*12.6*	*64.2*
R_w (°Cd)$^{-1}$	0.0034	0.0053	0.0073	0.0048	0.0061	0.0024
Std error	*0.0010*	*0.0014*	*0.0016*	*0.0018*	*0.0014*	*0.0004*
M_w (°Cd)	1189	899	688	1006	786	1666
$C_{m,w}$ (g m^{-2} (°Cd)$^{-1}$)	0.69	1.15	0.68	0.52	0.41	0.25
1998						
Y_{max} (g m^{-2})	881.3	929.9	317.7	354.5	553.5	554
Std error	*92.3*	*26.9*	*26*	-	*42.7*	*7.5*
R_w (°Cd)$^{-1}$	0.0036	0.0048	0.0091	0.0087	0.0055	0.0041
Std error	*0.0007*	*0.0004*	*0.004*	-	*0.0011*	*0.0005*
M_w (°Cd)	1179	1035	766	996	1127	1409
$C_{m,w}$ (g m^{-2} (°Cd)$^{-1}$)	0.79	1.12	0.72	0.77	0.76	0.57

* Y_{max} Maximum dry matter;
R_w Relative weight increase;
M_w Time when species reached 50% of total biomass;
$C_{m,w}$ Maximum growth rate of the species at $TS_s = M_w$.

Table 3.3 Early relative leaf growth rate (RGRL, m^2 m^{-2} (°Cd)$^{-1}$) of the six legume species and the time course of canopy development (LAI=1) in 1997 and 1998.

	C. cajan	*C. juncea*	*M. pruriens*	*C. mucunoides*	*S. hamata*	*A. histrix*
Plant density (m^{-2})	40	40	20	20	160	160
LA0 (10^{-5} m^2 plant^{-1})	8.90	2.33	33.60	1.70	0.80	0.64
1997						
RGRL (m^{2}m^{-2} (°Cd)$^{-1}$)	0.0088	-	-	0.0103	0.0052	0.0094
TS_e (°Cd) at LAI=1	641			775	724	739
1998						
RGRL (m^2 m^{-2} (°Cd)$^{-1}$)	0.0115	0.0158	0.0105	0.0127	0.0092	0.0080
TS_e (°Cd) at LAI=1	430	447	476	629	673	869

recorded value for LAI at 26 DAS (days after sowing) already exceeded a value of one. For the other species, the highest RGRL was determined in *C. mucunoides* followed by *A. histrix*, *S. hamata* and *C. cajan* (Table 3.3).

In 1998, the highest RGRL was found with *C. juncea*, *M. pruriens*, *C. mucunoides* and *C. cajan*, which was having a considerable higher RGRL than in 1997. RGRL values for *S. hamata* and *A. histrix* were clearly lacking behind. These two species were very slow to establish, since they were also found to have the smallest apparent leaf area at emergence (LA0). In general, initial per plant leaf area was strongly related to seed size, with the highest value for the large-seeded *M. pruriens*. In 1998, the temperature sum to reach an LAI of one was around 450 °Cd for *C. cajan*, *C. juncea* and *M. pruriens*. This was considerably faster than for *A. histrix* and *S. hamata*. Surprisingly, *C. mucunoides* was also slow to establish, despite a relatively high RGRL value, due to a low-seeding rate and a small initial plant size. In 1997, the temperature sum to reach an LAI of 1 was higher for all of the four recorded species.

For most of the species, specific leaf area (SLA) first increased and then decreased gradually from about 45 DAS until 90 DAS (Fig. 3.3). This effect was more pronounced in 1998 than in 1997. The SLA of *A. histrix* was noticeably smaller than for the other species during large part of the growing season, except that *S. hamata* had a similar SLA in 1998. In both years, and particularly in 1997, the SLA of *M. pruriens* was largest among the species. From 19 to 62 DAS, the period corresponding to active vegetative growth, the SLA was significantly different among the species ($p<0.05$).

For plant height, only data for 1998 are presented as for all species the same trend was observed in both years. These data represent field measurement of canopy height, which is more relevant for competitive studies. The highest rate of height increase was observed in the erect species *C. juncea* and *C. cajan*. *C. juncea* grew fastest and became tallest ($C_{m,h}$=0.292 cm $(°Cd)^{-1}$, H_{max}=285 cm). The herbaceous species *S. hamata* and *A. histrix* showed a clearly slower height increase (0.060-0.077 cm $(°Cd)^{-1}$) with a maximum height of about 90 cm (Table 3.4). *M. pruriens*, though having a faster growth rate than *S. hamata* and *A. histrix*, only became nearly 70 cm as the growth period for *M. pruriens* was shorter, a phenomenon reflected in a M_h-value of about 600 °Cd. *C. mucunoides* was having the slowest growth rate, and only became 45 cm tall.

In Fig. 3.4, productivity in terms of biomass and N accumulation are related to early relative leaf area growth rate and maximum height. From this comparison it is clear that based on these characteristics the earlier mentioned distinction in three classes of legumes, namely the woody erect-growing species (*C. juncea* and *C. cajan*), the semi-erect shrubby-type species (*S. hamata* and *A. histrix*) and the creeping species (*M. pruriens* and *C. mucunoides*) is evident. The woody erect-growing species were the tallest and fastest-growing species, producing the highest amount of biomass and

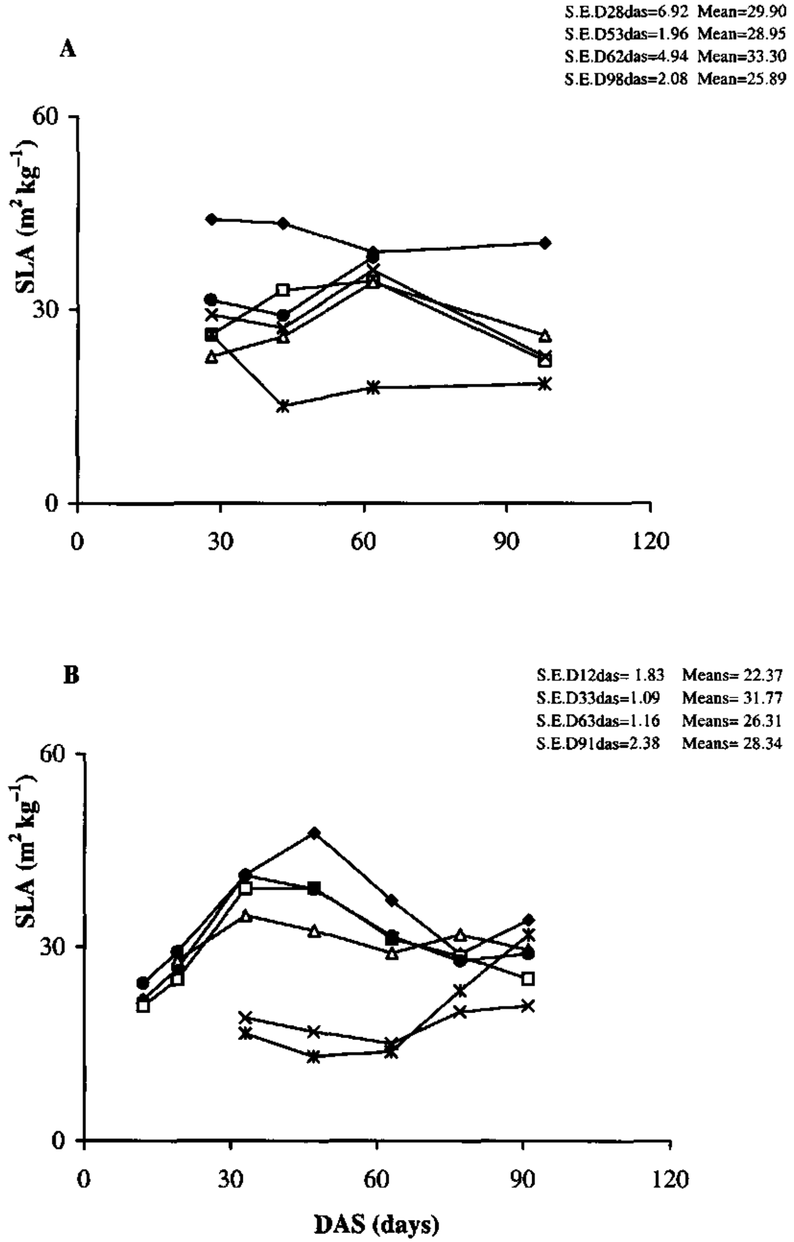

Fig. 3.3 Time course of specific leaf area (SLA) of the various legume species (×) *Stylosanthes*, (•) *Crotalaria*, (✶) *Aeschynomene*, (□) *Cajanus* (Δ) *Calopogonium*, (◆) *Mucuna* in 1997 (A) and 1998 (B). Standard errors of the means did not include the value for *A. histrix* and *S. hamata*.

Table 3.4 Parameter values for the logistic height growth eqn $H = H_{\mathrm{max}} / (1+B_{\mathrm{h}}\times\exp(-R_{\mathrm{h}}\times TS_{\mathrm{s}}))$ describing plant height and height increase rate of the six cover legumes.

	C. cajan	*C. juncea*	*M. pruriens*	*C. mucunoides*	*S. hamata*	*A. histrix*
H_{max} (cm)	252	285	69	45	91	91
Std error	12.7	9.9	3	2.8	7.3	8.4
R_{h} (°Cd)$^{-1}$	0.0029	0.0041	0.0052	0.0038	0.00260	0.00340
Std error	0.0003	0.0004	0.0011	0.0006	0.00028	0.00045
M_{h} (°Cd)	1172	904	588	1082	1370	1471
$C_{\mathrm{m,h}}$ (cm (°Cd)$^{-1}$)	0.182	0.292	0.089	0.043	0.060	0.0770
R^2	0.99	0.99	0.96	0.98	0.99	0.99

H_{max} Maximum height

R_{h} Relative height increase

M_{h} Time when species reached 50% of maximum height

$C_{\mathrm{m,h}}$ Maximum height increase rate of the species at $TS_{\mathrm{s}} = M_{\mathrm{h}}$.

accumulating a substantial amount of N. Of the two species, *C. juncea* had a fast initial leaf area development rate, whereas the RGRL of *C. cajan* was just below average. Opposite these two species were the semi-erect shrubby-type species. Biomass and N accumulation of *A. histrix* and *S. hamata* were low and along with that also the characteristics representing competitive ability were below average. The creeping species held an intermediate position. Though biomass production was comparable to that of *S. hamata* and *A. histrix*, the accumulated amount of N was comparable to *C. juncea* and *C. cajan*. Both species, because of their creeping habitat, did not grow very tall. RGRL values were similar to the one for *C. cajan*. However, the high leaf area of *M. pruriens* at emergence (Table 3.2) combined with its rapid height growth rate (Table 3.4) makes that the competitive ability of this species during early growth stages is high.

Discussion

In general, the common important traits that determine competition for light between plants are inherent to the species. amongst these traits are growth rates and the architecture of the canopy (Davis and Garcia, 1983; Kropff and van Laar, 1993). In a study of competition between maize and *Datura stramonium*, Cavero *et al.* (1999) found that the high competitive ability of the maize was due to a faster increase in height and in leaf area. In upland rice, rather high tillering and large SLA contributed strongly to competitiveness but not plant height (Dingkuhn *et al.*, 1999). The contribution of these morphological and physiological attributes to the competitive ability of the species under field conditions and their interrelation is complex and dependent on growing conditions. In this study, different phenological characteristics and growth patterns were observed among cover crops species ranging from the short-lived species *M. pruriens*, which germinated quickly and covered the ground surface rapidly (LAI = 1 at TS_e = 476 °Cd), to the long-lived species *A. histrix*, which is slow to establish and only reached a canopy LAI of 1 at around 800 °Cd. These characteristics make *M. pruriens* a relatively strong competitor which may explain its use against the perennial grass *Imperata cylindrica* in maize-based systems in Africa and North Honduras (Versteeg and Koudopon, 1990; Akobundu, 1993; Triomphe, 1996). Based on early growth characteristics, *C. juncea, C. cajan* and *M. pruriens* can be considered as species with a higher competitive ability than *C. mucunoides*, *S. hamata* and *A. histrix*. This can be explained by the combination of high initial growth rates for height and leaf area development. Additionally, the large

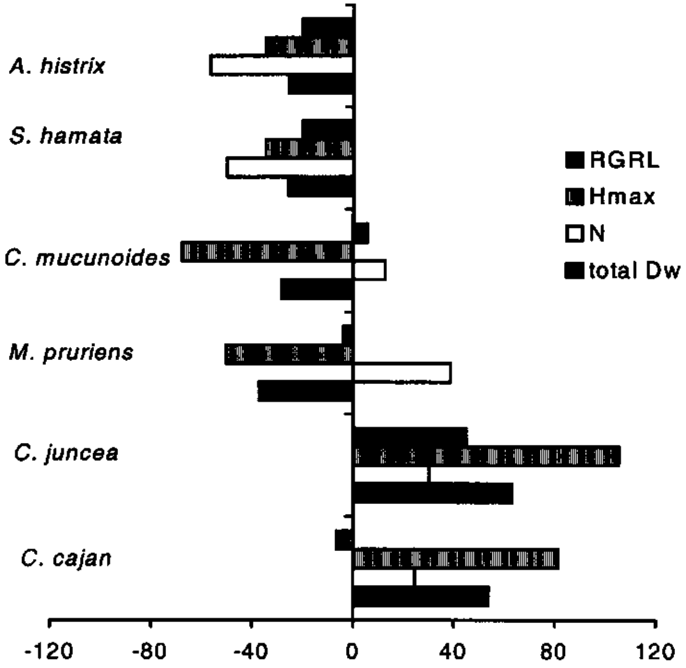

Fig. 3.4 Relationship between early relative growth rate of the leaves, maximum height, N accumulation and dry matter production of the six cover crops species. The axis represents the deviation (in %) of the mean estimate of the different parameters. Relative growth rate of the leaves (RGRL, 0.0109 $m^2 m^{-2} (°Cd)^{-1}$), maximum height (H_{max}, 139 cm), nitrogen accumulation (N, 56 kg ha^{-1}) and total shoot dry weight (total Dw, 552 g m^{-2}).

final height of *C. juncea* and *C. cajan* may confer higher competitiveness throughout the growing season. Relationships between these morphological traits are widely used in competition models to study the competitive strength of the species (Bastiaans *et al.*, 1997; Kropff and van Laar, 1993; Lindquist and Mortenson, 1997).

With respect to biomass production and N accumulation, the experimentally tested legume species can be classified in three distinct groups. *C. juncea* and *C. cajan* produced the highest biomass and a substantial amount of N. *M. pruriens* and *C. mucunoides* accumulated a comparable amount of N, but biomass production was considerably lower. The third group, consisting of *S. hamata* and *A. histrix* only produced marginal amounts of biomass and N. Large variability in N accumulation by cover legumes may also depend on climate and soil (Becker and Johnson, 1998; Akanvou *et al.*, 2000).

The potential use of cover legumes as a component crop in a relay-intercropping system with upland rice offers new alternatives to increase system productivity and possibly provides additional products to farmers (e.g., food or forage; Osei-Bonsu *et al.*, 1995). However, the success of such a system would depend on the management of interspecific competition and, thus, on morphological and physiological characteristics of both the rice cultivar and the legume species. In intercropping situations, cover legumes must have minimum competition effects on rice yield while producing sufficient biomass for fallow improvement. For the six legume species examined in the current experiments, a clear link between productivity in terms of biomass and N accumulation on the one hand and competitive potential on the other hand was observed. High leaf-N accumulation of between 60 and 80 kg N ha^{-1} was found in *C. juncea, C. cajan, M. pruriens* and *C. mucunoides*. However, the first three of these species were also identified as potentially most competitive throughout the growing season. Whereas *C. cajan* and *C. juncea* grow very tall (>250 cm) and are likely to overtop the rice canopy (Fig. 3.4), the creeping *M. pruriens* and *C. mucunoides* might cause lodging due to its winding ability. Delaying the sowing time of the legumes might be a possibility to reduce these interaction effects. More studies are needed to determine the effects of sowing dates on biomass accumulation and its impact on N accumulation by the legumes.

Conclusions

Slow-growing species such as *S. hamata* and *A. histrix* are, based on the current observations, expected to be less competitive and, therefore, appropriate for early establishment in rice–legume intercropping systems. However, particularly N accumulation of these species was found to be low, which might be a constraint. Such species should also have the ability to recover after the harvesting of the rice crop.

The results of the current study indicate the wide variability in productivity and competitive ability of the selected legume species that might fit the upland rice system. At the same time the results suggest a clear link between productivity and competitive ability: the most competitive also being the more productive in terms of N accumulation and biomass. Consequently, it can be expected that a specific optimum time of introduction exist for each legume species when used as a component crop in a rice–legume intercropping system. Further studies, therefore, need to explore the competitive relations of the legumes relative to rice, and determine the implications for sustainable rice production.

CHAPTER 4

Evaluating the use of two contrasting legume species as relay intercrop in upland rice cropping systems

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CHAPTER 4

Evaluating the use of two contrasting legume species as relay intercrop in upland rice cropping systems

Abstract
In the savanna zone of West Africa with a prolonged dry season, the successful growth of legumes as short-season fallow necessitates relay establishment of cover crops into the preceding food crop. Inappropriate choice of legume species and establishment dates may result in severe interspecific competition for light, water and nutrients and a subsequent yield loss in the main crop. In the current study, the highly competitive *Cajanus cajan* L. and the weakly competitive *Stylosanthes hamata* Taub. were relay-seeded into two upland rice cultivars with different competitive ability (WAB56-50, WAB450-24-3-2-P18-HB syn. V4*)* at different sowing dates, ranging from 0 to 84 days after rice sowing (DARS). Using a logistic function was adequate to describe rice grain yield, final rice biomass and legume biomass at one week after rice harvest as a function of legume sowing date. Rice biomass and grain yield were significantly ($p<0.001$) reduced when legumes were established between 0 and 28 DARS. Beyond 56 DARS no competition effects on rice were observed. At these late sowing dates only relatively low amounts of legume biomass were obtained, due to a combined effect of a more severe competition by the rice crop and a shorter growing period. The derived yield loss – legume biomass relationship showed that *C. cajan* was the most appropriate legume species of the two under study, that can suit a relay intercropping system with upland rice, as it produced reasonable amounts of biomass at low levels of rice grain yield loss. This conclusion was confirmed by results on the after-effect of the legumes, where only the improved fallow by *C. cajan* gave a significant increase in the yield of the subsequent rice crop. Optimum sowing time of *C. cajan* was between 30-35 DARS. The impact of selecting a specific legume was found to surpass the influence of choosing either one of the two rice cultivars, for which contrasting results were obtained in the two years of experimentation.

Keywords*:* *Oryza sativa, Cajanus cajan, Stylosanthes hamata,* Savanna zone, Competition, Residual effect

Introduction

In West Africa, upland rice ecosystems represent the major rice-growing environment with 2.5 million ha or 60% of the rice growing area. This proportion is responsible for 40% of the regional production (Terry *et al.*, 1995). Average grain yield of 1.0 t ha^{-1} is low compared to world average yield of 1.5 t ha^{-1} for upland rice. Yield gap analysis in three agro-ecological zones in Ivory Coast showed that weeds, nitrogen and to some extent drought were the major factors limiting rice productivity (Becker and Johnson, 1998). Introducing legume cover crops into rice cropping systems for short fallow improvement offers alternative cheap inputs to farmers with limited resources to increase yield. Yield of upland rice increased by 30% following dry season cover crops (Becker and Johnson, 1998). Besides being an efficient source of N for rice, well-adapted cover crop species may contribute to the control of weeds and pests (Nye and Greenland, 1960; Buckles and Triomphe, 1999). So far, adoption of green manure cultivation by farmers has been limited by the scarcity of labour and the need for equipment for residue management (Becker and Assigbe, 1995; Osei-Bonsu and Buckles, 1993). Furthermore, the opportunity cost of growing cover crops which do not yield immediate returns as a food cash crop constitutes an important factor reducing the adoption of cover crops in the savanna environment of West Africa (Tarawali *et al.*, 1999). The savanna environment is characterized by a dry season between November and February. Therefore, successful establishment of a cover crop that is able to survive the dry season necessitates seeding of the legume during the preceding rainy season, which ends during the ripening of the rice crop. Relay seeding of legume cover crops into a standing crop of upland rice may result in severe interspecific competition. The extent of competition-induced rice yield loss and the amount of accumulated legume biomass are likely to depend on the competitive ability of the component species and on the date of legume seeding. Therefore choice of legume species and rice cultivar, and time of legume establishment seem relevant management options in this specific system.

In studies on crop–weed interactions, morphology and growth characteristics of the species and the relative time of establishment are often identified as main determinants of competitive relationships (e.g., Kropff and van Laar, 1993; Lindquist and Mortensen, 1999). Modification of the cropping environment is another way to manipulate competitive relations. Planting density, fertilization and a change in relative planting time of the companion crop are important management strategies in intercropping systems to reduce competition effects on the main crop (Midmore, 1993). In maize for example, yield loss was reduced from 40 to 22% when *Crotalaria ochroleuca* was intercropped three weeks after planting instead of planting both species simultaneously (Fischler and Wortmann, 1999). The delay in sowing time of one component in the intercropping system can give an early competitive advantage to the earlier sown component. Strong reduction in maize yield occurred in maize–cowpea intercropping system when the relatively more competitive maize was sown after the less competitive cowpea (Ofori and Stern, 1987). In contrast to maize intercropping systems, no published reports exist on upland rice–legume intercropping systems. The objectives of this study were to evaluate the productivity of the two components of an upland rice–cover legume intercropping system, as affected by legume species, rice cultivar and relative sowing date of the legume. In addition, residual effects of cover legumes on the yield of a subsequent crop of upland rice were investigated.

Materials and methods

The study was conducted over a three year period (1997-1999) at the West Africa Rice Development Association (WARDA) main research station (7° 52 N, 5° 06 W) at Bouaké, Ivory Coast. The site is located in the savanna zone characterized by a cumulative annual rainfall of about 1000 mm. In 1997, an experiment was laid out on high-input farmland whereas, in 1998, the fertility level of the experimental field was relatively low as it had been used for low-input experiments.

Land was ploughed and fertilized with 30 kg P (triple superphosphate) and 34 kg K (KCl) at field preparation and 30 kg ha^{-1} of urea-N, applied at 30 days after rice sowing. Two rice cultivars were intercropped with two cover crops using an additive experimental design. Rice cultivars comprised the improved japonica WAB56-50 and the interspecific hybrid progeny WAB450-24-3-2-P18-HB also called V4, selected from a cross between *Oryza sativa* (WAB56-104) and *O. glaberrima* (CG14). The two cover crop leguminous species were the erect fast growing *Cajanus cajan* and the semi-erect slow-growing forage legume *Stylosanthes hamata*. Each legume species was sown at four different dates after sowing of the rice crop (DARS).

The experiment was laid out in a randomized complete block design of three replicates with three factor combinations consisting of two rice cultivars, two cover crop species and four relative dates of legume introduction into the standing rice crop. In addition to mixture plots, monoculture plots of rice (one sowing date) and of legumes (4 sowing dates corresponding to the dates of legume introduction in intercropping) were established to facilitate analysis of environmental effects due to time of sowing, resulting in a total of 26 treatments (Table 4.1). Rice was sown on June 18 in 1997 and July 2 in 1998. In 1997, the relative sowing dates were 0 (D1), 28 (D2), 56 (D3), 84 (D4) days after rice sowing (DARS) for the introduction of the two legume species in V4. Because of poor plant stand, WAB56-50 was resown 10 days after first sowing, resulting in relative introduction dates of the legumes that were 10 days earlier than scheduled except for the first introduction date when *C. cajan* was resown and establishment of *S. hamata* was slightly delayed. In WAB56-50 this resulted in relative introduction times of –6, 18, 46 and 74 for *S. hamata* and 0, 18, 46, 74 for *C. cajan*. In 1998, legume sowing dates were modified based on experiences of the previous year in which we found; (1) after 56 DARS rice yield was hardly affected by legume establishment, and (2) during the first four weeks, both rice yield and legume biomass were extremely sensitive to legume introduction time. For these reasons, D1 to D4 were set at 0, 14, 28, and 56 DARS, respectively.

Individual plots measured 6 m × 4 m including 3 m^2 (3 m × 1 m) area for non-destructive measurements and final harvest. Rice was dibble-seeded at 0.25 m × 0.20 m and thinned to three seedlings per hill after three weeks, resulting in 60 plants per m^2. At each sowing

Table 4.1 Factors and treatments applied for the field experiment conducted during the rainy seasons of 1997 and 1998.

Factors	Levels		Description
Rice cultivar	2		WAB56-50, V4
Legume species	2		*C. cajan*, *S. hamata*
Legumes introduction date*			
1997	4		0, 28, 56, 84 DARS **
1998	4		0, 14, 28, 56 DARS
Treatments	**Number of combinations**		
Rice monoculture	2		
Rice × Legume × Date	16	(2 × 2 × 4)	
Legume monoculture × Dates	8	(2 × 4)	
Total	26		

* First sowing date in 1997 was June 18th , and July 2nd in 1998.

** Days after rice sowing.

date, 12 plots (2 rice × 2 legume × 3 replicates) were intercropped by sowing legumes in between rows of rice. *C. cajan* was seeded in single rows between rice rows at 0.25 m × 0.20 m with two plants per hill (40 plants m^{-2}) whereas *S. hamata* was seeded in double rows. Rows were 12.5 cm apart and planting distance in the row was 10 cm. Three weeks after sowing, plants were thinned to 2 plants per hills (160 plants m^{-2}). Legumes in monoculture were sown in the same density using the same spatial arrangement as in mixture. Weeds were removed manually if required. A stick measurement of rice and legume plant height was determined in the field by measuring the distance from soil surface to the top of the plant every two weeks. At maturity, grain yield at 14% moisture and yield components (spikelet number, panicle number and 1000-grain weight) were determined from the 3 m^2 harvest area. Spikelet number was determined on 10 randomly harvested panicles. Legume biomass was measured at one week after final rice harvest. In 1998, N content in the foliage was periodically determined by chemical analysis using a standard colorimetric method (Anderson and Ingram, 1993).

After the removal of rice harvest residues, the legumes remained in the field during the dry season until the following cropping season in June. With the onset of the rainy season in 1999, all residues were cut and incorporated mechanically. Rice cultivar WAB56-50 was dibble-seeded using the same arrangement and the same density as in the 1998 experiment to evaluate the after-effects of short season legume fallow on a subsequent crop of upland rice. Final harvest was on October 18, 1999. Grain yield at 14% moisture and biomass were based on 6 m^2 area. Analysis of variance and comparison of means were performed using Genstat (1998). The level of significance is indicated by the least significant difference between the means (LSD) at 5% probability.

Rice grain yield and shoot biomass at harvest and legume shoot biomass at one week after rice harvest (*Y(t)*; kg ha^{-1}) were fitted to a logistic function, using the relative sowing time of the legume (*t*; DARS) as an explanatory variable:

$$Y(t) = \frac{Y_{\max}}{1 + b\exp^{-ct}} \quad (1)$$

in which $Y_{\max}$ is the maximum grain yield or shoot biomass (kg ha^{-1}), and *b* (-) and *c* (d^{-1}) are parameters describing the logistic equation. The non-linear regression option of Genstat was used to obtain the best fitting logistic functions. For rice, the maximum biomass and grain yield ($Y_{\max}$) were set equal to the biomass and grain yield in monoculture, and consequently only parameters *b* and *c* were estimated.

Results

Rice biomass in mixture

Advancing the establishment date of legumes reduced yield and shoot biomass of upland rice. In each year, rice shoot biomass at harvest could be accurately described by a logistic function of the relative legume establishment date (Fig. 4.1). Total above-ground dry weight increased significantly ($p<0.001$) from 0 DARS to 56 DARS during 1997 and 1998. In 1997, results clearly indicated that the strongest reduction in rice biomass was obtained by advancing the introduction time of the cover crops from 28 to 0 DARS. Maximum dry weight obtained in monoculture was 9 t ha^{-1} for V4 and 9.8 t ha^{-1} for WAB56-50. V4 lost 84% of total dry weight at 0 DARS and 17% at 28 DARS when *C. cajan* was the intercrop component. When *S. hamata* was the intercrop, loss in dry weight was only 45% at 0 DARS and slightly less than 1% at 28 DARS. For WAB56-50, introduction dates were slightly different, as this cultivar was resown after the poor establishment of the first sowing, but observed trends were quite similar. In competition with *C. cajan* 92% loss in dry weight was observed at 0 DARS and 24% if the relay crop was introduced 18 days later. In combination with *S. hamata*, reductions in biomass of 70% and 19% were observed at –6 and 18 DARS, respectively.

In 1998, the trial was conducted on a 'low input' site of the research station, which explains the lower maximum values for rice dry weight in monoculture of 4.8 t ha^{-1} and 4.5 t ha^{-1} for V4 and WAB56-50, respectively. Furthermore, the inclusion of an extra introduction time of the legumes during the early growth phase of rice at 14 DARS, allowed for a more precise fit of the logistic function, which was particularly reflected in a lower standard error of parameter *b* (data not shown). The observed relationship

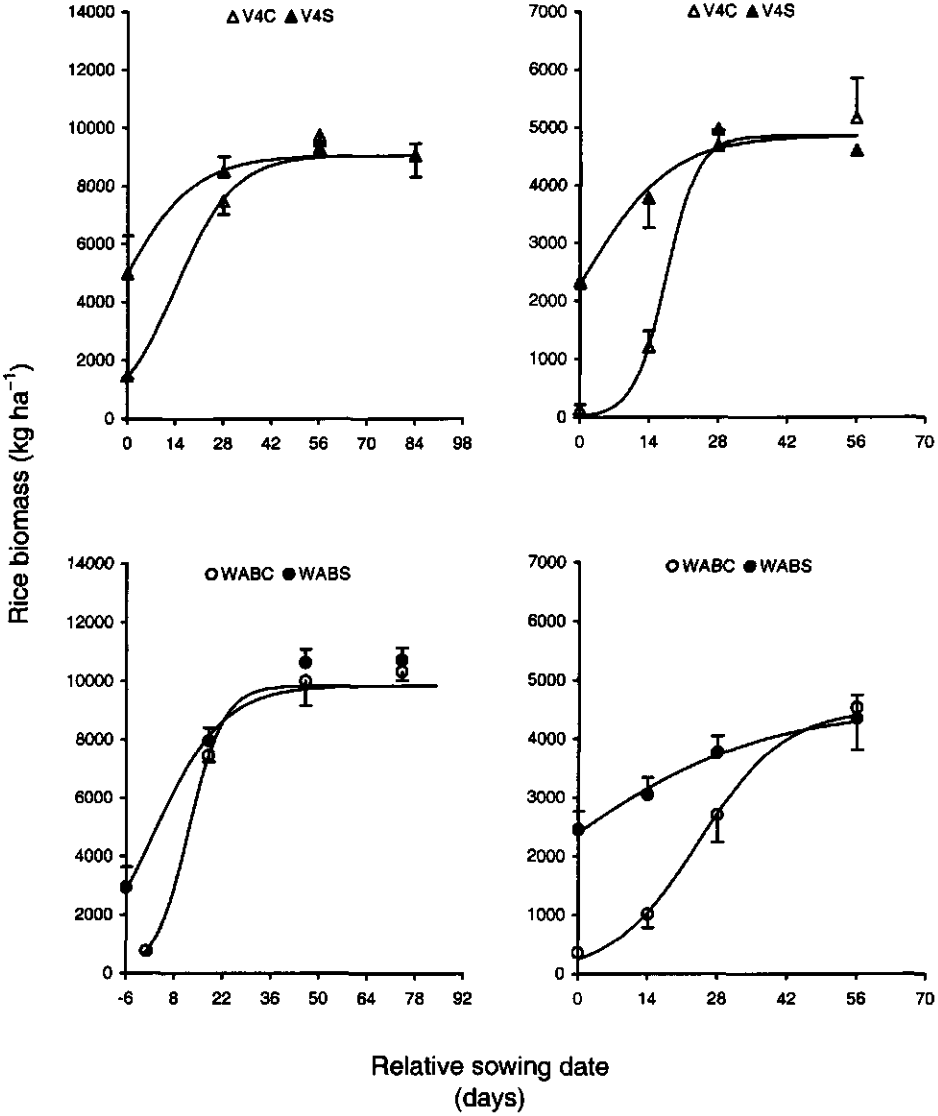

Fig. 4.1 Effects of different relay sowing dates of cover legumes on shoot dry weight (kg ha^{-1}) of rice (V4 and WAB56-50) during the wet season of 1997 and 1998. (▲ V4 in mixture with *S. hamata* (V4S), ● WAB56-50 in mixture with *S. hamata* (WABS), ○ WAB56-50 in mixture with *C. cajan* (WABC), Δ V4 in mixture with *C. cajan* (V4C)). Bars represent standard errors of the observations.

between biomass production and relative date of legume establishment was largely the same, though it was obvious that WAB56-50 still suffered from legume introduction at 28 DARS, whereas reductions in V4 were only observed at 0 and 14 DARS (Fig. 4.1). *C. cajan* again showed to be a stronger competitor than *S. hamata*.

In both years, the competitive ability of the legume species relative to the rice cultivar as well as the sowing date of the legume determined rice biomass production. Furthermore

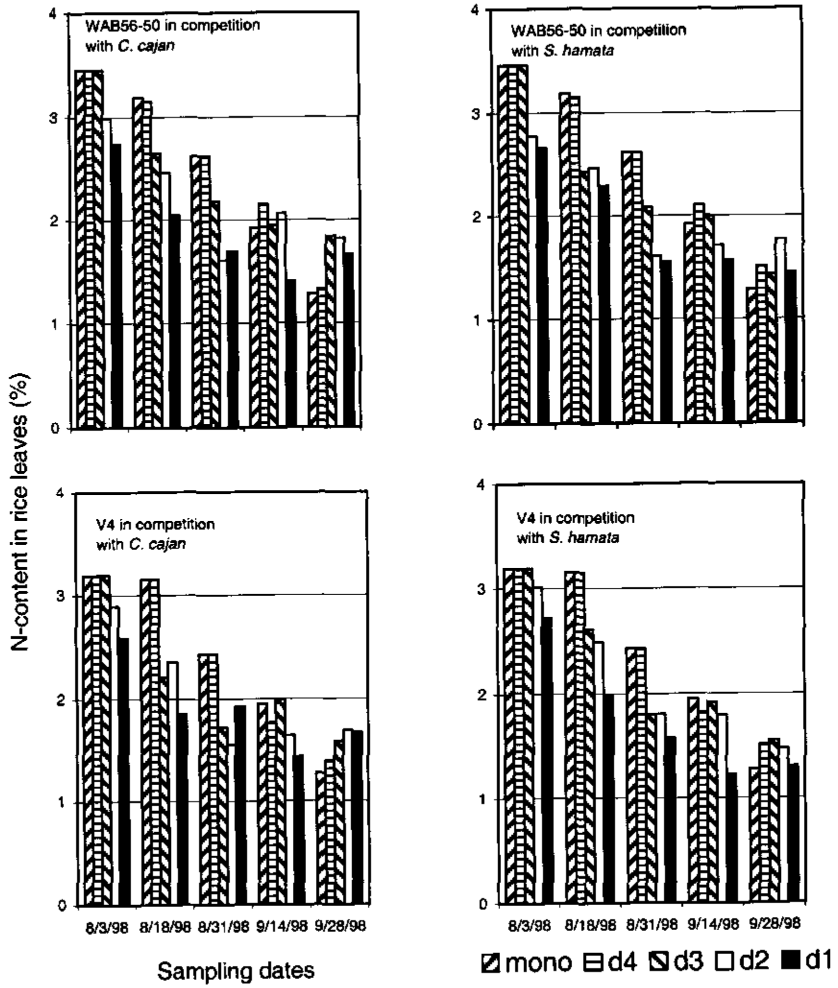

Fig. 4.2 Time course of N-concentration (%) in foliage of rice cultivars V4 and WAB56-50 in the 1998 experiment, as affected by relay-intercropping two different legume species (*C. cajan* and *S. hamata*) at different times after rice sowing (d1 = 0 DARS; d2 = 14 DARS; d3 = 28 DARS; d4 = 56 DARS; mono = rice monoculture).

it was found that in 1997, V4 suffered more from the presence of the legumes than WAB56-50, whereas in 1998 the opposite was observed (Fig. 4.1). When legumes were established at 56 DARS or later, no significant reductions in biomass were observed for either rice variety. In Fig. 4.2, biweekly data on foliage N-content of both rice cultivars in monoculture as well as in competition with *C. cajan* and *S. hamata* are presented for the 1998 experiment, starting from around one month after rice sowing. Particularly in the second month after sowing a clear reduction in N-content of the rice foliage was observed for legume sowing dates of 0 and 14 DARS. Legume introduction at 28 DARS

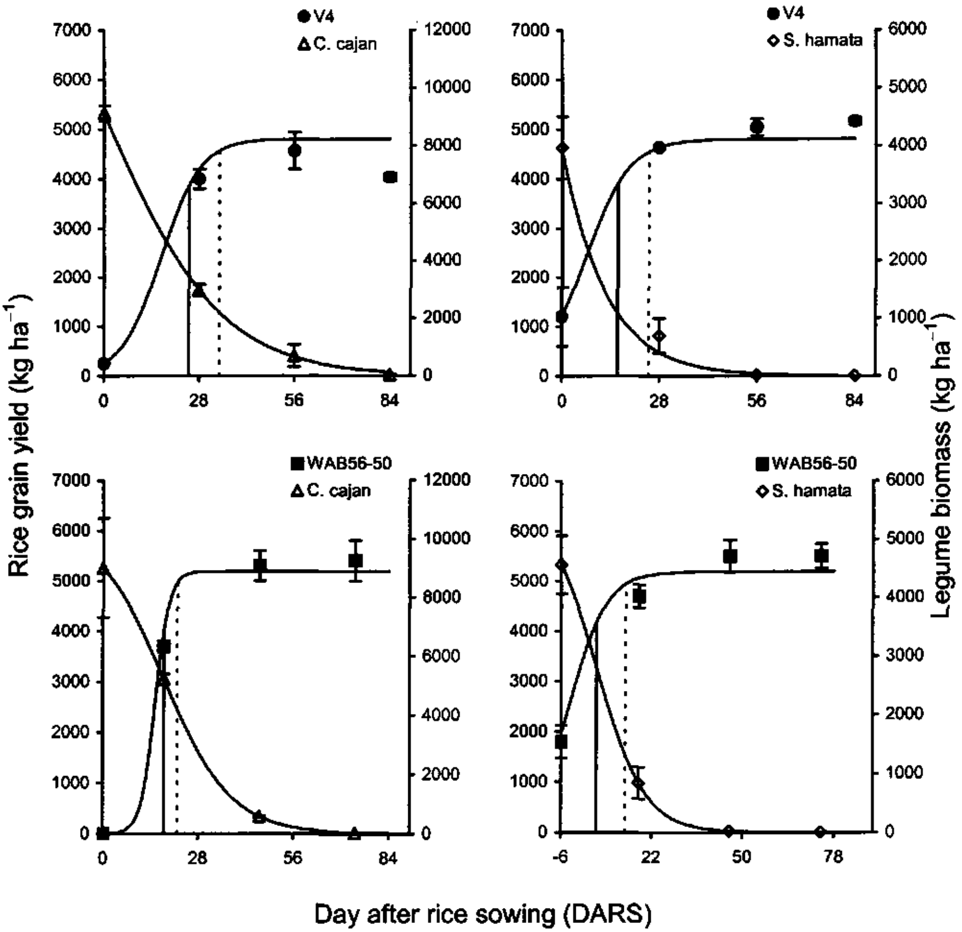

Fig. 4.3 Rice grain yield (kg ha^{-1}) and accumulated shoot dry weight of cover crops at one week after rice harvest (kg ha^{-1}) in 1997 as a function of legume sowing date (days after rice sowing; DARS). Vertical lines indicate yield loss in rice grain yield of 5% (broken line) and 20% (solid line). Bars represent standard errors of the observations.

also resulted in a clear but slightly delayed reduction, which was first observed in mid-August. With maturation of the rice crop N content in the foliage gradually decreased and differences between treatments disappeared.

Legume development in mixtures

In each year, clear differences in biomass production of both legumes in monoculture were observed. At simultaneous sowing with rice, *C. cajan* produced an average of around 9 t ha^{-1}, whereas *S. hamata* produced around 5 t ha^{-1}. Figs. 4.3 and 4.4 present

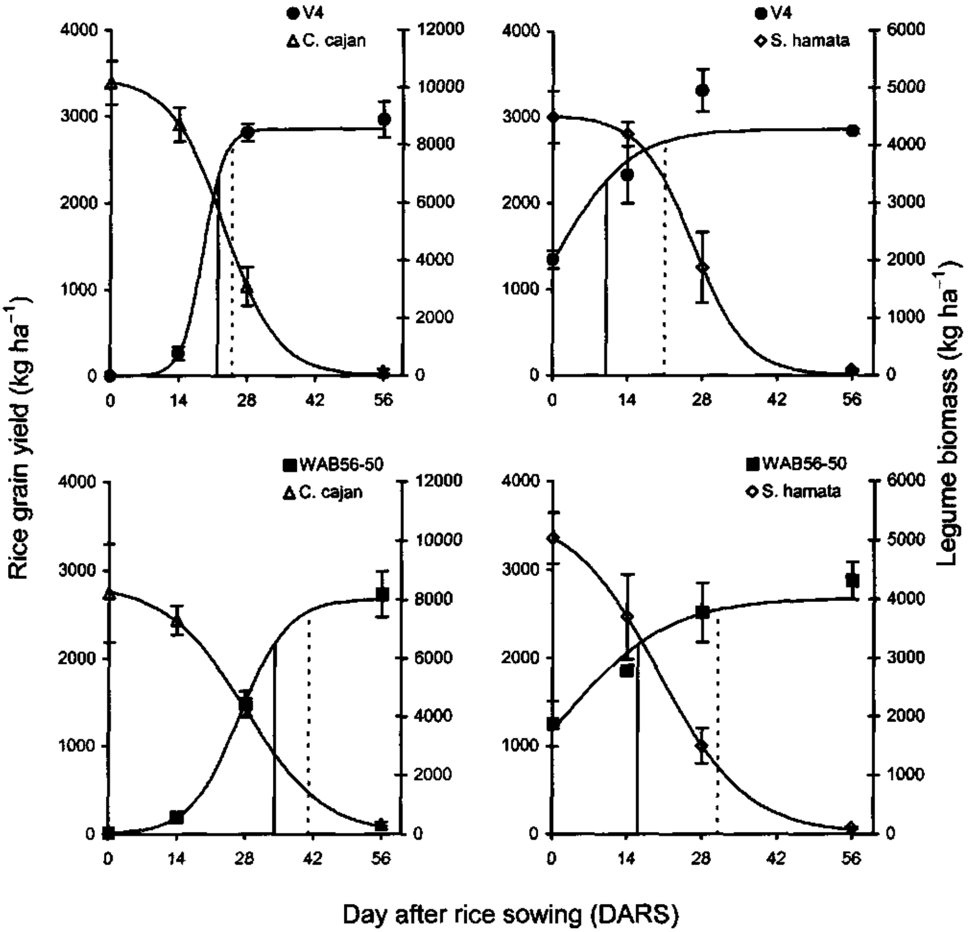

Fig. 4.4 Rice grain yield (kg ha^{-1}) and accumulated shoot dry weight of cover crops at one week after rice harvest (kg ha^{-1}) in 1998 as a function of legume sowing date (days after rice sowing; DARS). Vertical lines indicate yield loss in rice grain yield of 5% (broken line) and 20% (solid line). Bars represent standard errors of the observations.

results of rice grain yield and accumulated legume biomass in mixtures as a function of date of cover crop sowing. Legume biomass in mixtures decreased with the delay in legume sowing date.

In 1997, the logistic fit suggests a steep reduction in biomass production of both legumes starting from the first introduction date. Compared to 1997, the initial reduction in 1998 was much more gradual. This difference might be a consequence of the different time steps in sowing dates that were used in both years. The additional observation point that resulted from the smaller time step used in 1998, allowed for a more accurate description of the relationship between legume biomass and introduction date.

In Table 4.2, the overall reduction in legume biomass production at later sowing dates was dissected into its underlying causes. For this, monoculture legume biomass for all sowing dates was expressed as a fraction of monoculture legume biomass produced at first sowing. Additionally, legume biomass produced in competition was expressed as a fraction of the reference biomass produced in monoculture. Relative monoculture yields of *C. cajan* and *S. hamata* sown at 56 DARS were respectively 15% and 18% of to the monoculture yields of the earliest sown legumes (Table 4.2). Similarly, for both legume species the relative biomass produced in competition decreased rapidly with a later moment of introduction. For instance, in competition with V4 and at a sowing time of 56 DARS, relative biomass production of *C. cajan* and *S. hamata* was only 9% and 10%, respectively. From these results it is evident that both the reduced growing period as well as the more severe competition of the rice crop contributed markedly to the lower legume biomass obtained at later introduction dates. Similar results were found in 1997.

Late sowings also affected the rate of height increase of the cover crops in competition (Fig. 4.5). In this graph time is expressed as time after legume introduction (DALI) to enable better comparison between the various dates of introduction. Initially, hardly any differences were present between height growth rate of the plants introduced at the different dates. *S. hamata* introduced at 56 DARS started to lag behind from 45 DALI on, whereas height in the 28 DARS treatment was reduced from 70 DALI onwards. For *C. cajan* the latest time for introduction started to lag behind earlier from about 30 DARS on, whereas the 28 DARS treatment was hardly affected. Only from around 80 DALI on, the height growth rate was slightly reduced for the early-established legumes.

For each legume species, hardly any difference was observed between the first and the second time of introduction. Maximum height decreased from 325 cm at D1 to 127 cm at D4 for *C. cajan* and for *S. hamata,* from 91 cm in D1 to 35 cm in D4.

Rice grain yields and yield parameters

The reduction in rice grain yield followed the same trend as the reduction in total rice shoot biomass although at high competitive stress (early legume establishment) the

Table 4.2 Accumulated biomass (kg ha^{-1}) of *C. cajan* and *S. hamata* at one week after rice harvest in monoculture and mixture with rice (cultivar V4 or WAB56-50), as affected by sowing date and rice cultivar, in the 1998 experiment. Values in monoculture and mixture were expressed relative to the biomass obtained in monoculture at first sowing date (0 DARS), whereas values in mixture were additionally expressed relative to their reference biomass obtained in monoculture. Relative values were used to distinguish between the effect of a reduced growing period and the effect of an increased rice competition on biomass production of the legumes in relay intercropping.

	In monoculture		**In competition with V4**			**In competition with WAB56-50**		
	Biomass (kg ha^{-1})	Relative to monoculture at t=0	Biomass (kg ha^{-1})	Relative to reference monoculture	Relative to monoculture at t=0	Biomass (kg ha^{-1})	Relative to reference monoculture	Relative to monoculture at t=0
C. cajan								
t (DARS)								
0	10365	1.00	10176	0.98	0.98	8225	0.79	0.79
14	9620	0.93	8711	0.91	0.84	7299	0.76	0.70
28	6358	0.61	3107	0.49	0.30	4226	0.66	0.41
56	1578	0.15	146	0.09	0.01	339	0.21	0.03
S. hamata								
t (DARS)								
0	4954	1.00	4497	0.91	0.91	5040	1.00	1.00
14	4011	0.81	4195	1.05	0.85	3701	0.92	0.75
28	2803	0.57	1876	0.67	0.38	1492	0.53	0.30
56	900	0.18	88	0.10	0.02	103	0.11	0.02

relative reduction in grain yield was stronger (Figs. 4.3 and 4.4). This is also reflected in Fig. 4.6 where harvest index is plotted against the relative biomass of the rice crop. Only in situations where biomass was severely reduced, harvest index (HI) dropped considerably reflecting the more than proportional reduction in grain yield at high levels of competition.

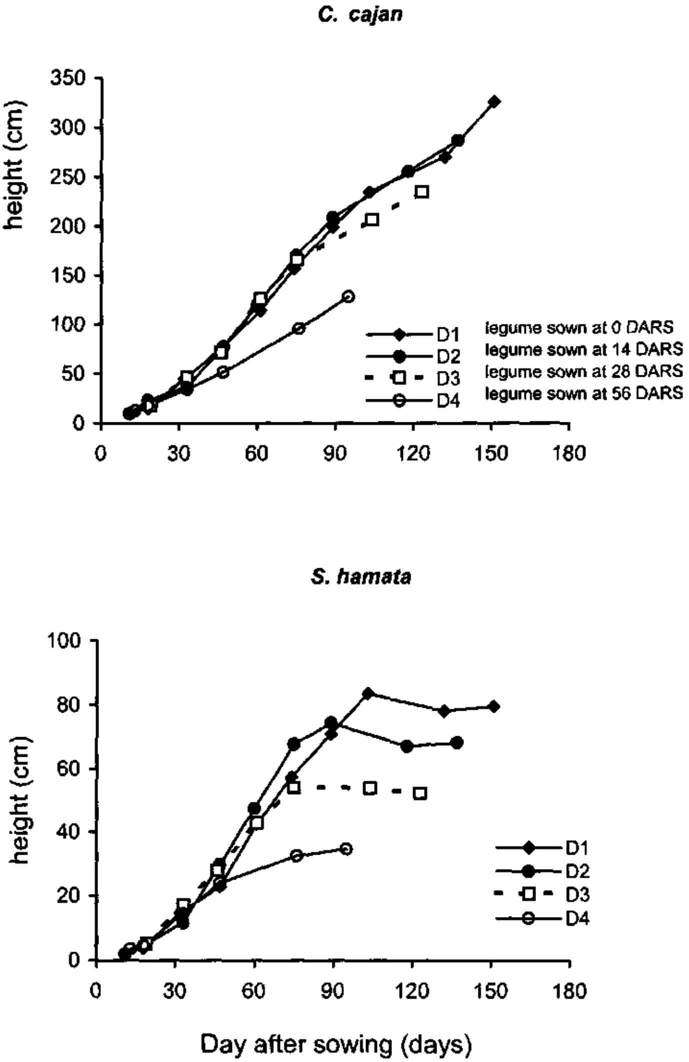

Fig. 4.5 Time course of height increase of *C. cajan* and *S. hamata* in intercropping with rice at different relative sowing times of the cover crops in 1998. (—◆—) 0 DAS, (—●—) at 14 DARS, (···❑···) at 28 DARS (—O—) at 56 DARS.

Yield component analysis of both rice varieties showed that the observed reductions in yield, resulting from competition by either one of the two legume species, were caused by a reduction in panicle number, a reduction in number of spikelets per panicle or a combination of the two (data not shown). The reductions in HI were observed when the rice cultivars were mixed with *C. cajan* at between 0 and 28 DARS. Only in that situation, a reduction in 1000-grain weight contributed to the observed reductions in grain yield, in addition to considerable reductions in the above-mentioned yield parameters. The less competitive *S. hamata* hardly affected HI as well as 1000-grain weight.

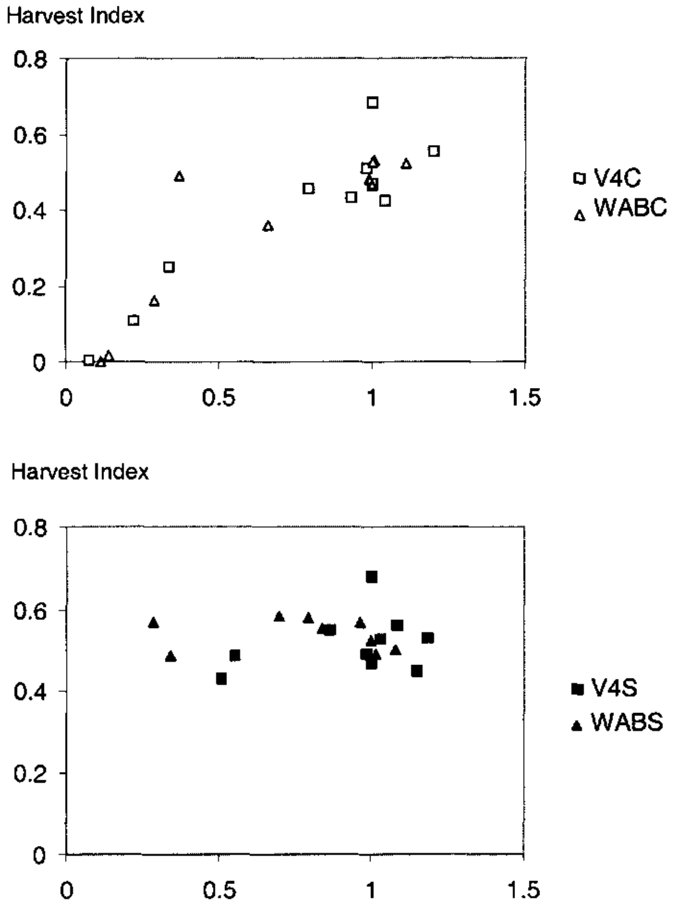

Fig. 4.6 Effects of the competitive legume species (*C. cajan)* and the non-competitive species (*S. hamata)* on rice harvest index (HI) as a function of relative yield (biomass in mixture/total biomass in monoculture) in 1997 and 1998. (■ V4 in mixture with *S. hamata* (V4S), ▲ WAB56-50 in mixture with *S. hamata* (WABS), Δ WAB56-50 in mixture with *C. cajan* (WABC), ❑ V4 in mixture with *C. cajan* (V4C))

Nitrogen concentration and fallow legume effects on the succeeding rice crop

N accumulation in foliage declined with later establishment dates of the cover crops (Fig. 4.7). The highest amount of N measured at one week after rice harvest was observed with *C. cajan*. On average of both years, the amount of N decreased from 100 kg N ha^{-1} at legume introduction at 0 DARS, to 52 kg N ha^{-1} at 14 DARS, 35 kg N ha^{-1} at 28 DARS

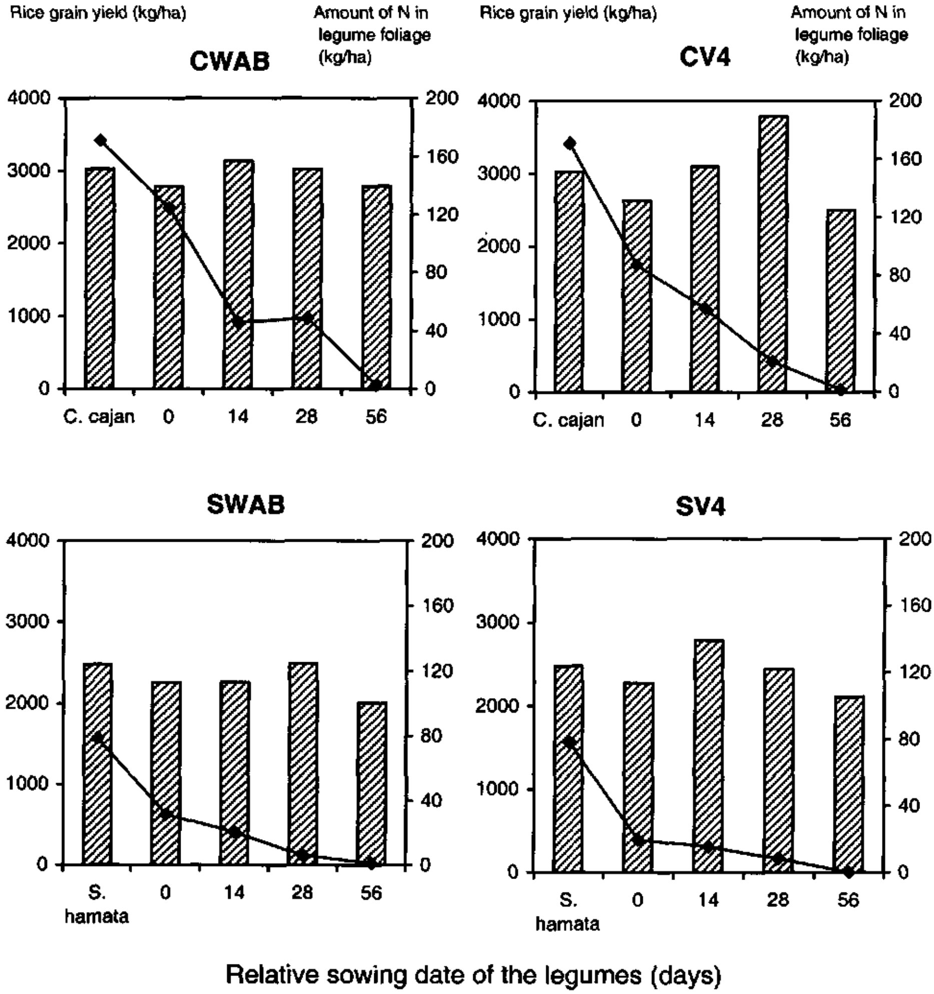

Fig. 4.7 Relationships showing the after-effects of legume fallow on rice grain yield of WAB56-50 (bars) as measured in 1999. The amount of N (line) and the relative sowing dates of the cover crops refer to the 1998 trial. On the figure, CV4 refers to *C. cajan* in mixture with rice cultivar V4, SV4 to *S. hamata* in mixture with rice cultivar V4, CWAB to *C. cajan* in mixture with rice cultivar WAB56-50 and SWAB to *S. hamata* in mixture with rice cultivar WAB56-50.

and 2.5 kg N ha^{-1} at 56 DARS. For *S. hamata*, 25, 18, 7 and 1 kg N ha^{-1} were found for these dates of establishment, respectively.

In 1999, rice grain yield following *C. cajan* fallow was significantly higher (p=0.001) than following *S. hamata*. Fallow legume establishment dates in the previous year had also a significant effect (p=0.0036) on grain yield. No interaction effect of dates by legumes was found. No significant increase was observed in rice yield after a fallow of *S. hamata*, likewise no significant effect of rice cultivar was observed. The residual effect of *C. cajan* on rice yield was less pronounced after late establishment (56 DARS) because the legumes only produced very low amount of biomass and N in this situation. Unexpectedly, the earliest established fallow did not produce the highest increase in grain yield although this fallow legume accumulated the highest amount of nitrogen. Relative increase in rice grain yield (relative to rice after rice without fallow crop) following *C. cajan* was 6.7% when the legume was established at 0 DARS, 23% at 14 DARS, 34% at 28 DARS and about 4% at 56 DARS. The pure stand cover crop of *C. cajan* established at rice sowing time increased rice yield by 19%.

Discussion

The current study on rice–cover legume intercropping systems showed that rice biomass and grain yield increased with a delay of the relative sowing time of the cover legume component. Productivity of *C. cajan* in monoculture, sown at the same time as rice, was around 9 t ha^{-1}, whereas *S. hamata* produced only 5 t ha^{-1}.

For both legume species in mixture with rice, the decrease in biomass resulting from a delay in sowing followed a logistic pattern. At late relay establishment of both legume species a very low amount of biomass was produced, which could be attributed to the combined effect of a stronger competition of the rice crop and a shorter growing period. *C. cajan* was found more competitive than *S. hamata*. This is in line with earlier observations on both legumes, in which *C. cajan* was identified as a legume with a higher growth rate, a higher early leaf area expansion rate, and a faster early height growth rate than *S. hamata* (see Chapter 3). Apart from that, a maximum height of 325 cm was found for *C. cajan*, whereas *S. hamata* had a maximum height of 90 cm, which is comparable to that of the rice cultivars. These differences give *C. cajan* a greater opportunity to have access to light compared to *S. hamata*, when grown as a relay crop in rice. Solar radiation provides the energy for the photosynthetic processes which determine productivity (Goudriaan and Van Laar, 1994). Therefore, if an intercrop component is taller and develops more leaf area at the top of the canopy with horizontal leaf orientation, it might be less depressed by the other crop (Keating and Carberry, 1993). A comparison of the time course of N-content in rice foliage of the different treatments strongly suggest that at least for early introduction of the legume species competition for nitrogen is likely to have occurred. A distinction between growth reduction resulting from either competition for light or competition for nitrogen is difficult to make, as competition is a dynamic process and competition for these resources will mutually influence one another.

In upland rice intercropping systems the timing of fallow establishment is crucial. Adjusting the relative planting time to the benefit of the cover crop would allow for higher legume biomass accumulation. However, such early planting must not lead to high grain yield reduction for producers are not willing to tolerate this. Relationship between rice grain yield, accumulated biomass by the cover crops and time of cover crop sowing were presented in Figs. 4.3 and 4.4. For illustration purposes, legume introduction dates that resulted in rice grain yield reductions of 5% and 20% were indicated. Based on the results of the 1997 experiment, WAB56-50 was identified as the most competitive rice cultivar. Compared to V4, the specified levels of rice yield reduction were obtained at relative early times of legume introduction, indicating that WAB56-50 was better able to sustain the presence of both legume species. For 1998, the opposite was observed. In this case V4 was found more competitive than WAB56-50, as identical levels of yield reduction were obtained with earlier introduction times of the legumes. This last result is more in line with our original expectations, as cultivar V4 was reported to be a competitive cultivar against weeds (Dingkuhn *et al.*, 1997). The increase in rice yield as a function of the relative introduction time of the legume was described with a logistic function. In 1997, this description was less precise, as no observations were made between 0 and 28 DARS. Results however clearly indicated that this period represents a sensitive phase as small changes in day of legume sowing greatly affected competitive relationships between rice and cover crops. In 1998, this was corrected by replacing the latest relative introduction date (84 DARS) by an additional early introduction date of 14 DARS. Consequently, the interpolation of observed results through curve fitting based on results of 1998 is believed to give a better description of competitive relationships within the upland rice relay cropping system. Irrespective of this, the results indicated that differences resulting from using either one of the two rice cultivars were marginal compared to the differences following the choice of legume species.

The aforementioned relationship is presented differently in Fig. 4.8, by making a direct connection between absolute legume biomass at one week after rice harvest and relative yield loss in rice, using the fitted logistic functions presented in Figs. 4.3 and 4.4. Days of legume introduction in rice can be found as different symbols on the obtained lines. The relation between legume biomass and relative yield loss in rice followed an S-shaped curve, particularly with the more competitive *C. cajan*. For this species, the two curves representing each rice cultivar initially followed the same pattern, but with earlier introduction dates (top of the curve) differences got larger. At similar introduction dates,

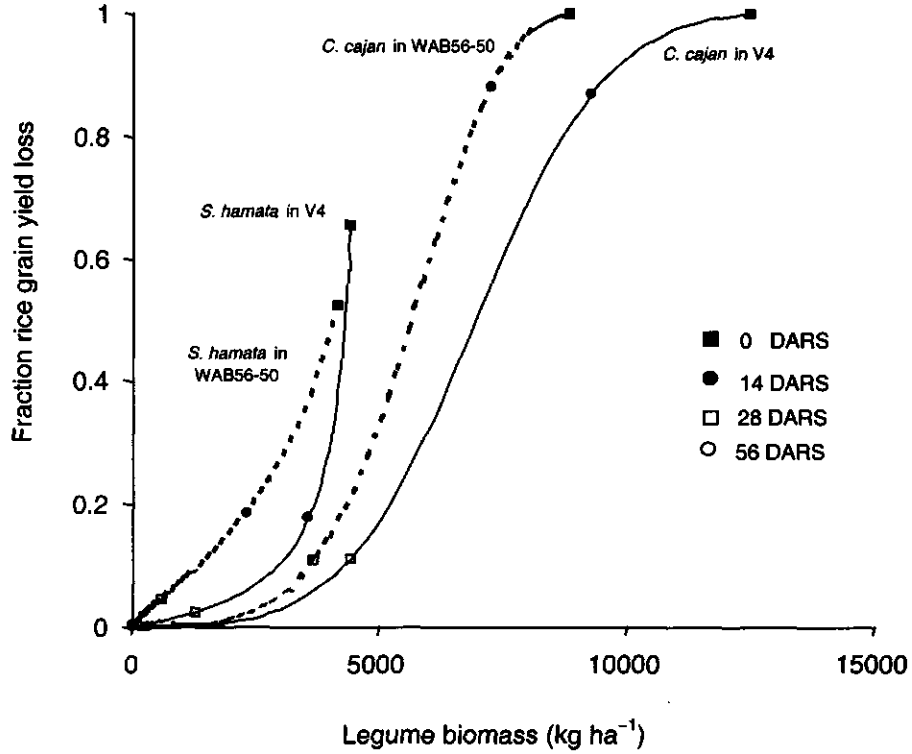

Fig. 4.8 Relationships between yield loss in rice grain yield and accumulated legume biomass at one week after rice harvest for different rice legume combinations, based on the 1997 and 1998 field experiment. Markers refer to actual sowing dates of the legumes.

a larger amount of legume biomass was produced in combination with V4, at the cost of a similar fraction of rice yield loss, suggesting that on average V4 was tolerating the presence of the legume better than did WAB56-50. Differences between both legumes were quite obvious. Whereas *C. cajan* was able to produce around 12 t ha^{-1}, while completely outcompeting the rice crops, *S. hamata* was able to produce slightly over 4 t ha^{-1} at maximum, thereby causing a rice yield reduction of about 60%. At late relative introduction times of *S. hamata* (bottom of the curve), differences between V4 and WAB56-50 were apparent. Also in mixture with this legume, V4 was identified as the cultivar that was better able to sustain the presence of the companion crop. With WAB56-50 even the very first tons of biomass produced by *S. hamata* resulted in reduction in rice grain yield, whereas initially with V4 only a small reduction in grain yield was observed. For practical application, the lower part of Fig. 4.8 is most relevant as it describes the relationship between legume biomass production and rice grain yield loss at low levels of yield loss. Introduction of the more competitive *C. cajan* led to higher amounts of biomass for comparable rice yield losses and should, therefore, be preferred.

Only for *C. cajan* a significant after-effect on the yield of the subsequent rice crop was observed. This residual effect of the *C. cajan* fallow was significantly affected by the date of legume establishment in the previous crop. However, residual effects on the subsequent rice crop were not linearly related to the amount of foliage nitrogen of the legumes determined at one week after rice harvest. Such a linear relation was observed by Akanvou *et al.* (2000) and Becker and Johnson (1998), when studying the after-effect of different legume species in rotation with upland rice. Plots with the earliest established legume (0 DARS) accumulated the highest amount of N, but this resulted in a limited effect on the subsequent rice crop. This indicates that apart from the amount of N accumulated, also the availability of N to the next rice crop is important for the short-term gain of this production system. Many authors pointed out that after-effects depend on N mineralization from the residue which often is low (Kuo and Jellum, 2000). Residue management (Akanvou *et al.*, 2000; Becker and Johnson, 1998, Hougnandan, 2000) and the influence of residue N on soil N availability (Kuo and Jellum, 2000) may affect the yield of a subsequent crop as well. Furthermore, residue decomposition and nutrient release from cover crops may not synchronize with the demand of the following crop. In South America, as much as 50% of major nutrients were released within 4 weeks from *Desmodium* and *Pueraria* residue (Luna-Orea and Wagger, 1996).

In intercropping systems, successful crop combinations have involved components of different duration in which the short-duration or dominant component matures before the late-maturing component (Balasubramanian and Rao, 1988). Generally, farmers give priority to the main crop by cropping it at the optimum density (Rao, 1986). Such combination is found in West African farming systems where, for example, cowpea and millet are kept at low density in intercropping systems with maize. Similarly in rice–cover legume systems, rice represents the important crop. Therefore, the legume component should compete the least possible with rice. In addition, legume species that may fit into the system should provide a net N benefit to the system (Willey *et al.*, 1983). The optimum period to establish the intercrop component is a key to successful intercropping systems. In maize–*Mucuna* systems, 40 to 45 days between the sowing of the two species has been suggested to avoid maize yield reduction (Osei-Bonsu and Buckles, 1993). The current study clearly suggests that in upland rice–cover legume relay systems most benefit might be expected from the use of a competitive species. A sowing time of 30 to 35 DARS was identified as optimum for intercropping *C. cajan* in upland rice while accepting a possible loss in rice yield of up to 5%. This period is close to the period when the highest residual effect on the subsequent rice crop was observed. An intercropping system involving the less competitive species *S. hamata* performed less good, but might be acceptable in combination with a competitive rice cultivar. This legume could be introduced as early as three to four weeks after rice sowing. However, no significant after-effects were observed over the short term.

Conclusions

Legume species and sowing dates of the legume were found important for relay-intercropping cover crops in upland rice cropping systems. The findings indicate that minimization of yield loss in the current rice crop is incompatible with maximization of legume biomass production due to competition between the intercrop components. At predefined levels of yield loss of 5% and 20%, the analysis showed that the competitive *C. cajan* could be introduced later as compared to the less competitive *S. hamata*. Using a competitive species was more beneficial as more biomass could be obtained at identical levels of yield loss. The impact of selecting a specific legume was found to surpass the influence of choosing either one of the two rice cultivars, for which contrasting results were obtained in the two years of experimentation. Cover crops can be established as relay crop to replace the natural fallow for short fallow improvement. Over this short term of experimentation, only the improved fallow by *C. cajan* gave a significant increase in subsequent rice grain yield, which was largest when established at 28 DARS. The derived yield loss–legume biomass relationship gave the opportunity to select the most appropriate rice cultivar–legume species combination and subsequently to determine the appropriate introduction time of the legume given the level of yield loss that farmers are willing to tolerate.

CHAPTER 5

Parameterization and validation of a crop growth simulation model for two contrasting cover legume species in the Savanna environment of West Africa

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CHAPTER 5

Parameterization and validation of a crop growth simulation model for two contrasting cover legume species in the Savanna environment of West Africa

Abstract

Agricultural systems that utilize legume species in cropping systems are becoming increasingly important. Reducing the long fallow period by replacing the natural fallow with fast-growing legume species necessitate selection of suitable and efficient species to restore soil productivity. The use of mechanistic models can provide a solid basis for accurately understanding and predicting biomass production of selected species for optimization of the system.

A SUCROS type model (INTERCOM) was used to simulate growth of two different cover crops species in monoculture. Model inputs were weather data, plant density and species-specific parameters describing phenological, physiological and morphological processes. The model was parameterized for the two leguminous species *Cajanus cajan* and *Stylosanthes hamata* commonly found in the savanna zone of Africa, using data from an experiment conducted in 1998. Simulation of growth of the cover crops and comparison with independent data from a previous experiment conducted in 1997 revealed that for *S. hamata* the morpho-physiological parameters relative growth rate, specific leaf area and dry matter allocation were not stable across years. Instability in parameters describing early leaf area development was also found in the validation process, when biomass production at different emergence dates was simulated and compared with field observations. *C. cajan* was found far less sensitive to changes in growing environment as only specific leaf area was found to differ markedly across years. It was concluded that the currently developed models need further improvement to explain environmental effects on morphological features for explorative studies covering a wide range of environments.

Keywords: Simulation models, Legume cover crops, *Stylosanthes hamata*, *Cajanus cajan*

Introduction

Nitrogen fixing leguminous species that belong to the family of Leguminosae or Fabacaea are often used as cover crops. Generally considered as low-cost sources of N (Buckles and Triomphe, 1999), cover crops during fallow periods can contribute to sustain productivity (Becker and Johnson, 1998; Schultz *et al.*, 2000). In the southern Brazilian states, more than 125000 small and medium-scale farmers use several different green-manure cover crops to improve soil fertility, to control weeds or to grow forage for animal food (Calegari *et al.*, 1997). In West Africa, the most commonly used species in agricultural systems is *Mucuna pruriens* or Velvet bean (Buckles, 1995; Versteeg *et al.*, 1998). Other species such as *Dolichos lablab* and *Stylosanthes hamata* have also been used as green manure or as a component to improve forage quality (Kouyaté and Juo, 1998; Tarawali *et al.*, 1998).

One option for integrating cover crops in a cropping system is to introduce it as a relay crop. This is an important alternative in tropical environments where crop survival and good soil cover during the dry season may necessitate early establishment of the legume crops into the main crop (Balasubramanian and Blaise, 1993). In such intercropping systems the growth period of the component crops overlaps. In that situation, sharing of resources over time and space by the component crops determines competition effects or complementarity between the species (Midmore, 1993). The productivity of the overall system, therefore, depends on the competitive ability of each component of the intercropping system together with its management. Relay intercropping appears promising if the legume species is well established before the end of the rainy season to guarantee substantial N accumulation in the system and adequate weed suppression. However, early introduction of a cover crop conflicts with another prerequisite of the system, which is avoidance of severe competition effects on the main crop. Choice of species and relative planting dates have shown to be major determinants of successful intercropping systems (see Chapter 4). In a study of upland rice and cover legume intercropping systems, the results of Akanvou *et al.* (2001) indicated that the potential to combine both objectives was largely determined by the selection of legume species and rice cultivars. At the same time, each combination of rice cultivar and cover crops had its optimum time of legume introduction. These results were in line with earlier studies that demonstrated that morphological and physiological traits of the species largely determine the outcome of interactions between the component crops (Kropff and van Laar, 1993). In cassava–legume intercropping systems, relative canopy height (Leihner, 1979) and canopy width (Cenpukdee and Fukai, 1992) were found to determine competitiveness when water and nutrients are not limiting factors.

To date, the selection of cover crops that may fit into mixed cropping systems is still based on general descriptive and empirical information (Weber *et al.*, 1997; Kiff *et al.*, 1996). As cultivation of legume cover crops expands, the need to accurately understand how the system works has become increasingly important. Simulation modelling of resource competition offers the potential to combine morphological and physiological crop characteristics for selecting suitable species on the basis of their competitive ability. Additionally, it offers the opportunity to investigate the effects of environment on development and adaptability of the cover crops as these appear important to predict phenology, and, therefore, the suitability of the cover legumes to a specific environment (Keatinge *et al.*, 1996, 1998; Qi *et al.*, 2000). Furthermore, the model could be used to optimize cropping systems and evaluate management strategies, particularly introduction time, to assist farmers.

Many crop growth models have been developed for monoculture systems, but only a few for multi-species systems. The model INTERCOM (Kropff and van Laar, 1993), widely used and well evaluated, has shown to be a powerful tool to improve understanding of crop–weed interactions. The model has been validated for several crop–weed combinations including crops such as maize (Lindquist and Mortenson, 1997; Cavero *et al.*, 2000), rice, sugar beet (Kropff and van Laar, 1993), wheat (Weaver *et al.*, 1994), leek and celery (Baumann, 2001). It is basically a model that combines existing 'SUCROS-type' growth models (Bouman *et al.*, 1996) of two or more species and links them through additional routines that govern distribution of resources such as light and water over the competing species. Although SUCROS-type growth models for several crops are available, for cover crops, these growth models have not been used so far. Therefore, the objective of this paper was to parameterize and validate the INTERCOM model for two contrasting cover crops legumes, *Cajanus cajan* and *Stylosanthes hamata*, commonly found in tropical Africa. In subsequent studies, the models will be used for studies on interactions between main crop and cover crops.

Materials and methods

General description and structure of the model

In this study, the model INTERCOM (Kropff and van Laar, 1993) was the basic model used to simulate growth of two cover crops *S. hamata* and *C. cajan* in monoculture. INTERCOM is a dynamic model based on morphological and physiological processes. The components of the model are based on the 'Wageningen models' such as the Simple and Universal Crop Growth Simulator SUCROS (Goudriaan and van Laar, 1994; Bouman *et al.*, 1996). It assumes that under favourable conditions light is the main factor determining growth rates of the crop. The model simulates potential growth and dry matter accumulation of the plants based on their response to environmental factors mainly radiation, temperature and water. In the model, the profile of leaf photosynthesis is simulated based on the light profile in the canopy and the photosynthesis response curve of individual leaves. The rate of CO_2 assimilation is a function of the photosynthetically active radiation (PAR) absorbed by the canopy, which itself is a function of incoming radiation, the leaf area of the crop and the extinction coefficient. The carbohydrates produced as end product of the photosynthetic process are used in part for maintenance of the existing biomass. The remaining carbohydrates are converted to structural dry matter (Penning de Vries *et al.*, 1974). In the model, the dry matter is first allocated to shoot and root. The above-ground dry matter is further partitioned to the various shoot organs (leaves, stems and reproductive organs), as a function of the phenological development stage of the species, which is tracked in the model through the accumulated daily average temperature after emergence.

The model does not consider biological N fixation by the cover crops although it accounts for respiration losses for N fixation, and assumes that water and nutrients are not limiting. Inputs of the model are crop-specific parameters and actual weather data characterized by latitude, daily minimum and maximum temperature and total global radiation.

Phenology Crop development and ontogeny determine the partitioning of assimilates to the different organs. In the model, development is calculated using a temperature sum approach which assumes a linear relation between temperature above a certain threshold value and development (van Keulen and Seligman, 1987).

Light interception by the canopy The photosynthetically active radiation (PAR) supplies the plants with energy for CO_2 assimilation. Radiation fluxes in the canopy decrease exponentially with the cumulative leaf area index (LAI), and is calculated using Beer's law:

$$I_L = I_0 \, (1-\rho) \exp(-k \times \mathrm{LAI}) \qquad (1)$$

Where I_0 is the incoming radiation (MJ m^{-2} s^{-1}) at the top of the canopy; I_L, the net radiation flux at depth L (m) in the canopy; k (–) the extinction coefficient for diffuse radiation; LAI, the cumulative leaf area from top downwards of the canopy (m^2 leaf m^{-2} ground) and ρ the reflection coefficient of the canopy.

From equation (1) the rate of absorption I_{abs} (MJ m^{-2} s^{-1}) at depth L is obtained by taking the first derivative with respect to LAI:

$$I_{abs} = -\mathrm{d}I_L/\mathrm{d}L = k \, (1-\rho) \, I_0 \exp(-k \times \mathrm{LAI}) \qquad (2)$$

Biomass production Gross canopy photosynthesis of the species is calculated based on the photosynthesis light-response of individual leaves (Spitters *et al.*, 1989) which is characterized by the initial light use efficiency (ε, kg CO_2 ha^{-1} leaf h^{-1} / J m^{-2} leaf s^{-1}) and the light saturated rate of CO_2 assimilation (Amax, kg CO_2 ha^{-1} h^{-1}). The instantaneous rate of CO_2 assimilation is then integrated over the canopy leaf area index and over the day to obtain the daily rate of CO_2 assimilation of the species. Carbohydrate production is obtained by converting CO_2 absorbed into carbohydrates. In the process of growth, requirements for respiration costs and tissue synthesis were taken into account with values derived for *C. cajan* (van Heemst, 1988). The effect of temperature on maintenance respiration was accounted for with a Q_{10} value of 2.

Partitioning of biomass The daily net assimilate production, which is obtained after subtracting respiration costs from gross CO_2 assimilation, is first divided into shoot and root fractions. Further on, the shoot fraction is partitioned to leaves, stems and reproductive organs as a function of temperature sum based on data obtained from the first sowing of the 1998 field experiment. The partitioning is calculated as the fraction of new biomass production allocated to the different plant organs between two subsequent harvests, following a standard procedure described by Kropff *et al.* (1994).

Leaf area The expansion of leaf area is one of the factors determining the amount of intercepted light by the canopy. Prior to an LAI of 1, leaf area was simulated as an exponential function of accumulated degree-days (Kropff and van Laar, 1993):

$$\mathrm{LAI}(tsum) = \mathrm{LA0} \times \mathrm{N} \times \exp(\mathrm{RGRL} \times tsum) \qquad (3)$$

Where, LA0 is leaf area index at seedling emergence (m^2 leaf $plant^{-1}$); *tsum*, the accumulated degree-days since emergence (°Cd); RGRL, the relative leaf area growth rate $(°Cd)^{-1}$; and N the number of plants (m^{-2}).

When LAI exceeds 1, multiplying new leaf dry weight with the specific leaf area of newly formed leaves (SLA_{new}, m^2 kg^{-1}) simulates the increase in LAI to account for source limitation after the onset of canopy closure and shading (Kropff and van Laar, 1993). SLA_{new} was related to *tsum* and derived from field observations. It was calculated as the ratio of increase in newly formed leaf area and the increase in newly formed leaf dry weight.

Senescence of leaves and stems is represented by a relative death rate of leaves (RDRLV) and stems (RDRST) and included as a function of *tsum*. Both functions were calculated from the observed decrease in dry weight of the specific organ during the last part of the growing season.

Field experiments for model parameterization and validation

Two field experiments for model parameterization and evaluation were conducted during the rainy season (June-October) of 1997 and 1998 at the West Africa Rice Development Association (WARDA) main research station (7°52′ N, 5°06′ W, altitude 376 m) in Ivory Coast. Soil characteristics at the site are described as an Alfisol sandy clay loam according to the USDA soil classification system, with a pH of 5.8. Rainfall, radiation, minimum and maximum temperatures during the cropping period were recorded from a weather station located at 50 m distance from the field.

Two contrasting cover crop species *Cajanus cajan* (fast growing with a maximum height over 2 m) and *Stylosanthes hamata* (slow growing, shrubby type with maximum height below 1 m) were grown in monocultures at three sequential sowing dates (daynumbers

197, 225, 253) in 1997 and at four (daynumbers 182, 196, 210, 238) in 1998. The plots were laid out in a randomized complete block design with three replications. Individual plot size was 24 m^2 (6 m × 4 m). Seeds of *S. hamata* were first treated with concentrated sulfuric solution for two hours, then mixed with sand and dibble-seeded at 12.5 × 10 cm (80 hills m^{-2}). Three weeks after emergence, the seedlings were thinned to two plants per hill resulting in a density of 160 plants m^{-2}. *C. cajan* seeds were dry-dibble-seeded at 25 × 20 cm spacing using three seeds per hill. Two weeks after emergence, seedlings were thinned back to two plants per hill (40 plants m^{-2}). A small dose of starter N fertilizer (30 kg N ha^{-1} as urea) was applied basally to the legume species. Triple superphosphate and potassium chloride were also applied basally at rates of 30 kg P ha^{-1} and 34 kg K ha^{-1} and incorporated into the soil (0-15 cm) during land preparation. Plots were kept weed-free by frequent hoeing. Additional water was provided by weekly overhead-boom irrigation to complement natural rainfall.

Measurements started one week after emergence for the two species in 1998, but, in 1997, observations only started two weeks after emergence. During both years samplings were taken approximately every two weeks. At each periodic sampling, canopy height was recorded in the field. Destructive samplings were conducted on sub-plots of 0.4 m^2. Above-ground plant parts were separated from roots. Samples were further partitioned into leaves, stems and reproductive organs and oven-dried at 80 °C for 72 h. Leaf area was measured from a sub-sample of leaves using a LiCor LI-3000 equipment (Lincoln, Nebraska). Leaf area index was calculated as the product of leaf weight and specific leaf area. Parameters related to phenology, dry matter distribution and leaf area used for model parameterization were derived from the first sowing of 1998 field experiment. Comparison of simulated and observed data for the validation of the model was carried out using the linear regression option of Genstat (1998).

Results

Weather data during the experimental period are shown in Fig. 5.1. Total cumulative global incoming radiation for the 100-day growing period of the first sowing was 1345 MJ m^{-2} in 1997, and 1432 MJ m^{-2} in 1998. Average daily maximum and minimum temperature in these periods were 31.4 °C and 21.4 °C in 1997, and 31.4 °C and 22.6 °C for 1998, respectively.

Model parameterization

Values for morpho-physiological parameters of *C. cajan* and *S. hamata* used in the model are summarized in Table 5.1. These values were mainly derived from the first sowing of the 1998 field experiment and complemented with data from literature. Data from 1998 were used because measurements, in contrast to the 1997 experiment, started already one week after emergence. Non species-specific parameters used in the model are listed also in Table 5.1. These values are coefficients for calculating maintenance respiration and for converting assimilates into dry matter (van Heemst, 1988).

Phenology

For both species, thermal time was calculated using a base temperature (Tbase) of 8 °C. This value is comparable to that used for many studies conducted with tropical crops (Cavero *et al.*, 2000; Kropff and van Laar, 1993). For *C. cajan*, Odongo *et al.* (1991) reported a Tbase of 9.9 °C while Carberry *et al.* (2001) used 10 °C in their model. Flowering was recorded at 624 °Cd for *S. hamata* and at about 1500 °Cd for *C. cajan*.

Biomass production

During the experiments, light interception by the crops was not measured. An extinction coefficient (*k*) of 0.69 was used in the model after the LAI of the canopy exceeded a value of 1 (Sivakumar and Virmani, 1984). This *k*-value is in agreement with a range value of 0.6 and 0.8 found for *C. cajan* (Patel *et al.*, 2000, Ramakrishna *et al.*, 1992). Before LAI reached 1, *k* was set to 0.4 to account for the clustering of leaves early in the season. Maximum leaf CO_2 assimilation (Amax) for each species was used as a calibration factor. Its maximum value was set to 54 kg CO_2 ha^{-1} leaf h^{-1}, which is close to a value of 50 kg CO_2 ha^{-1} leaf h^{-1} suggested for C_3 plants (Spitters *et al.*, 1989). A constant initial light use efficiency (ε) of 0.45 kg CO_2 ha^{-1} leaf h^{-1} / J m^{-2} leaf s^{-1} was assumed based on values used for many species (Kropff and van Laar, 1993).

Dry matter partitioning

For *C. cajan* and *S. hamata*, leaf, stem, flower and root fractions were distinguished. Dry matter was first distributed equally to shoot and root using fixed coefficients as a function of *tsum*. From emergence until flowering, a linear decrease in the fraction of dry matter allocated to the roots was assumed. That fraction was set at 0.5 at emergence, whereas from flowering to maturity root dry matter allocation was set at zero. The fraction of new shoot biomass allocated to the various shoot organs was related to thermal time (Fig. 5.2). Both species maintained a high partitioning of assimilates to the stem throughout development.

Leaf area

The exponential increase in leaf area as a function of time (*tsum*, °Cd) during early growth stages (LAI<1) is presented in Fig. 5.3. *C. cajan* had a faster leaf area expansion rate than *S. hamata* which showed clear differences in both years. After the exponential phase, leaf area development was simulated by multiplying the newly formed leaf area

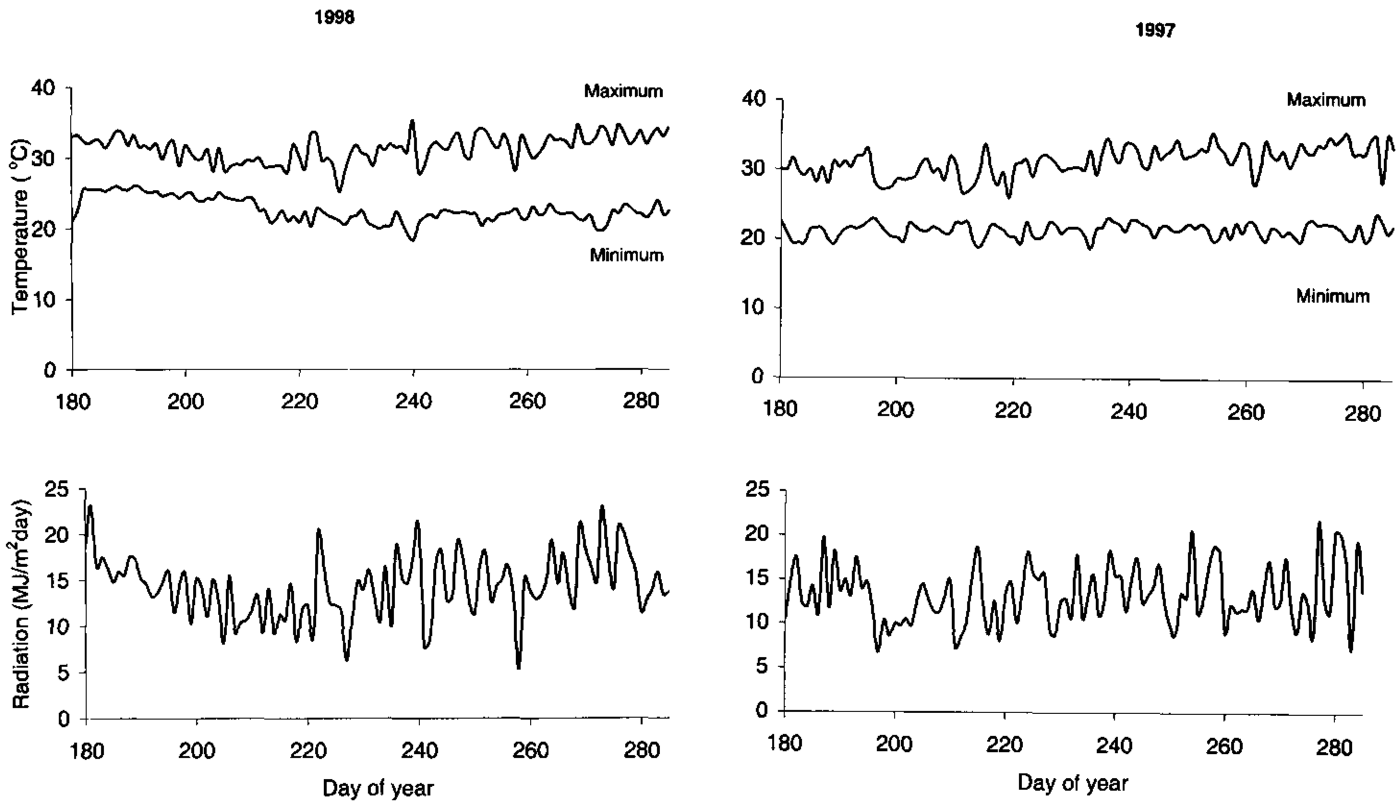

Fig. 5.1 Environmental conditions during the 1997 and 1998 growing season. Daily maximum and minimum temperature (°C) and incoming total global radiation in MJ m^{-2} day^{-1}.

Table 5.1 Description and summary of non species-specific parameters (after van Heemst, 1988) and function estimates used for the parameterization of the model for the two cover crop species. Species-specific parameters were derived from the first sowing date of the 1998 field trial used in the growth model for the two legume species.

Symbols	Description	Unit	Value	
Non-specific parameters				
MAINLV	Maintenance coefficient of leaves	kg CH_2O kg^{-1} d^{-1}	0.03	
MAINST	Maintenance coefficient of stems	kg CH_2O kg^{-1} d^{-1}	0.015	
MAINSA	Maintenance coefficient of above-ground storage organs	kg CH_2O kg^{-1} d^{-1}	0.01	
MAINRT	Maintenance coefficient of roots	kg CH_2O kg^{-1} d^{-1}	0.01	
ASRQLV	Assimilate requirement for leaf dry matter production	kg CH_2O kg^{-1} d^{-1}	1.47	
ASRQST	Assimilate requirement for stem dry matter production	kg CH_2O kg^{-1} d^{-1}	1.52	
ASRQSA	Assimilate requirement for above-ground storage organs dry matter production	kg CH_2O kg^{-1} d^{-1}	1.49	
ASRQRT	Assimilate requirement for leaf dry matter production	kg CH_2O kg^{-1} d^{-1}	1.45	
Specific parameters			*C. cajan*	*S. hamata*
KDF1	Extinction coefficient for leaves, LAI<1	-	0.4	0.4
KDF2	Extinction coefficient for leaves, LAI>1	-	0.69	0.69
RGRL	Relative growth rate of leaves, LAI<1	(°Cd)$^{-1}$	0.0115	0.0092
LA0	Initial leaf area per plant	m^2 plant^{-1}	0.000089	0.000008
HMAX	Maximum height	cm	252	92
HS	Parameter for height	(°Cd)$^{-1}$	0.00304	0.00265
HB	Parameter for height	-	23.85	37.77
RDRLV	Relative death rate of the leaves at *tsum*	(°Cd)$^{-1}$	1157; 0 1423; 0.0058 1671; 0.0152 1848; 0.0200 2000; 0.0164	1337;0 1586;0.003 1811;0.012 2000;0.012
RDRST	Relative death rate of the stem at *tsum*	(°Cd)$^{-1}$	0	1337; 0 1586; 0.004 1811; 0.007 2000; 0.007

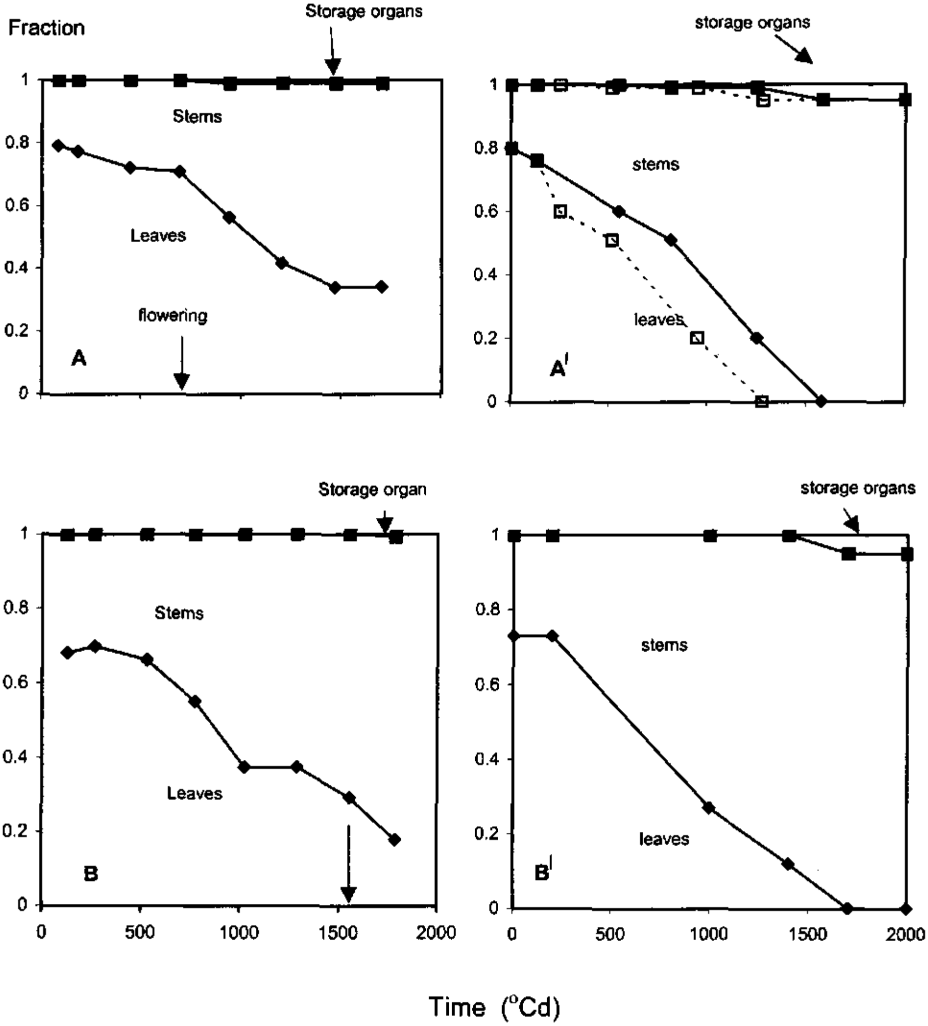

Fig. 5.2 Time course of the distribution of accumulated dry matter over the shoot organs (leaves, stems, storage organs) for *S. hamata* (A) and *C. cajan* (B) in the first sowing of the 1998 experiment. The graphs A' and B' represent the allocation of newly produced dry matter partitioned over the different organs as used in the model. The dotted line in the graph of *S. hamata* indicates the adjusted function based on the first sowing of the 1997 experiment and used for simulation of the experiment conducted in 1997.

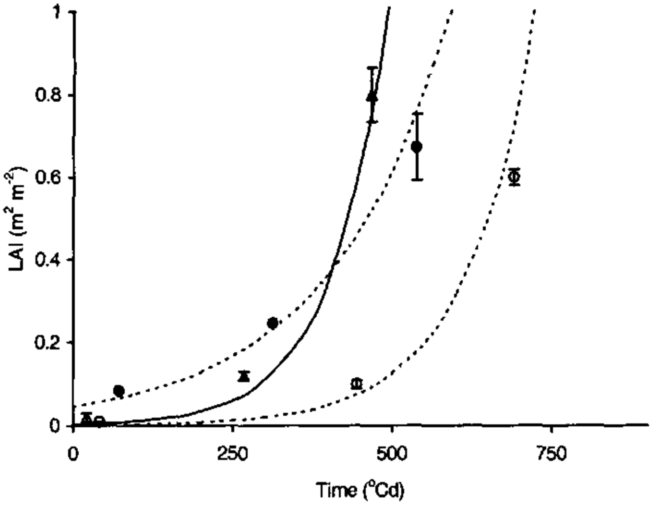

Fig. 5.3 Relationship between temperature sum after emergence (°Cd) and leaf area index (m^2 m^{-2}) for *S. hamata* and *C. cajan* pure stands in the first sowings of the 1998 and the 1997 experiment. Markers are observations, bars indicate standard error of means. Lines represent best fit exponential curves for *S. hamata* (1998 (--o--): LAItsum=0.00128×exp(0.0092×*tsum*); and 1997 (--•--): LAItsum=0.046×exp(0.0052×*tsum*)) and for *C. cajan* in both years (solid line): LAItsum=0.0035×exp(0.0115×*tsum*).

dry weight by SLA_{new}. In Fig. 5.4, the time course of SLA_{new} of the newly formed leaves is plotted as a function of thermal time.

Radiation use efficiency

A simple growth analysis of the first sowings of both legume species in terms of radiation interception (RI, MJ m^{-2}) and radiation use efficiency (RUE, g MJ^{-1}) revealed clear differences between both years (Fig. 5.5). In 1997, RUE of both species was higher than in 1998, whereas RI was substantially reduced. For *C. cajan*, this resulted in a reduction in productivity in 1997 as the reduction in RI (47%) surpassed the increase in RUE (23%). For *S. hamata*, productivity in 1997 was far less reduced as the reduction in RI (37%) was nearly compensated by the increase in RUE (34%). Because of these differences, it was decided to conduct an independent calibration of the model for each year.

Calibration

The calibration process was conducted in two steps using observed data on leaf area

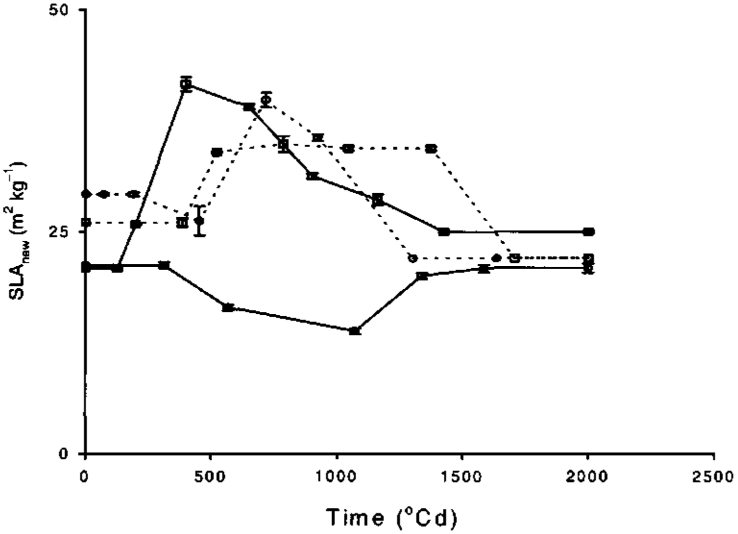

Fig. 5.4 Relationship between thermal time (°Cd) after emergence and Specific Leaf Area of newly produced tissue (SLA_{new}; m^2 kg^{-1}) as observed in the first sowing of the 1998 (—) and 1997 (----) experiments for *C. cajan* (□) and *S. hamata* (○). Markers indicate observed values with standard error bar. The lines indicate the relation used in the model.

development and shoot dry matter production of the first sowing treatments. In the first step, simulation runs with the model were conducted with the measured temporal changes of LAI for each species as input to exclude errors in simulation of leaf area. In this step, the maximum assimilation rate (Amax) of the species was adjusted to fit the simulation of shoot dry matter production to observed field data. In a second step, the model was run by dynamically simulating LAI in order to validate simulation of leaf area development. Fig. 5.6 shows the time course of the calibrated Amax in both years as a function of thermal time for the two species.

Using parameters derived from the first sowing of the 1998 experiment, the calibration for 1998, resulted in a good agreement between observed and simulated data for both *C. cajan* and *S. hamata*. However, in 1997 no such adequate results could be obtained as leaf area of *C. cajan* was not properly simulated. Including SLA_{new} values derived from the 1997 experiment solved this problem and resulted in an adequate simulation indicating that differences in SLA values between experiments needed to be accounted for. For *S. hamata*, more difficulties were encountered. Apart from specific leaf area, year specific parameters for exponential leaf area development (RGRL, LA0), as well as a

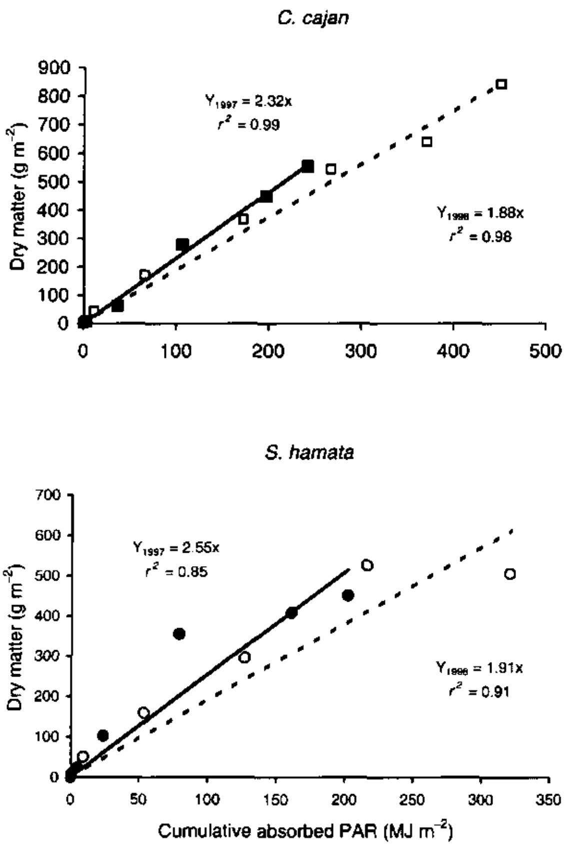

Fig. 5.5 Relationship between cumulative intercepted photosynthetic active radiation and dry matter for the two cropping seasons for *C. cajan* and *S. hamata*. The slopes of the linear regression represent the radiation use efficiency (RUE; g MJ^{-1}) of the species.

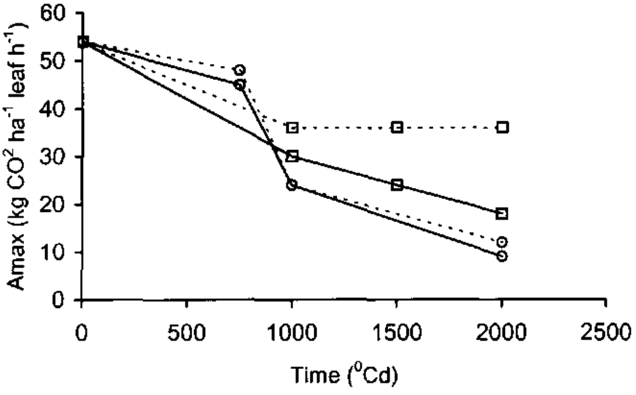

Fig. 5.6 Time course of the calibrated maximum CO_2 assimilation rate (Amax) of *C. cajan*us (□) and *S. hamata* (○) as a function of thermal time (°Cd) in 1997 (----) and in 1998 (—). Calibration was performed using observed data of the first sowing in each year.

shift in the partitioning table of shoot organs in the order of 300 °Cd had to be included to obtain an adequate simulation (Fig. 5.7).

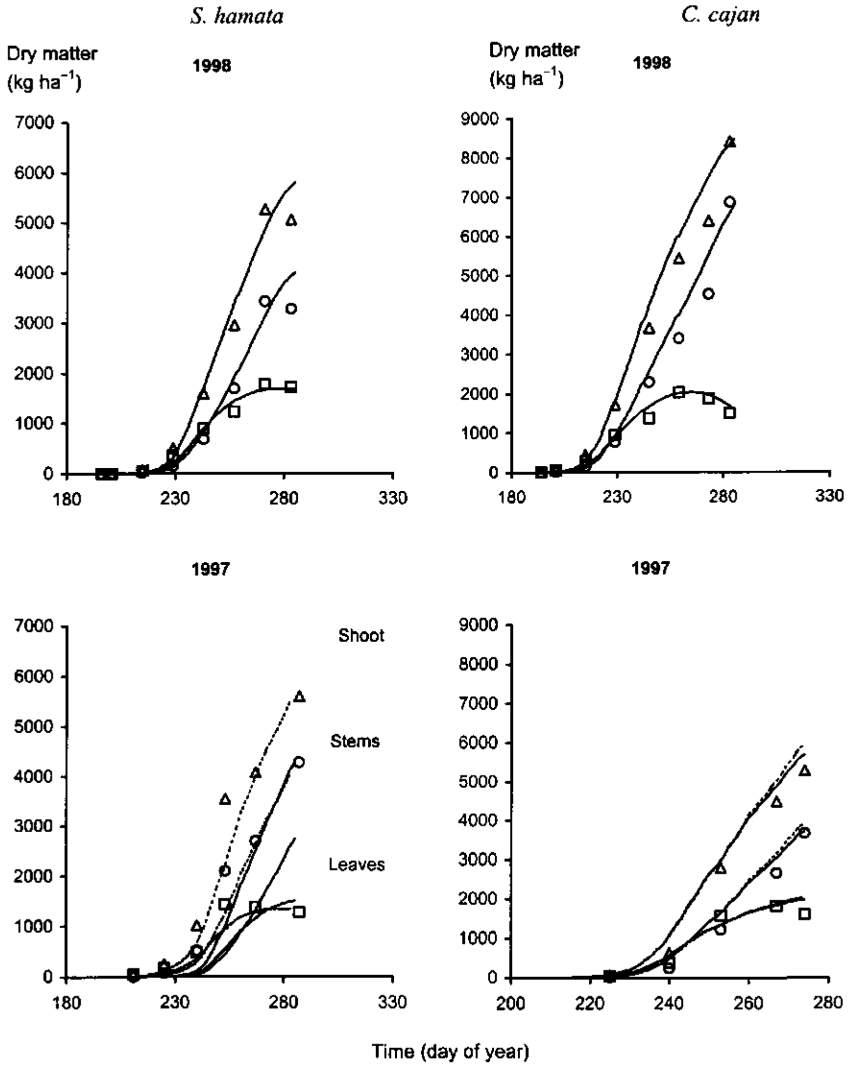

Fig. 5.7 Comparison of simulated (lines) and observed data (symbols) of leaf (□), stem (O) and shoot dry weight (Δ). Solid lines represent simulations with parameters derived from the first sowing date of the 1998 trial. Dotted lines represent the model simulation after introduction of the year-specific parameters for the first sowing in 1997. These parameters were RGRL, SLA$_{new}$, dry matter partitioning for *S. hamata* and for *C. cajan* SLA$_{new}$.

Model validation

Validation of the calibrated growth models for both years was conducted by using the late sowings treatments of 1997 and 1998. For this purpose, simulations were made using the observed emergence dates of each species sown at 14, 28 and 56 days after first sowing in 1998 and at 28 and 56 DAS in 1997. Such validation is relevant in this case because the models are intended for future analysis of rice–legume relay systems.

In 1998, for *C. cajan*, the model adequately fitted the observed data although a slight underestimation of final leaf weight and shoot weight were observed at 14 DAS (Fig. 5.8). Model simulation results for the other sowing dates showed reasonably good agreement with the observed total biomass. The linear regression of observed over simulated shoot dry weight was $0.83x$ (SE = 0.131) at 14 DAS, $0.95x$ (SE = 0.050) at 28 DAS and $1.41x$ (SE = 0.035) at 56 DAS. In 1997, the linear regression of observed over simulated dry weight at 28 DAS was $1.12x$ (SE = 0.025) and $1.30x$ (SE = 0.11) at 56 DAS (Fig. 5.9).

For *S. hamata*, sensibility to the delay in sowing was observed in the simulation of leaf and shoot biomass production in both years. Simulation of total shoot dry weight as well as LAI and leaf dry weight at the different sowing dates using the calibrated model was largely overestimated (Fig. 5.10 and 5.11). This result suggested that leaf area development might have been affected by the delay in sowing. Therefore actual relative growth rates of the leaves derived from the observed data were introduced to simulate production at these sowing dates (Table 2). With these treatment-specific parameters, a satisfactory model performance was obtained. Final simulation of the 1998 experiment is represented in Fig. 5.10. The comparison of observed over simulated dry weight could be described by the linear regression of $0.95x$ (SE = 0.052) for the plants established at 14 DAS. For the plant established 28 DAS, the equation of the regression line was $0.75x$ (SE = 0.006) and $0.61x$ (SE = 0.003) at 56 DAS (Fig. 5.10). Results of the simulation runs for the validation of the 1997 experiment was conducted using the calibrated model for that year

Table 5.2 Summary of relative leaf growth rate (RGRL, d^{-1}) and leaf area at emergence (LA0, m^2 $plant^{-1}$) of *S. hamata* emerging at four different sowing dates in 1997 and 1998.

		Days after sowing		
		0	14	28
1997	RGRL	0.0052	-	0.0039
	LA0	0.000287	-	0.000287
1998	RGRL	0.0092	0.0081	0.0078
	LA0	0.000008	0.000008	0.000008

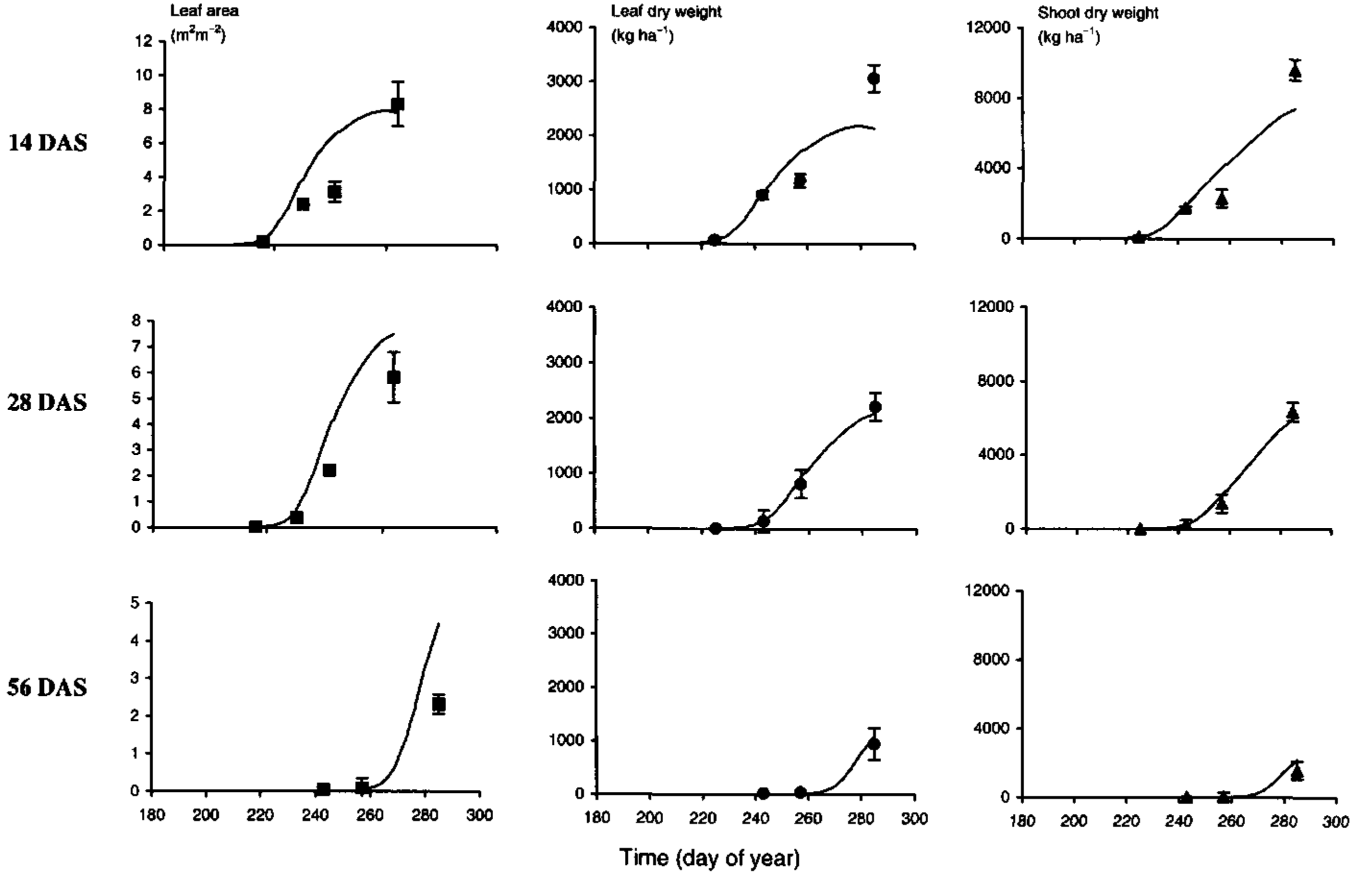

Fig. 5.8 Simulated and observed leaf area index ($m^2 m^{-2}$), leaf dry weight (kg ha^{-1}), and total shoot dry weight (kg ha^{-1}) of *C. cajan* emerging at 14, 28 and 56 days after first sowing (daynumber 182) in 1998.

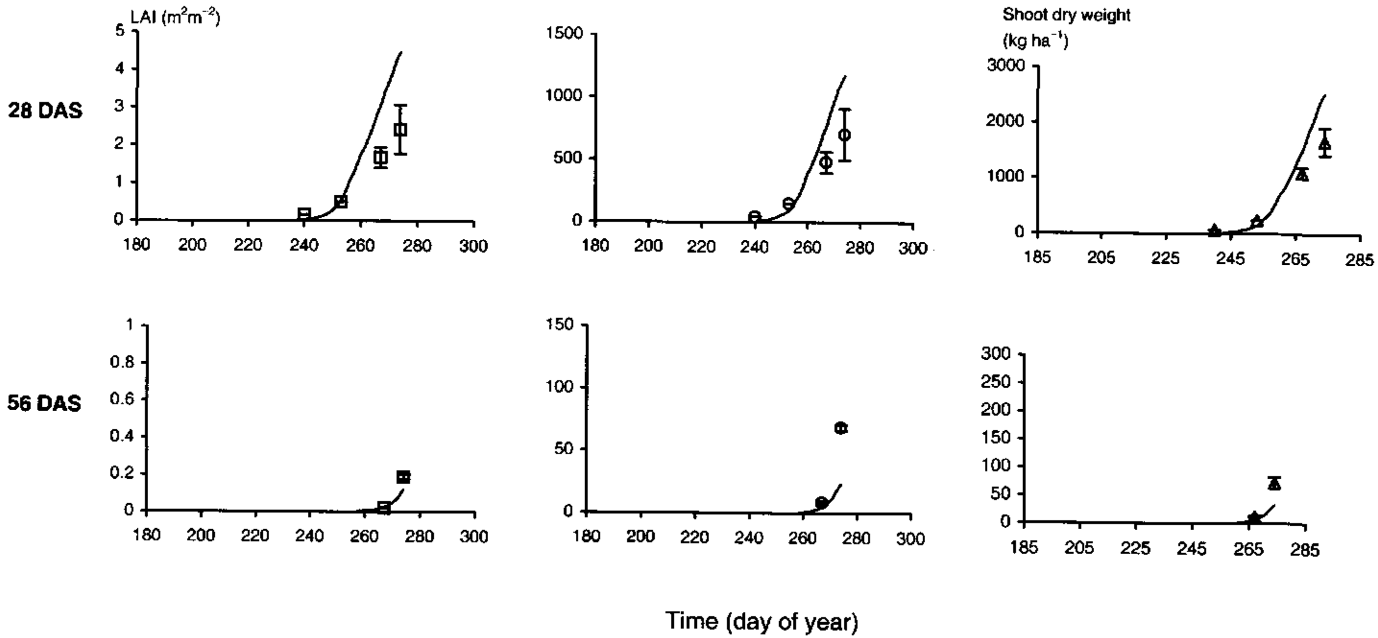

Fig. 5.9 Simulated and observed leaf area index (m^2 m^{-2}), leaf dry weight (kg ha^{-1}), and total shoot dry weight (kg ha^{-1}) of *C. cajan* emerging at 28 and 56 days after the first sowing date (daynumber 197) in 1997.

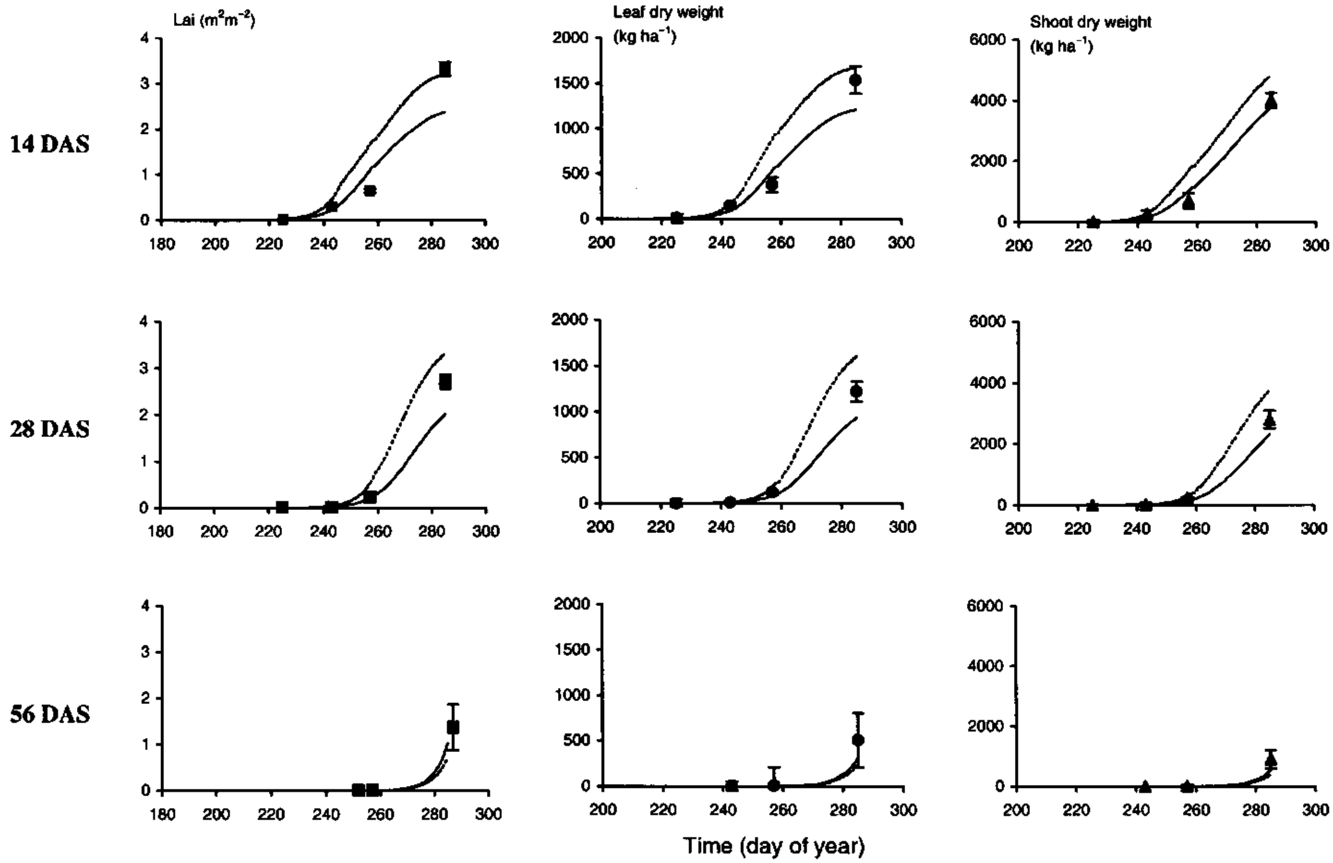

Fig. 5.10 Simulated (lines) and observed total shoot dry weight and leaf dry weight of *S. hamata* established at 14, 28 and 56 days after the first sowing date (daynumber 182) in 1998. Dotted lines were obtained using the model for the first sowing date. The solid lines were obtained using adjusted RGRL derived from field data and Specific Leaf Area as inputs.

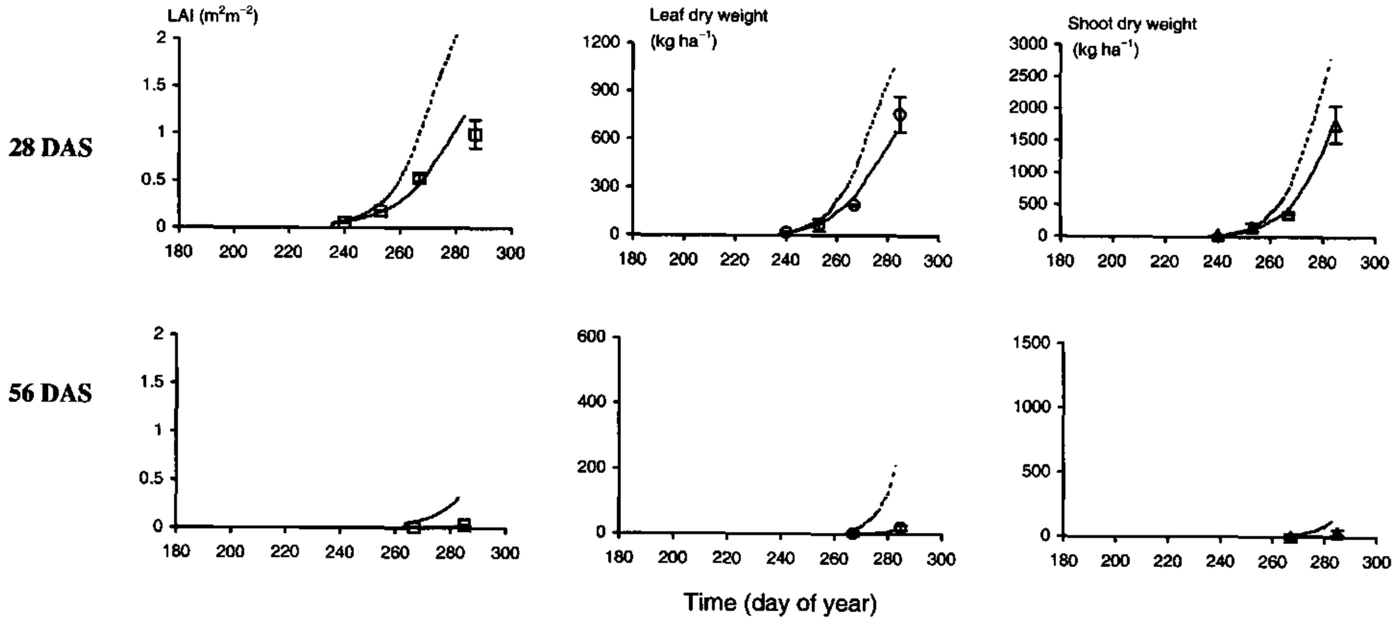

Fig. 5.11 Simulated (lines) and observed total shoot dry weight and leaf dry weight of *S. hamata* established at 28 and 56 days after the first sowing date (daynumber 197) in 1997. Dotted lines were obtained using the model for the first sowing date. The solid lines were obtained using adjusted RGRL derived from field data. Bars represent standard errors of the means.

as described in the calibration process. The model prediction of dry weight production for *S. hamata* could be described by a linear regression of $1.10x$ (SE of the slope = 0.042) at 28 DAS and $0.45x$ (SE = 0.013) at 56 DAS (Fig. 5.11).

Discussion

Two years of experiments were conducted with two leguminous species, *C. cajan* and *S. hamata* at different sowing times. Biomass production of the first sowing of *C. cajan* was higher than for *S. hamata*. Productivity of *S. hamata* was also more decreased by the delay in sowing time and the shortening of the growing period.

The results of this study indicated differences in the level of stability of the parameter values required for the simulation of the growth of the two cover crops. For *C. cajan,* the model parameterized using data of the 1998 experiment adequately simulated experimental data of the independent trial in 1997. Initial leaf area per plant and the relative growth rate of the leaves during the initial growth stages were found to be stable over the years. Only SLA_{new} values were found to differ markedly between years. Nevertheless, the consequences for the simulation of dry matter production were small, as, irrespective of SLA, simulated LAI was so high that, during large part of the growing season, nearly all radiation was intercepted. However, as these models are intended to be used for competition studies, a proper simulation of LAI is required because leaf area is an important determinant of competitiveness (Lotz *et al.*, 1995). Consequently, year-specific SLA_{new} values were introduced.

For *S. hamata* the model was less 'robust'. Apart from introducing year-specific values for SLA_{new}, initial growth rate represented by LA0 and RGRL, and the allocation pattern of newly produced dry matter needed to be made year-specific for a proper simulation of dry matter production and leaf area development. This 'instability' in parameter values compared to *C. cajan* was also observed during the validation process. Values for RGRL tended to reduce with the delay in sowing time. In the model, early leaf area development is assumed to proceed exponentially with temperature as the driving variable. For *S. hamata,* such an approach seemed to be inadequate. Variations in RGRL have been observed in many other species. In maize differences in RGRL were found in four improved varieties between years (Lindquist and Mortenson, 1999). In many weed species, changes in relative growth rate have also been observed over the years (Hunt and Lloyd, 1987). Furthermore, RGRL has been described as strongly dependent on temperature, radiation and seed size (Goudriaan and van Laar, 1994; Sattin and Sartorato, 1997). This in fact confirms that the single use of air temperature as an explanatory variable for early leaf area development is not sufficient, at least for many species. There is clear evidence that competition is another factor that influences the morphological parameters, particularly in situations where species emerge under shading conditions

(Cavero *et al.*, 2000). The magnitude of changes in morphological development of *S. hamata* as affected by environmental conditions was also reflected in SLA and dry matter partitioning. Little information on the plant–environment interactions and the physiological response by *S. hamata* is available in the literature. The current study clearly indicated variability in growth between years and within year when sowings were delayed from 14 to 56 days. From these results it becomes obvious that a model in which temperature and radiation mainly drive growth and development, is insufficient to explain growth differences in a range of environments. This particularly holds for plant species that seem extremely responsive to environmental factors. When applying the model in competition situations, these effects have to be accounted for.

The impact of environment on biomass production is complex due to interactions between radiation, rainfall, temperature and soil resources. In this study, water was assumed non-limiting, whereas nutrient availability and its effects on growth were only implicitly accounted for in the calibration process, where the time course of Amax was set. Apart from physiology, the phenology of species might be affected by environmental factors. For most legume species, mainly temperature and photoperiod control the development stage (Robert and Summerfield, 1987). During the growing period, the species were exposed to a daylength of 13h04 in July to 12h36 in November, and, therefore, the current data set in not very suitable for unraveling the response of both species to daylength. Also in literature very little information on the effects of daylength is available. *S. hamata* has been found to be a short-day species (Qi *et al.*, 2000; Ison and Humphreys, 1984). More recently it has been indicated that *C. cajan* is a qualitative short-day plant, which implies that flowering does not occur at photoperiod greater than a certain critical value (Carberry *et al.*, 2001).

Conclusions

Cover crops are grown primary to protect the soil and to improve the fertility of the soil, not as a cash crop. In that aspect, the potential biomass production and the impact of accumulated nitrogen on the subsequent crop become important criteria for selecting a suitable species. In the current study, it was attempted to develop a model for the simulation of legume phenology, as well as canopy growth and biomass accumulation of two morphologically different legume species. The results indicated that with limited availability of independent data, the performance of the model still needs to be further evaluated. Model improvement will be necessary to explain environmental effects on traits such as SLA, dry matter partitioning and RGRL to enable simulation of growth under a wide range of conditions, particularly for *S. hamata*. In earlier simulation studies, site and year-specific parameterization of growth models for monoculture crops were conducted as a first step in analysing the competition in crop–weed and crop–crop systems (Bastiaans *et al*., 1997; Baumann, 2001). In line with this, the currently developed models with procedures to account for effects of environmental factors on parameter values of SLA, RGRL and dry matter distribution will be used for competition analysis of upland rice in intercropping systems.

CHAPTER 6

Analysing productivity of upland rice and legume cover crops in relay intercropping systems using a mechanistic competition model

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CHAPTER 6

Analysing productivity of upland rice and legume cover crops in relay intercropping systems using a mechanistic competition model

Abstract

Improved fallows with legume species enhance soil fertility and sustain crop yield in Sub-Saharan Africa. The existence of a pronounced dry period between cropping seasons in the savanna zone makes relay intercropping of legume species with the main crop an attractive option for fallow improvement. Relay cropping systems with upland rice and the highly competitive *Cajanus cajan* and the weakly competitive *Stylosanthes hamata* were experimentally evaluated during two years. The INTERCOM model for competition was used to analyse the data to improve understanding of the system based on phenological, physiological and morphological characteristics of the component species.

The model was parameterized based on characteristics of the plants in monoculture and tested using two years of field data from experiments conducted in mixture. Competition between *C. cajan* and rice cultivars WAB450-24-3-2-P18-HB (V4) and WAB56-50 was adequately simulated. Competitiveness of *S. hamata* was underestimated, even when the formation of thinner leaves due to shading as observed in the field experiment, was accounted for. The relation between accumulated legume biomass and yield loss in rice showed that at low levels of yield loss both legumes performed in a similar way. At slightly higher levels of rice yield loss the more competitive *C. cajan* performed better as it was able to produce higher amounts of biomass. Model analysis revealed that differences in produced legume biomass at a specified level of rice yield loss were mainly created in the growth period following rice maturity, which is restricted by water availability and generally lasts 3-4 weeks. The inferior performance of *S. hamata* was indirectly caused by its weak competitiveness, which required a relatively early introduction of this legume. The combination of early introduction and short growth duration of this species prevented a rapid leaf canopy development after rice harvest, resulting in the relatively poor biomass production. It was concluded that options to improve legume biomass production in upland rice–legume intercropping systems in the savanna zone of West Africa should strongly focus on maximization of legume biomass production in the period following rice maturity, when residual soil moisture still allows for additional growth.

Keywords: INTERCOM, *Oryza sativa*, *Cajanus cajan*, *Stylosanthes hamata*, West Africa

Introduction

Intercropping is widely used in Latin America, Asia and Africa as a means for production of food and feed crops. It may involve all mixtures of annual and perennial crops. According to Fageria (1992), who reviewed the importance of multiple cropping systems and crop yield, intercropping systems comprise various methods which include mixed cropping, row intercropping, strip cropping, relay cropping and alley cropping. The relay intercropping system is defined as a system which consists of growing two or more crops simultaneously, during part of the life cycle of each of the crop (Vandermeer, 1989). In weed management, the success of using intercropping as a strategy to control weeds is based on an efficient way of resource capture by desired plants in time and in space (Willey, 1979; Liebman and Dyck, 1993). For the resource light, this is achieved by minimizing the proportion reaching the soil through an increased interception of light by the mixed crop canopy (e.g., Baumann, 2001). Generally a relay intercropping system consists of a main crop which is sown first and a secondary crop. The system can therefore be managed according to farmer's production objectives by varying sowing density and relative introduction time of the second crop to minimize yield reduction in the main crop.

A key characteristic of intercropping is the interaction between the component crop species (Willey, 1979). Competition among plants is complex because of the many factors such as plant density, growth rate and morphological traits, that are involved and their interactions. Differences in emergence dates between the competing species can give advantage to the first species due to an earlier access to resources. All of these factors are relevant in relay-cropping systems. Descriptive models are often used to quantitatively characterize the outcome of competition. The yield loss – weed density model of Cousens (1985) or the relative leaf area model (Kropff and Spitters, 1991) can be used to describe yield reduction of crops due to weeds. In relay cropping systems of rice and cover crops, rice yield loss can be described by a logistic function of the relative sowing date of the component cover crop (Chapter 4). Using two contrasting leguminous species, *Cajanus cajan* and *Stylosanthes hamata*, and adding those to two rice cultivars of different competitive ability, it was observed that species characteristics determine whether a specific rice–legume combination can meet the production objectives. In addition, for suitable rice–legume combinations, the introduction time of the companion species was found to determine whether the production objectives are realized (Akanvou *et al.*, 2001).

In relay cropping systems of rice and a cover legume species, the main objective is to obtain large amounts of accumulated N by the legume biomass that may improve soil quality in the following years without loosing much rice yield in the current year. This approach necessitates an optimum management of the system where choice of suitable species and appropriate establishment dates of the cover legume determine the required optimum between short-term (current rice yield) and long-term objectives (after-effects on yield of future rice crops). Empirical evaluation of optimum combinations and establishment dates is extremely complex because of the large number of options and the year to year variation in climatic conditions.

Dynamic simulation models for competition seem an appropriate approach for a better understanding of the complex interactions that occur in rice–legume relay intercropping systems. Using that approach, morphological and physiological species characteristics, combined with management options such as sowing density and relative introduction time, are integrated to analyse the outcome of competition as observed in a well selected small number of experiments. Using the INTERCOM model, Kropff and van Laar (1993) determined that important characteristics, which confer competitive ability in e.g. sugar beet, were the early growth of leaf area and the earliness of height development. Similar findings have been reported in rice and maize as well (Bastiaans *et al.*, 1997; Cavero *et al.*, 2000). Baumann (2001) combined mechanistic and descriptive models for resource competition to analyse, explore and optimize a leek–celery intercropping system. After parameterization and validation, he used the mechanistic model to explore the system by making several runs, in which total density and mixing ratios of the two component crops were varied. Accordingly, he summarized the results of these simulations by using a simple descriptive model for resource competition (Spitters, 1983) which allowed evaluation of the intercropping system in terms of productivity, crop quality and weed suppressive ability. In the current study, a combination of mechanistic and descriptive models will be used for analysis of the upland rice–cover crop relay intercopping system.

In Chapter 5, simulation models for growth and development of *Cajanus cajan* and *Stylosanthes hamata* were developed and evaluated. In this chapter, an existing rice model will be parameterized for two rice cultivars that differ in competitive ability. In addition, rice and legume models will be combined to analyse competition in relay intercropping systems of upland rice with cover crops. Possibilities for combining the production of a substantial amount of legume biomass with a marginal reduction in rice yield will be explored and the main determinants of a successful relay intercropping system will be identified.

Materials and methods

Field experiments

Field experiments, comprising monocultures of two rice cultivars, two cover crop species and their mixtures at a range of relative introduction times of the cover crops, were conducted during the wet season of 1997 and 1998 at the main research station of the West Africa Rice Development Association (WARDA) in Ivory Coast (7°52′ N, 5°06′ W). This site is located in the savanna zone characterized by a cumulative annual rainfall of about 1000 mm.

The experiment was set-up as a randomized complete block design with three replications. It comprised factorial treatments of two rice cultivars (*Oryza sativa* variety WAB56-50 and WAB450-24-3-2-P18-HB (V4), which is an improved progeny of a cross between *O. sativa* and *O. glaberima*), and two legume species (*Cajanus cajan* (tall, fast-growing) and *Stylosanthes hamata* (short, slow-growing)) and four relative sowing dates of the legumes. Pure stand treatments of the rice cultivars (2) and legume species (2 × 4 sowing dates) were added. In 1997, the relative sowing dates were 0, 28, 56, 84 days after rice sowing (DARS) for the introduction of the two legume species in V4. Because of a poor plant stand, WAB56-50 was resown 10 days after first sowing, resulting in relative introduction dates of the legumes that were 10 days earlier than scheduled except for the first introduction date when *C. cajan* was resown and establishment of *S. hamata* was slightly delayed. In WAB56-50, this resulted in relative introduction times of –6, 18, 46 and 74 for *S. hamata* and 0, 18, 46, 74 for *C. cajan*. Based on results of the 1997 experiment, relative sowing dates in 1998 were set to 0, 14, 28 and 56 DARS as it was found that after 56 DARS rice yield was hardly affected. Individual plots measured 6 m × 4 m. In monoculture, rice was dibble-seeded at 0.25 m × 0.20 m spacing and thinned after three weeks to 60 plants m^{-2} (3 plants per hill). *C. cajan* was sown using the same arrangement as in rice but at a density of 40 plants m^{-2} (2 plants per hill). *S. hamata* was established at 160 plant m^{-2} (2 plants per hill) using a spacing of 0.125 m × 0.100 m. Plots were kept weed free by hoeing. Land was ploughed and fertilized with 30 kg P (triple superphosphate) and 34 kg K (KCl) at field preparation and with 30 kg ha^{-1} of urea-N, applied at 30 days after rice sowing. The soil was well drained and moisture not limiting due to supplementary overhead-boom irrigation.

Measurements were conducted every two weeks. A stick measurement of plant height was recorded during the 1998 experiment in the field from soil surface to the top of the plant. Destructive samplings were taken on 0.40 m^2 areas. Dry weight was determined from oven-dried materials at 70 °C for 48 hours. Plants were separated into leaves, stems and storage organs to determine the partitioning of dry matter to the various above ground organs. Leaf area was determined from leaf sub-samples using an LAI meter (Licor 3000, Lincoln, Nebraska). Further details and results of these experiments are presented in Chapter 4.

Model description

In this study, the model INTERCOM, of which the general structure is shown as a relational diagram in Fig. 6.1, was used to simulate and analyse growth of the crops in the rice–legume relay intercropping system. INTERCOM basically constitutes of a number of crop growth models equal to the number of competing species, which are linked through additional subroutines that account for the distribution of resources (light, water and nutrients) over the competing species (Kropff and van Laar, 1993). The component growth models are based on SUCROS (Goudriaan and van Laar, 1994; Bouman *et al.*, 1996) a carbohydrate driven model, which simulates the dry matter

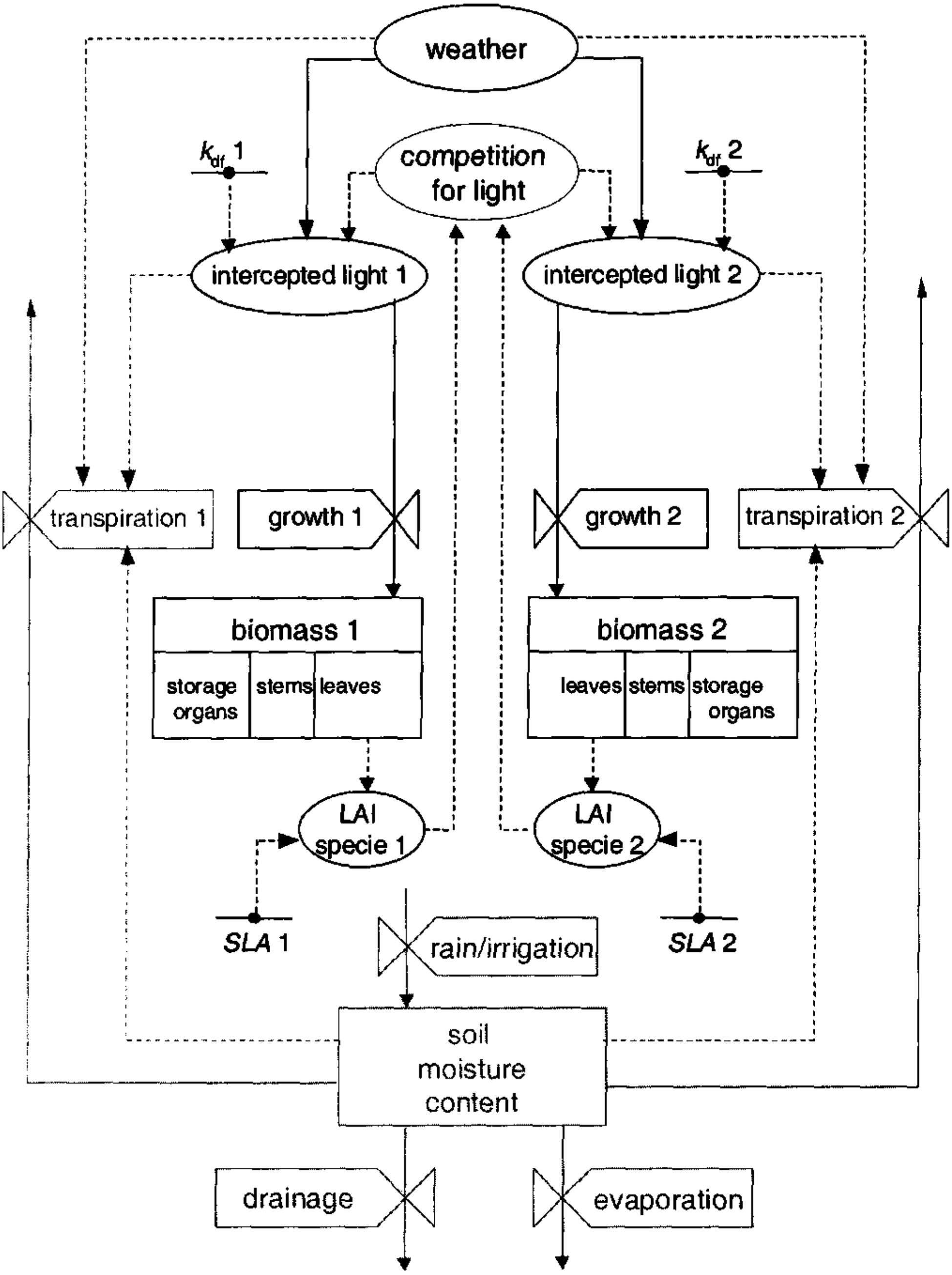

Fig. 6.1 General structure of the eco-physiological model for plant competition (INTERCOM redrawn after Kropff and van Laar, 1993), explaining interrelationships amongst major physiological processes. Solid lines indicate flow of materials, dashed lines indicate flow of information, valves are rates, rectangles are quantities and circles are auxiliary variables.

increase over time based on crop specific parameters and weather data, using a time step of one day. In the current study, water and nutrients were assumed non-limiting to rice and the legume species and, therefore, only competition for light was considered.

Because the light resource as such cannot be stored in the system like water and nutrients, competition for light is simulated as an instantaneous process of resource capture. The efficiency of resource capture is related to the light absorption characteristics of a species, which are related to leaf thickness, leaf angle distribution, LAI and vertical leaf area density profile. Leaf area, as well as leaf thickness and leaf angle distribution, which are implicitly accounted for in the light extinction coefficient (k), are all included in the calculation of light interception of monoculture models. The vertical leaf area density profile is not included in these models as for simulation of light interception in monocultures only the amount and not the vertical distribution of leaf area is relevant. In species mixtures, however, the situation is different, and the vertical leaf area density profile has to be specified to enable the calculation of light capture at different heights in the canopy. In INTERCOM this is realized by coupling a dynamic description of plant height development to a static standard function of vertical leaf area distribution. Plant height development (h_{ts}; m) is described by a logistic function using temperature sum (ts; °Cd) as driving variable:

$$h_{ts} = h_{max} / (1 + h_b \, e^{-h_s ts}) \qquad (1)$$

where h_b and h_s are coefficients defining the shape of the function and h_{max}, the maximum height of the species (m), operates as a scaling factor. Early height growth is determined by h_s (°Cd)$^{-1}$.

Incoming radiation is partly reflected by the canopy and the remaining fraction is potentially available for absorption by the canopy. In a mixed canopy radiation fluxes attenuate from the top downwards according to:

$$I_h = (1 - \rho) I_0 \exp(-\sum_{j=1}^{n} k_j L_{h,j}) \qquad (2)$$

where I_h is the net flux (PAR) at height h (J [m^{-2} ground] s^{-1}), ρ the reflection coefficient of the canopy, I_0 is the amount of incoming radiation at the top of the canopy (J [m^{-2} ground] s^{-1}), k the extinction coefficient for PAR, and $L_{h,j}$ is the cumulative LAI of species j above height h ([m^2 leaf][m^{-2} ground]). The leaf areas ($L_{h,j}$), weighted by their extinction coefficients (k_j), are summed over the j=1,..., n plant species in the mixed vegetation. Similar to a monoculture situation, the light absorbed by species i at a height h in the canopy ($I_{a,h,i}$, J [m^{-2} leaf] s^{-1}) is obtained by taking the derivative of equation (2) with respect to the cumulative LAI:

$$I_{\mathrm{a,h,i}} = -\frac{dI_{\mathrm{h,i}}}{dL_{\mathrm{i}}} = k_{\mathrm{i}}(1-\rho)I_0 \exp(-\sum_{j=1}^{n} k_{\mathrm{j}} L_{\mathrm{h,j}}) \tag{3}$$

From the light flux absorbed at depth *L*, the assimilation rate at that specific canopy height can be calculated. This procedure is followed for sunlit and shaded leaves separately because the relation between light flux and assimilation rate is non-linear. The assimilation rate at each height in the canopy is the sum of the assimilation rates of sunlit and shaded leaves. Rather than dividing the canopy in numerous small layers and using numerical integration, the CO_2-assimilation rate of each species is calculated as the weighted average of the CO_2 assimilation rates at five selected depths in the canopy using Gaussian integration (Goudriaan, 1986). Instantaneous canopy CO_2 assimilation rates for each species in the mixture are calculated at three selected times during the day and weighted according to a 3-point Gaussian integration procedure, to obtain the daily rate of CO_2 assimilation for each species, separately.

From here on the simulation models of the component species are similar to the simulation models of monocultures. Absorbed CO_2 is converted into carbohydrates and maintenance requirements of the existing biomass are subtracted. The remaining carbohydrates are first partitioned over root and shoot, whereafter the carbohydrates allocated to the shoot are further partitioned over the various shoot organs like leaves, stems and reproductive organs. The allocation pattern is related to phenological development, which in the model is tracked using a temperature sum approach. In the process of conversion of carbohydrates into structural dry matter, part of the weight is lost as growth respiration and these losses are accounted for in the model.

Depending on the development stage, part of the newly produced dry matter is partitioned to leaves. The area of green leaves is the major determinant for light absorption and CO_2 assimilation of a crop. The LAI follows from the balance between leaf growth and senescence rates. Light flux and temperature are the environmental factors influencing the rate of leaf area expansion. During juvenile growth, temperature is the overriding factor, as the rate of leaf appearance and cell division and leaf expansion are constrained by temperature, rather than by supply of assimilates. In these early stages, leaf area increases approximately exponentially over time. In later development stages, leaf area expansion is increasingly restricted by assimilate supply as the number of sites per plant where leaf initiation can take place increases and mutual shading of species further reduces the assimilate supply per growing point. During this stage, the model calculates the growth of leaf area by multiplying the simulated increase in leaf weight by the specific leaf area of new leaves (SLA_{new}). Senescence rate of leaf area is related to ageing.

Monoculture models

The rice monoculture treatments of the earlier described field experiments were used for parameterization and calibration of the rice monoculture models. As particularly more frequent observations were made early in the season in the 1998 experiment, the data from this experiment were used for model-parameterization. In the model, the phenological development stage (DVS) of the rice crop was defined by a value of 0 at emergence, 1 at flowering and 2 at maturity. The development rates $(°Cd)^{-1}$ were calculated as the inverse of the period required to proceed from emergence to flowering (vegetative development rate, DVRV) and from flowering to maturity (reproductive development rate, DVRR). Both development rates and physio-morphological characteristics (relative leaf area growth rate, dry matter allocation, SLA_{new} and senescence) were determined following standard procedures described by Kropff *et al.* (1994).

After parameterization, the models were calibrated in a two step procedure using observed data on leaf area development and shoot dry matter production as a reference. In the first step, simulation runs were conducted with the observed temporal changes of LAI for each cultivar as input, to exclude errors in the simulation of leaf area. In this step, the maximum assimilation rate of individual leaves (Amax) was adjusted to fit the simulation of shoot dry matter to observed field data. In a second step, the model was run by dynamically simulating LAI in order to validate simulation of leaf area development as well. As yield levels for 1998 and 1997 differed markedly, it was decided to conduct independent calibrations of the models for each year.

For the two legume species *C. cajan* and *S. hamata* the parameterization and calibration procedure of the monoculture models was conducted in the same way and the procedure and results were comprehensively described and discussed (Chapter 5). Parameters of *S. hamata* were found to differ greatly between both years and therefore the parameters related to early leaf area development (LA0 and RGRL), dry matter distribution and specific leaf area of newly developed leaves (SLA_{new}) were made year-specific. Parameters of *C. cajan* were found more stable and therefore only SLA_{new} needed to be adjusted. As both legumes were sown at a variety of sowing dates, the models were parameterized and calibrated using the first sowings, whereas the later sowing dates were used for validation. For *S. hamata* it was observed that early leaf area development reduced considerably with sowing time. Based on the results of the two years of experimentation a relation between sowing time and RGRL was derived and included in the model.

Vertical leaf area profile

As indicated earlier, apart from monoculture models of the component crops, the competition model INTERCOM contains additional routines for the distribution of light over the competing species. In INTERCOM this is realized by coupling a dynamic description of plant height development to a standard function of vertical leaf area distribution. For height development, the observed data on plant height were fitted to a logistic function (equation (1)), using the non-linear regression option of Genstat (1998). As no observations on vertical leaf area distribution were made, a parabolic vertical leaf area distribution, with leaf area present from the top of the plant till ground level and with maximum leaf area density at half the plant height, was assumed for both the rice cultivars and the two leguminous species. For rice and many other species vertical leaf area distribution often follows a parabolic function (Kropff and van Laar, 1993), though sometimes more skewed functions have been observed (Graf *et al.*, 1990).

Evaluation of the rice–cover crop competition model

Competition models were derived by combining the monoculture models of rice with the monoculture models of the cover crops two by two to test whether the performance of the mixtures could be explained by using exclusively parameters of the monoculture models. As each monoculture model would have a 1997 and a 1998 version this resulted in a total of 2 × 4 versions of the competition model. Evaluation of these competition models was done by comparing simulated and observed rice and legume biomass at rice harvest for all introduction times of the cover crops. In an earlier analysis of the field experiments, it was observed that both final rice and legume biomass could be described by a logistic function of relative sowing date of the cover crop (Chapter 4). Therefore, simulated rice and legume biomass of each rice–legume combination (Y_r and Y_l, respectively; kg ha^{-1}) were fitted against relative sowing date of the cover crop (t; days after rice sowing) using a logistic equation:

$$Y_r(t) = \frac{Y_{r,\max}}{1 + b_r \exp^{-c_r t}} \quad \text{and} \tag{4}$$

$$Y_l(t) = \frac{Y_{l,\max}}{1 + b_l \exp^{-c_l t}} \tag{5}$$

in which $Y_{\max}$ = maximum produced biomass (kg ha^{-1}), and b (-) and c (d^{-1}) are parameters describing the logistic equation. The non-linear regression option of Genstat was used to obtain the best fitting logistic functions. For rice the maximum produced biomass at harvest was set to the value obtained in monoculture, and consequently only the parameters b and c were estimated. The logistic functions were plotted against the relative sowing date of the cover crop and compared with observed data to assess model performance.

The evaluation of the competition models was conducted in two steps. In the first step, simulation runs with the model were conducted using observed leaf area and plant height for both species. In this step it could be judged whether given the morphological characters important for competition, an accurate simulation of dry matter production of both crops could be achieved. In a second step leaf area and plant height were simulated, and the model evaluation could be focused on the simulation of these morphological features.

Analysis of the rice–cover crop intercropping system

In the field experiments two contrasting leguminous species, two rice cultivars differing in competitive ability and various relative sowing times of the cover crop were combined. Suitability of a rice–legume combination is determined by its ability to produce a reasonable amount of legume biomass at the cost of only a marginal loss in rice yield. To enable a proper evaluation of the various rice–legume combinations, simulated loss in rice grain yield was expressed as a function of simulated legume biomass. For this purpose, similar to rice and legume biomass, simulated rice grain yield was fitted to a logistic function of relative sowing date of the cover crop, using the non-linear regression option of Genstat. Equation (5), describing the relation between legume biomass and relative introduction time of the cover crop, was then rewritten to:

$$t = -\frac{\ln\left(\frac{Y_{l,\max}/Y_l(t)-1}{b_l}\right)}{c_l} \tag{6}$$

and introduced in equation (4):

$$Y_r(t) = \frac{Y_{r,\max}}{1+b_r \exp^{-c_r t}} = \frac{Y_{r,\max}}{1+b_r \exp(c_r(\ln((Y_{l,\max}/Y_l(t)-1)/b_l)/c_l))} \tag{7}$$

Which could then be rewritten to obtain a relation between rice yield loss (YL_r) and legume biomass:

$$YL_r = 1-\frac{Y_r(t)}{Y_{r,\max}} = 1-\left(\frac{1}{1+b_r \exp(c_r(\ln((Y_{l,\max}/Y_l(t)-1)/b_l)/c_l))}\right) \tag{8}$$

In the field experiment rice and legumes were harvested at about one week after physiological maturity of the rice. For a further analysis of the relay intercropping system, simulated legume biomass both at rice maturity and at three weeks thereafter, corresponding to a conservative estimate of the length of the period in which water availability still allows for a period of extended growth, were determined. Differences in simulated legume biomass between *C. cajan* and *S. hamata* were then explained in terms of differences in legume biomass at maturity of rice and differences in legume biomass production in the period following rice maturity. These last differences were then assigned to differences in starting position of the legumes at rice maturity, particularly LAI and development stage, and differences in growth characteristics of the legumes. This last analysis was performed by conducting additional simulations for the final three weeks of legume growth after gradually replacing the starting position, particularly LAI and phenological development, of *C. cajan* at rice maturity by that of *S. hamata* and vice versa. The level of difference between simulation results after replacement of a specific characteristic then reflects the contribution of the specific factor for the overall difference. In this simulation study, rice cultivar V4 was used and differences in productivity of *C. cajan* and *S. hamata* were compared at rice yield reductions of 5, 10 and 20%. In a final analysis, height growth characteristics of *C. cajan* and *S. hamata* were exchanged to further explore the outcome of using highly and weakly competitive legume species in rice–legume relay intercropping.

Results

Monoculture models for rice

For rice, parameter values used for characterization of V4 and WAB56-50 were derived from the 1998 experiment. The temperature sum required to reach flowering (DVS = 1) and the additional temperature sum to reach maturity (DVS = 2), was calculated using a base temperature of 8 °C (Kropff *et al.*, 1994). Developmental rates for the vegetative (DVRV) and the reproductive (DVRR) periods are presented in Table 6.1. For V4 and WABb56-50, values were identical as both cultivars flowered and matured at the same time.

In the model, leaf area expansion during early growth stages is described by an exponential increase of which the rate is determined by relative leaf area growth rate (RGRL, $(°Cd)^{-1}$) and apparent leaf area per plant at emergence (LA0, m^2 $plant^{-1}$). Values for these two parameters were determined by fitting an exponential curve through leaf area observations until an LAI of 1. Values were markedly different for both years (Table 6.1). Early leaf area development in 1997 was faster than in 1998. After the exponential growth phase, leaf area is simulated by multiplying the increase in dry weight by the specific leaf area of newly formed leaves (SLA_{new}). For both cultivars SLA_{new} fluctuated around a value of 23 m^2 kg^{-1}, with the values for V4 slightly higher than for WAB56-50 during the first part of development (Table 6.1).

Partitioning coefficients of dry matter over shoot and root were kept identical to Kropff *et al.* (1994), whereas the time course of partitioning over leaves, stems and storage organs was derived from field observations. Results for both cultivars were nearly the same (Fig. 6.2) and reflect the pattern generally found for rice crops (Dingkuhn and Kropff, 1996).

Table 6.1 Summary of the parameters estimates for the two rice cultivars V4 and WAB56-50. Functions in the table are related to thermal time (°Cd).

Value or function description	Acronym	Units	1998		1997	
			V4	WAB56-50	V4	WAB56-50
Development rate during vegetative phase	DVRV	$(°Cd)^{-1}$	0.000848	0.000848		
Development rate during reproductive phase	DVRR	$(°Cd)^{-1}$	0.00154	0.00154		
Light extinction coefficient for leaves	KDF		0.6	0.6		
Photosynthetic rate	AMAX	kg CO_2 ha^{-1} leaf h^{-1}	0,54;1000,45 1200,12;2000,6	0,54;1000,42 1200,18;2000,9	0,54;1000,51 1200,45;2000,42	0,54;1000,51 1200,45;2000,42
Dry matter distribution pattern above ground (leaves-stems-panicles)			Fig. 6.2	Fig. 6.2		
Relative growth rate of leaf area	RGRL	$(°Cd)^{-1}$	0.0073	0.0076	0.0115	0.0108
Initial leaf area	LA0	m^2 $plant^{-1}$	0.0000868	0.0000163	0.0000163	0.0000608
Relative death rate of the leaves	RDRLV		1179,0; 1445,0.0052 1782,0.033; 2000,0.033	921,0; 1179,0.0099 1445,0.0025; 1782,0.033 2000,0.033		
Specific leaf area	SLA	m^2 kg^{-1}	0,22.6;148,22.6 218,26;420,26.4 674,18;921,18 1350,25;2000,25	0,18.3;148,18.3 218,23.3;420,25 674,18.7;921,18 1350,25;2000,25		

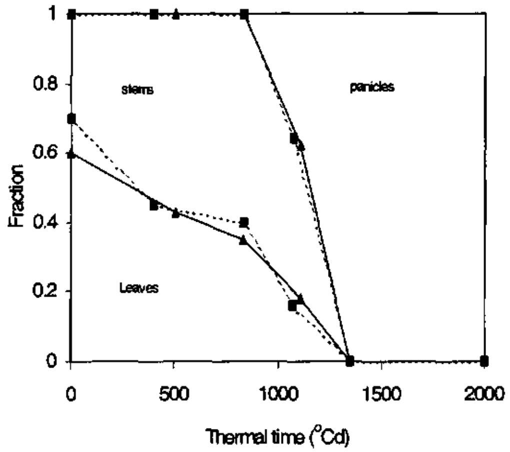

Fig. 6.2 The fraction of new dry matter partitioned among the different shoot organs as a function of thermal time for rice cultivars V4 (—) and WAB56-50 (----).

Simulations using the observed temporal changes of LAI as input showed that for accurate simulations of shoot dry weight a rapid decline in Amax during the second half of the growing season was necessary in 1998 (Table 6.1).

In 1997, a much more gradual decline in Amax until maturity was required. After the first calibration step, the models were run by dynamically simulating LAI. Accurate simulation results were realized by introducing year-specific parameters for early leaf area development (RGRL and LA0), whereas for all other parameters the 1998-values were appropriate. For both cultivars this led to accurate simulations of shoot dry matter (Fig. 6.3).

Height development

The observed time course of plant height for the rice species and the two cover crop species could be accurately described by a logistic function of thermal time $(°Cd)^{-1}$ after emergence (Fig. 6.4). Correlation coefficients surpassed 0.96 whereas residual variance was homogeneously distributed over the fitted curves. In Table 6.2, parameters describing the logistic increase in height are summarized. V4 and WAB56-50 had similar maximum height, and a similar relative height growth rate (H_s). The slightly postponed development of WAB56-50 was reflected in a higher H_b value. Values for *S. hamata* were nearly similar to rice except for maximum height, which was only 91cm. Height development for *C. cajan* was clearly the fastest as both relative height growth rate and maximum height surpassed those of *S. hamata* and the two rice cultivars. The maximum rate of height increase in the inflection point reflected the differences with values of 0.182 cm $(°Cd)^{-1}$ for *C. cajan*, 0.06 cm $(°Cd)^{-1}$ for *S. hamata* and 0.075 and 0.071 cm $(°Cd)^{-1}$ for V4 and WAB56-50, respectively.

Table 6.2 Estimated parameter values and standard errors in parenthesis using a logistic regression model to fit observed height over time during the 1998 experiment.

	V4	WAB56-50	*C. cajan*	*S. hamata*
$H_{\max}$ (cm)	118 (18)	121 (20)	251 (13)	92 (8)
H_s (°Cd)$^{-1}$	0.0024 (0.0007)	0.0025 (0.0008)	0.0030 (0.0003)	0.0026 (0.0003)
H_b (-)	14.5 (8.0)	23.6 (18.2)	23.9 (5.5)	22.5 (4.5)
r^2	0.96	0.97	0.99	0.99

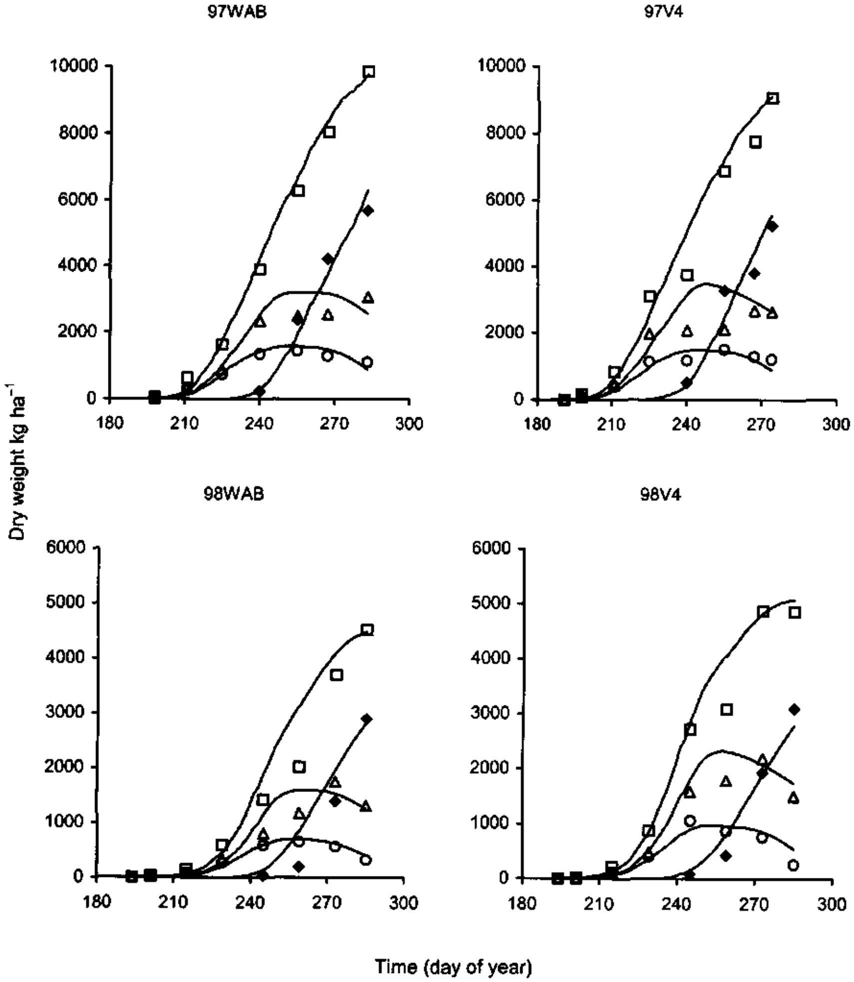

Fig. 6.3 Simulated (line) and observed (markers) leaf, stem panicle and total shoot dry weight after parameterization of the model for the two rice cultivars V4 and WAB56-50 in 1997 and 1998.

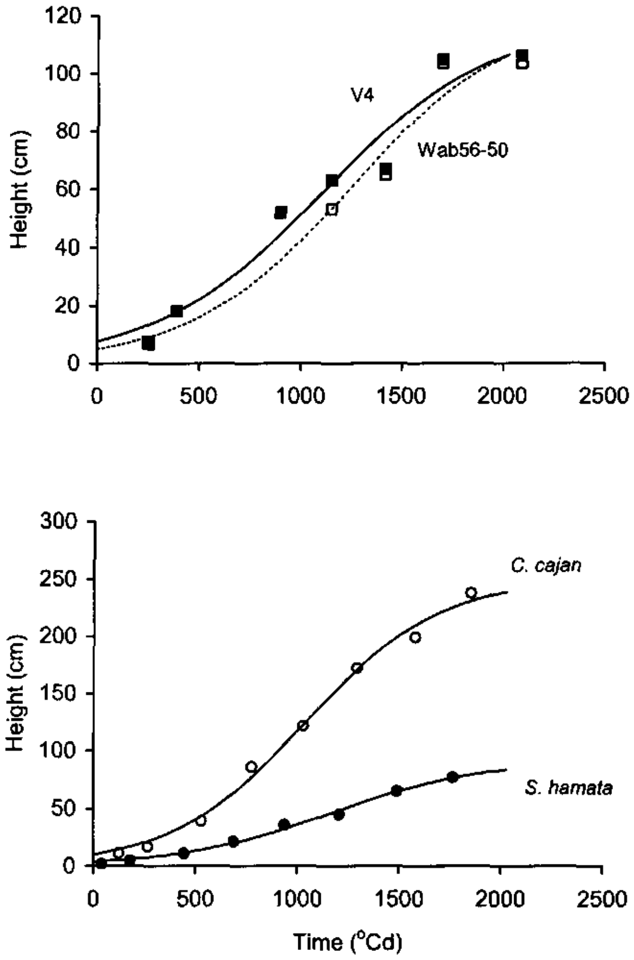

Fig. 6.4 Time course of height increase as a function of temperaure sum (°Cd) after plant establishment in monoculture experiments conducted in 1998. Parameter estimates for the two rice cultivars (V4, WAB56-50) and the two legume species (*C. cajan*, *S. hamata*) and standard errors are presented in Table 6.2.

Evaluation of the rice/cover crop competition models

Competition between rice and *C. cajan* or rice and *S. hamata*, was simulated by combining the validated monoculture models for both components (rice and the cover crops). Models for growth of the cover crops in monoculture were parameterized and validated at an earlier stage (Chapter 5). For both years, the performance of the competition models was evaluated by comparing the simulated time course of dry matter increase for both rice and the legumes with observed data.

In Fig. 6.5a, results of *C. cajan* in competition with both rice cultivars are presented. Simulated rice biomass at maturity and legume biomass at one week after rice maturity were fitted to a logistic function using day of legume introduction as an explanatory variable. A solid line presents the fitted function to simulated data, whereas markers represent observed data. The figures indicate that by delaying the time of legume introduction, rice biomass increases while legume biomass gradually decreases. In general, the models gave adequate simulations of the observed field data both for rice biomass and accumulated legume biomass. In 1998, a slight underestimation of legume biomass was observed when *C. cajan* was sown at 0 and 14 DARS in competition with V4.

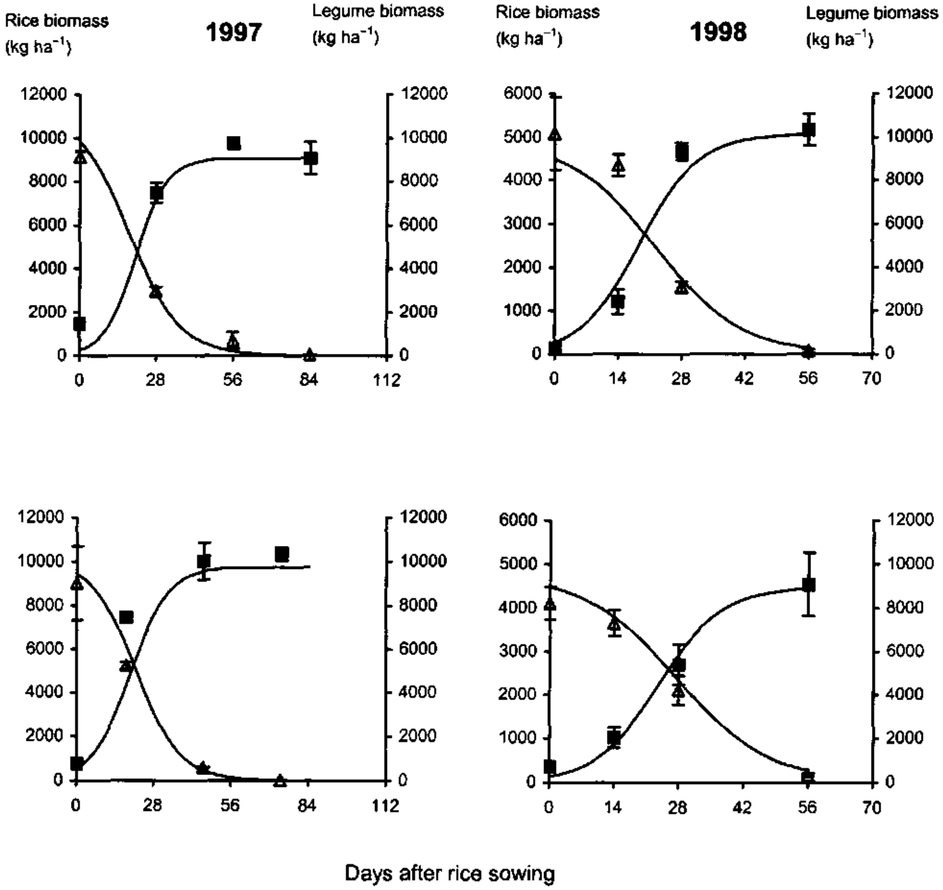

Fig. 6.5a Comparison of simulated (lines) and observed (markers) final biomass of rice (V4 and WAB56-50) and *C. cajan* in competition at different sowing times during 1997 and 1998. Simulated curves were derived after fitting the data to a logistic function. Bars represent standard errors of the observed values.

Despite adequate simulations of *S. hamata* in monoculture, the simulation of competition of this legume with the two rice cultivars, using exclusively parameters from the monoculture of rice and *S. hamata*, was poor (Fig. 6.5b). The discrepancy between observed and simulated data was mainly found at 0, 14 and sometimes 28 DARS. For the later dates of introduction, the rice completely outcompeted the legume, both in the field and in the simulations. The models clearly underestimated the competitiveness of *S. hamata*, resulting in an overestimation of rice biomass and an underestimation of legume

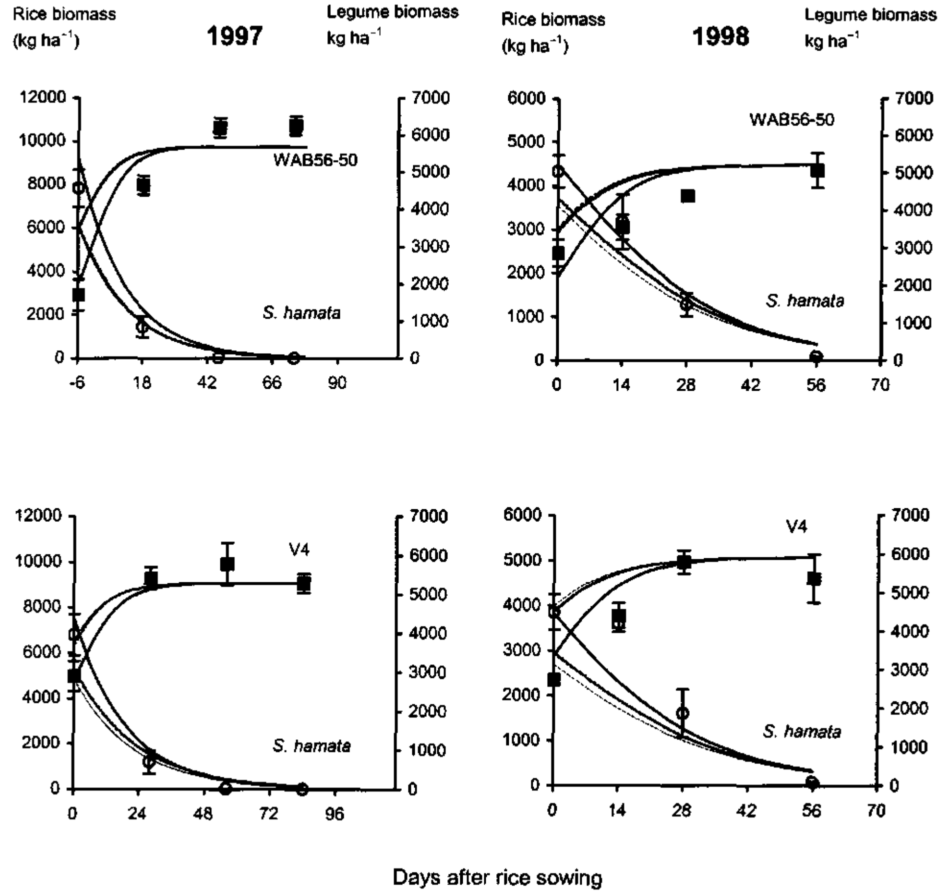

Fig 6.5b Comparison of simulated (lines) and observed (markers) final biomass of rice (V4 and WAB56-50) and *S. hamata* in competition at different sowing times during 1997 and 1998. Simulated curves were derived after fitting the data to a logistic function. Bars represent standard errors of the observed values. The different lines represent simulation using SLA values from the monoculture (-----), taking into account the effect of shade (– --- –), and adding a coefficient to describe the lower boundary (lb=0.5) of the canopy of *S. hamata* (—).

biomass. These observations were found across years with both rice cultivars V4 and WAB56-50. Further inspection of observed data learned that in competition with rice, SLA of *S. hamata* increased compared to SLA in monoculture. Intercropping alters the light environment of component crops especially in the degree of shading experienced by the second species, which grows under another established plant. Effects of shade on the morpho-physiology of plants have regularly been observed (Hawkins, 1982; Kropff and Spitters, 1992; Cavero *et al.*, 2000; Baumann, 2001). Main changes are generally found in dry matter partitioning, height growth and leaf thickness. To determine the consequences of an increased SLA, simulations were conducted in which the measured time course of SLA_{new} of *S. hamata* in the mixture was included as an explicit function in the model. This resulted on average in a relative increase in biomass of about 15% in *S. hamata* while rice biomass was decreased by less than 2% for the introduction dates 0, 14 and 28 DARS. Based on these results, it was decided to include a procedure that accounts for morphological adaptations of newly formed leaves of *S. hamata* as a result of shading by the rice crop. Dynamic simulation of SLA is necessary for further use of the model as a tool for analysis. The introduced procedure was based on Cavero *et al.* (2000), and consisted of the determination of a shading stress index (SSI) which was calculated as the ratio between the PAR absorbed by the portion of the rice canopy located above the *S. hamata* plants and total incoming PAR. A multiplicative factor (MF) was derived from the ratio of SLA in mixture over that in monoculture and this factor was related to SSI (Fig. 6.6). Accounting for the formation of thinner leaves as a result of shading was insufficient to explain the underestimation of competitive ability of *S. hamata*.

Field observations however also revealed that most leaves were found in the upper part of the canopy. For this reason, the vertical leaf area distribution of *S. hamata* was adjusted in a more upward direction resulting in an increased competitiveness of this species. For this purpose, a lower boundary for leaves of *S. hamata* was specified, while the parabolic leaf area distribution was maintained. This lower boundary was defined as a fraction of actual plant height. The level of the current adjustment was not based on measurements, as patterns of vertical leaf area were not determined. Simulations demonstrated that a lower boundary at 50% of actual plant height was required to obtain reasonable agreement between observed and simulated data (Fig. 6.5b). It can not be excluded that in this way also the effect of competition for nitrogen was implicitly taken into account. Observations on N content of rice foliage demonstrated that particularly with early introduction of the legumes competition for N is likely to have occurred (Chapter 4). This would be in line with the current results, were deviations between simulated and observed results were mainly found with early introduction dates of *S. hamata*.

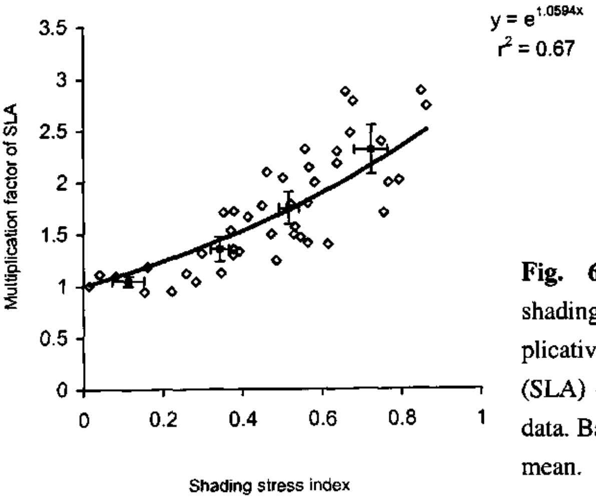

Fig. 6.6 Relationship between the shading stress index and the multiplicative factor of the specific leaf area (SLA) of *S. hamata* based on two-year data. Bars indicate standard errors of the mean.

Analysis of the cropping system

For a better understanding of the effects of establishing the cover crops in relay with upland rice, the relationship between simulated loss in rice grain yield and accumulated legume biomass was generated by using equation (8). In Fig. 6.7, only the simulated results of 1998 are presented, as similar trends were observed in both years. At rice maturity, similar yield loss–legume biomass relationships were obtained for all combinations of legume species and rice cultivars, though dates of legume introduction differed. Comparison of the open and closed markers, which refer to an introduction time of 28 DARS, demonstrate that *C. cajan* is more competitive than *S. hamata*, and should thus be introduced at a later moment to obtain comparable result in terms of rice grain yield loss and legume biomass production. Maximum yield loss caused by *S. hamata* was about 60% in V4 and 65% in WAB56-50, while *C. cajan* completely out-competed the two rice crops. At similar introduction dates both legume species produced slightly higher amounts of biomass in mixture with WAB56-50 compared to V4. This confirms that V4 is a rice cultivar with a relatively high level of competitiveness (Dingkuhn *et al.*, 1997). Simulations further revealed that a marked difference in the rice grain yield loss–legume biomass relationship between both legume species appears when the growth period of the legumes is extended with an additional three weeks. It was found that the increase in biomass of *C. cajan* surpassed that of *S. hamata*, whereas particularly for *S. hamata* the additional production at early introduction (top of the curve) was relatively small.

A further simulation analysis of the differences between the highly competitive *C. cajan* and the weakly competitive *S. hamata* was conducted using rice cultivar V4. At rice yield loss levels of 5, 10 and 20%, only small differences in simulated legume biomass at rice maturity were observed between both species (Table 6.3). This reflects the nature of competition, as the production of legume biomass is at the cost of rice production, and consequently the opportunities for biomass production of any legume is largely predefined by setting the accepted level of yield reduction for rice. However, to obtain

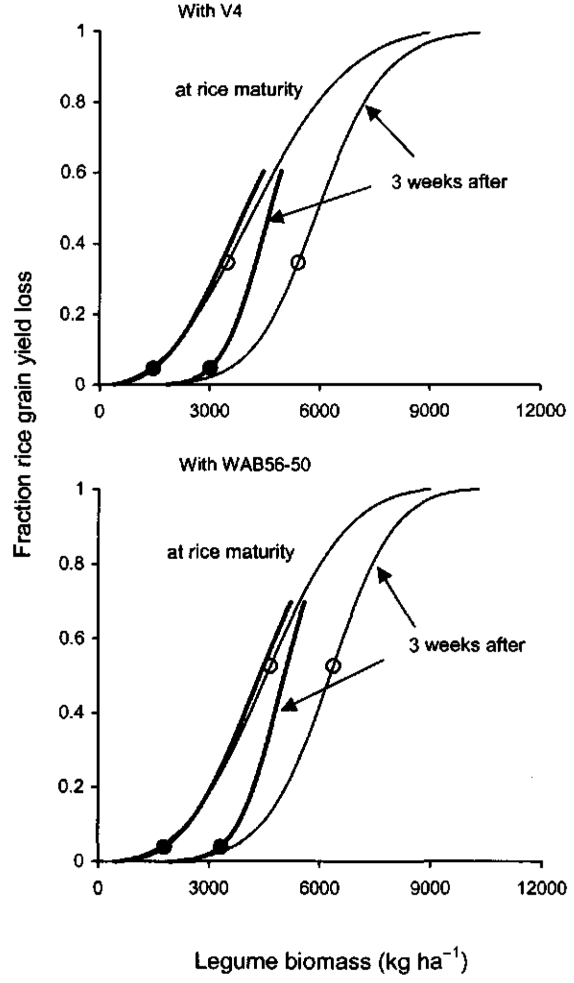

Fig. 6.7 Relationships between simulated rice grain yield loss (expressed as a fraction) and accumulated legume biomass (kg ha^{-1}), using the competition model parameterized with the 1998 data. Simulations were stopped either at physiological maturity of rice, or three weeks after. Bold lines refer to simulations with *S. hamata*, the normal lines represent simulations with *C. cajan*. Markers represent results obtained when legumes are introduced at 28 DARS (closed symbols: *S. hamata*; open symbols: *C. cajan*).

Table 6.3 Summary of simulation results reflecting phenology and LAI of two relay-cropped legume species (*C. cajan* and *S. hamata*) in rice cultivar V4 at rice maturity for legume introduction dates that resulted in simulated rice yield losses of 5, 10 and 20%. Differences in simulated overall accumulated legume biomass at three weeks after rice maturity were attributed to differences in phenology, LAI and growth characteristics of both legumes.

Yield loss	5%			10%			20%		
	C. cajan	*S. hamata*	*differences*	*C. cajan*	*S. hamata*	*differences*	*C. cajan*	*S. hamata*	*differences*
Day of legume introduction	228	212		221	203		215	196	
At rice maturity									
Phenological age (°Cd)	1053	1264		1177	1428		1282	1562	
LAI ($m^2 m^{-2}$)	1.33	2.10		1.79	2.34		2.55	2.68	
Differences in biomass accumulation of the legumes									
A. Biomass at rice maturity (kg ha^{-1})	985	1293	–308	1615	1899	–284	2599	2696	–97
B. Additional growth (kg ha^{-1})	2373	2074	299	2539	1722	817	2623	1407	1216
Differences (kg ha^{-1}) attributed to:									
Phenological age			*444*			*519*			*493*
LAI			*–567*			*–313*			*–54*
Legume growth characteristics			*478*			*667*			*783*
Interaction			*–47*			*–56*			*–6*
A+B. Biomass 3 wks after rice maturity	3358	3367	–9	4154	3621	533	5222	4103	1119

these results the less competitive *S. hamata* had to be introduced between 16 to 19 days earlier, for yield reduction levels of 5 and 20%, respectively (Table 6.3). Consequently, at rice maturity phenological development of *S. hamata* expressed in degree-days was on average 250 °Cd more advanced than that of *C. cajan*. At the same time, the less competitive *S. hamata* was allowed to have developed clearly more leaf area, most likely because competitive ability on a leaf area basis was smaller for *S. hamata* than for *C. cajan*. This difference was particularly obvious at a rice yield reduction of 5%, whereas differences at 20% were only marginal. The consequences of these differences for legume biomass production in the three weeks following rice maturity were analysed by performing additional simulation runs for this specific period, in which characteristics of the starting position of both legumes at rice maturity, particularly phenology and LAI, were successively exchanged. As mentioned previously, these additional three weeks correspond to the length of the period in which, under rainfed conditions, water availability still allows for a period of extended growth. If a rice yield reduction of only 5% was permitted, legume biomass production after three weeks was nearly the same, though for both legumes these yields were realized in a different way. Accumulated biomass of *S. hamata* at rice maturity was about 300 kg ha^{-1} higher. Furthermore, this legume had a clearly higher LAI at rice maturity, resulting in a better light interception and an increased biomass production of around 570 kg ha^{-1}. On the other hand, phenological development of *S. hamata* was more advanced, resulting in a lower production of around 440 kg ha^{-1} due to ageing, whereas the differences in growth characteristics were responsible for a 480 kg ha^{-1} production deficit of *S. hamata* compared to *C. cajan*. Overall these effects counterbalanced one another resulting in nearly the same legume biomass production at three weeks after rice maturity.

If larger rice yield losses were permitted, clear differences in simulated legume biomass production between *S. hamata* and *C. cajan* started to appear, and these differences enlarged with higher rice yield losses. These differences are in line with earlier analysis of experimental results, where legume biomass was evaluated at one week after rice harvest. The current analysis revealed that a combination of factors was responsible for this effect. First, the difference in accumulated biomass at rice maturity became smaller. Secondly the difference in starting position switched to the benefit of the more competitive *C. cajan*. Whereas the effect resulting from the difference in phenological age between both legumes was found relatively stable, the effect caused by a difference in LAI was found to decrease at higher rice yield losses. First because the difference in LAI became smaller, and secondly because the absolute values of LAI were getting higher, through which the additional light interception for each additional unit of leaf area became smaller. Finally these higher LAI-values at rice maturity gave *C. cajan* the ability to better demonstrate its higher growth potential relative to *S. hamata*.

In a final simulation analysis, height growth characteristics of *S. hamata* and *C. cajan*, specifically H_{max}, H_b and H_s, were mutually exchanged to create a competitive *Stylosanthes* and a weakly competitive *Cajanus*. Comparisons between the legumes were made for a predefined level of rice yield loss of 10%. Again these simulations were performed using model parameters and weather data of 1998, and V4 as the companion rice cultivar. Similar to the previous analysis, legume performance at rice maturity and at three weeks thereafter were compared (Table 6.4). At rice maturity striking similarities between the original *C. cajan* and the competitive version of *S. hamata* were observed. Required introduction date as well as phenological development, LAI and accumulated biomass at rice maturity were largely identical. The additional growth in the three weeks period following rice maturity were also nearly the same, resulting in an identical overall legume biomass production. These results illustrate the prominent role of height growth rate characteristics in explaining the differences in competitive ability between *C. cajan* and *S. hamata*. Comparison of simulation results obtained by using the original *Stylosanthes* and the weakly competitive version of *Cajanus* showed also clear similarities for characteristics like required introduction date, phenological development and LAI. However, marked differences were observed for biomass accumulation at rice maturity and additional growth in the three weeks following rice maturity, resulting in an overall difference in biomass accumulation of around 770 kg ha^{-1} to the benefit of the weakly competitive version of *C. cajan*. This points at the Achilles' heel of the use of *S. hamata* as a cover crop in rice legume relay cropping systems. The poor competitiveness of *S. hamata* demands for an early introduction of this legume, resulting in a relatively old crop at rice maturity. For the poorly competitive version of *C. cajan* this was not found to be a problem, as productivity at this stage was still substantial. However, the short-duration character of *S. hamata*, reflected in an early decline in productivity of this species (see Chapter 3), caused biomass accumulation of this legume species to be relatively poor in the period after removal of the rice crop.

Discussion

Relay intercropping cover crops in upland rice in the savanna zone of West Africa was analysed with two very contrasting leguminous species using a mechanistic approach. *C. cajan* or pigeon pea, a highly competitive species characterized by a fast early growth rate and a maximum height of over 250 cm, was compared with *S. hamata*, a very slow growing species with a maximum height of less than 95 cm. The performance of both species in a rice relay cropping system was compared by introducing the legumes at various times after rice sowing in two rice cultivars that differed in competitive ability. Previously, the INTERCOM model was parameterized and validated for the growth of both legumes in monoculture (Chapter 5). In this study the INTERCOM model was

Table 6.4 Summary of simulation results reflecting phenology, LAI and height of two relay-cropped legume species (*C. cajan* and *S. hamata*) in rice cultivar V4 at rice maturity for legume introduction dates that resulted in a simulated rice yield loss of 10%. Height growth characteristics of both legume species were exchanged to analyse the effect of competitive ability on legume performance. Differences in simulated overall accumulated legume biomass at three weeks after rice maturity were attributed to differences in phenology, LAI and growth characteristics of both legumes.

	C. cajan			*S. hamata*		
	original	less competitive	differences	original	more competitive	differences
Day of legume introduction	221	202		203	222	
At rice maturity						
Phenological age (°Cd)	1177	1523		1428	1085	
LAI ($m^2 m^{-2}$)	1.79	2.25		2.34	1.86	
Differences in biomass accumulation of the legumes						
A. Biomass at rice maturity (kg ha^{-1})	1615	2262	−647	1899	1667	232
B. Additional growth (kg ha^{-1})	2539	2132	407	1721	2390	−669
Differences (kg ha^{-1}) attributed to:						
Phenological age			*549*			*−765*
LAI			*−306*			*261*
Height			*180*			*−155*
Interaction			*−15*			*−10*
A+B. Biomass 3 weeks after rice maturity (kg ha^{-1})	4154	4394	−240	3620	4057	−437

parameterized and calibrated for both rice cultivars, and satisfactory simulations for growth of both cultivars in monoculture were obtained. The newly parameterized and calibrated models, were then combined and used to simulate growth of rice and legumes in mixtures. Adequate simulations were obtained in competition for all rice–legume combinations with *C. cajan* at the different sowing dates. For *S. hamata* in competition with any of the two rice cultivars the combination of monoculture models did not result in adequate simulations, as the model underestimated the competitiveness of *S. hamata*. Comparison of observed plant characteristics in monoculture and mixtures revealed that for *S. hamata*, particularly late introduction increased SLA in competition due to shading of the rice crop. Production of thinner leaves resulting from shading is a commonly observed morphological adaptation (Hawkins, 1982), whereas the importance of SLA in competition was pointed out by, e.g., Kropff and Spitters (1992) and Cavero *et al.* (2000). Accounting for higher SLA-values resulting from shading was only partly able to explain the underestimation in simulated competitiveness of *S. hamata*. For that reason the vertical leaf area distribution of *S. hamata* was adjusted and a more upward skewed leaf area density profile was introduced in the model. Alteration of vertical leaf area density profiles with a higher concentration of leaf area in the top of the canopy resulting from competition for light have more often been reported (e.g., Cavero *et al.*, 2000; Baumann *et al.*, 2001). Moreover, Spitters (1989) pointed at the relevance of an accurate simulation of the light profile in a mixed canopy for modelling competition for light. In the current study, the foundation for introducing a skewed leaf area distribution was solely based on qualitative observations and the level of skewness was adjusted to obtain a good level of fit. This indicates that for *S. hamata* more studies are needed to further characterize its morphology as well as its plasticity in response to light stress. In the present study, competition for water and nutrients was not accounted for. Competition for water is unlikely to have occurred, as the experimental field was boom-irrigated on a weekly basis. Root observations showed that both legume species nodulated very well (data not shown), as is generally observed in the upland area of the experimental site of the WARDA-research station in Mbé, Ivory Coast.

However, competition for nitrogen can not be excluded, as nitrogen supply was moderate to promote nodulation. Furthermore clear reduction in N content of rice foliage in treatments with legume sowing were observed at around one to two and half months after rice sowing (Chapter 4). It is likely that the introduced adjustment in vertical leaf area profile in the model partly accounted for growth reduction in rice due to competition for N.

In relay intercropping systems of rice–cover crops, accumulation of legume biomass for fallow improvement has to be realized under the condition that current rice yield is hardly reduced. Experimentation and simulation showed that the attainable legume biomass depends on the combined effects of sowing time of the cover crops, the competitive ability of the cover crop species and the rice cultivar. Compared to early introduction, late introduction of the cover crop had little effect on rice production, but at the same time accumulation of legume biomass was small and consequently only small amounts of nitrogen were added to the system (Chapter 4). Delaying the sowing time has previously been identified as an important management factor in relay cropping systems, as it reduces the competitiveness of the relay-planted species (Gilbert, 1998; Fischler and Wortmann, 1999).

A clear difference in rice production as affected by introduction of the two legumes was observed. Simultaneous sowing of rice and *C. cajan* resulted in a complete loss of the rice crop, whereas at this introduction time the combination with *S. hamata* still yielded around 35% of the control yield. Also at later introduction times of the legumes the more competitive character of *C. cajan* was reflected in a higher loss in rice yield and a concurrent higher legume biomass production. Analysis with the competition model indicated that the differences in competitive ability between both species could largely be explained by their marked differences in early height growth rate and maximum plant height (Table 6.4). By plotting grain yield loss against produced legume biomass the two prerequisites for a successful relay cropping system are directly related. It then showed that identical results could be obtained by using either one of the legume species. The lower competitive ability of *S. hamata* could be compensated by earlier introduction of this legume in the rice crop. At moderate levels of rice yield loss, differences in introduction time of both species of about two and a half weeks were required to obtain similar results. The length of this period was partly due to a 4-day-delay in time of emergence for *S. hamata*. This result clearly reflects the principle of competition, where two or more species are contesting for the same resources and as a result the growth of one species will be at the cost of the other species.

Observed differences between the performance of the two rice cultivars in this relay cropping system can be explained by means of the same principle. At similar introduction dates of a legume, rice yield reduction of the more competitive V4 was found to be smaller, whereas less legume biomass was produced. In this case later introduction of legumes in the less competitive WAB56-50 gave comparable results. On average a delay of 5 days compensated for the lower competitiveness of WAB56-50. Consequently, one of the main conclusions of this study is that in the rice relay cropping system under study the attainable legume biomass production at rice maturity is nearly completely determined by the level of loss in rice grain yield that is considered acceptable. This conclusion is irrespective of selected legume species or choice of rice cultivar, taking into account that any combination of rice cultivar and legume species requires its own specific legume introduction time. Furthermore, it is also obvious that at low levels of rice yield reduction only marginal amounts of legume biomass will be obtained at rice maturity.

In the savanna zone of West Africa, residual soil moisture after maturity of the rice crop allows for an extended growth period of the relay crop. In the simulation study rice maturity was followed by three weeks of unrestricted growth before the upcoming dry period, which was assumed to be a reasonable estimate for this particular environment. The importance of such an extended growth period for the cover crops was clearly demonstrated in Fig. 6.7. Legume biomass markedly increased, particularly at lower levels of rice yield reduction. The simulations further suggest that the performance of *C. cajan* surpasses that of *S. hamata*, an observation in line with earlier reported experimental results of Chapter 4, where the legumes were allowed to grow for an additional period of 7-10 days after rice maturity. Model analysis helped to explain the differences in performance of both legumes. The weaker competitive ability of *S. hamata* necessitates an earlier introduction of this species, resulting in a phenologically older crop at rice maturity. Particularly in combination with the short-duration character of *S. hamata*, this resulted in the relatively poor production of this species in the additional period of growth. Based on the experimental results it was concluded that the use of competitive legumes in rice cover legume intercropping systems was more promising than the use of more weakly competitive ones. This conclusion can be made more specific now, as the model analysis suggests that only the combination of poor competitiveness and short duration is unfavourable in this particular system.

In the simulation analysis conducted in this study, temperature and light were used as the main driving variables. Nitrogen and water were not explicitly accounted for, although competition for nitrogen between rice and legume could not be precluded, and water availability obviously played an important role, as it largely determines the length of the additional growth period. This implies that the results of the simulations should be interpreted with caution. Nevertheless, the simulations greatly helped in developing a better insight in the complex rice–relay cropping system and particularly in identifying the main options for optimizing this system. Given the fact that only small reductions in current rice grain yield will be tolerated by farmers, main legume biomass production and concurrent N-accumulation have to come from the growth period after rice maturity, making use of residual soil moisture. One way of improving the rice relay cropping system seems the shortening of the rice growth period, which in this case will lengthen the rice-free growth period of the legumes. Analysis of rice production in various environments showed, however, that in most situations selecting for rice cultivars that yield highest in a given environment has resulted in selection of cultivars with an optimum duration (Yin, 1996). This suggests that use of cultivars with shorter duration than commonly used might lead to a reduction in actual yield. A less risky way would be the selection of suitable legume species. The current study strongly suggest that desirable characteristics of such legume species will be related to an optimum utilization of the growth period after rice harvest, like a fast growth rate and drought tolerance.

Conclusions

Relay intercropping legume cover crops in upland rice can create considerable yield loss in rice depending on the time of legume establishment and the competitive ability of the species. On average rice yield was reduced from 0 to 63% by *S. hamata* while *C. cajan* created up to 100% yield loss depending on the introduction time. Although *C. cajan* was more competitive than *S. hamata*, comparable amounts of biomass at rice maturity were produced if the level of rice yield loss was predefined. Under growth conditions of the savanna zone of West Africa, available soil moisture after maturity of the rice crop allows for an additional period of growth of the cover crop of around three weeks. The simulation study identified the crucial role of this additional growth period for realizing a reasonable amount of legume biomass at the cost of marginal reductions in rice yield. The lesser performance of *S. hamata* in the period following rice maturity was attributed to the difference in phenology, combined with the short-duration character of this species. Based on the gained insight in the rice–legume intercropping system in the savanna zone of West Africa it was concluded that this system would benefit most from rapidly growing, drought-tolerant legume species. Finally using shorter duration rice cultivars that, due to early rice harvest, would lengthen the growing period of the cover crop in a non-competitive environment was identified as an option that requires further investigation.

CHAPTER 7

General discussion

CHAPTER 7

General discussion

In the presented study, opportunities were explored for integrating legume cover crops in upland rice-based cropping systems to improve fallow quality and accordingly improve productivity of upland rice. Growth characteristics, nitrogen (N) content and potential biomass production of selected legume cover crop species were assessed. The effects of these legume species on soil quality, on weed dynamics and on rice grain yield were analysed under different residue management options. Furthermore, a detailed analysis focused on relay establishment of the legume cover crop fallow into the rice crop. The underlying mechanism of competition between the component species in that system was analysed and relationships between productivity of rice and cover crops were established to determine options to maximize production of the cover crop while minimizing interspecific competition with the associated rice. A combined analysis of the competitive interactions between the components of the system, using descriptive field data and dynamic simulation, was conducted to further understand the importance of morpho-physiological characteristics and dates of establishment of the legume species for successful relay intercropping systems. In this chapter, our findings on these different aspects as reported in the previous chapters are highlighted and further discussed in an integrated way.

Management of cover crop residue and subsequent effects on rice yield

Crop rotation with natural fallow is a wide-spread traditional cropping strategy in agriculture to restore soil fertility and maintain productivity (Sanchez, 1976; Ruthenberg, 1980). Crop rotation with legume species as improved fallow contributes to a rapid replenishment of soil fertility by adding a substantial amount of nitrogen in a shorter period as compared to the natural bush fallow. This additional benefit provided by legume species and their potential role in suppressing weeds and/or controlling pests has induced research to identify appropriate species and management systems. With great diversity existing in agro-ecosystems, adaptation and performance of these species varied. Results in Chapters 2 and 3 indicate that this variability was largely reflected in growth characteristics, biomass production and nitrogen accumulation by the cover crops. Highest N-accumulation was found with *Pueraria phaseoloides* (227 kg ha^{-1}) in the forest zone, *Cajanus cajan* (167 kg ha^{-1}) in the savanna zone and with *Canavalia ensiformis* and *Calopogonium mucunoides* (70-90 kg ha^{-1}) in the derived savanna zone.

The levels of N in the crop were comparable to most annual species which contain about 20 to 250 kg N ha^{-1} with a mean of about 100 kg N ha^{-1} (Giller and Wilson, 1991). For many of these legumes, it has been estimated that about 70% of the amount of N was derived from biological N-fixation (Peoples and Craswell, 1992; Becker *et al.*, 1995) making them a potential source of N in low-input agriculture as practiced in developing countries. Many legume species are not *Rhizobium*-specific and can nodulate invariably in different soils, enlarging their possibility to grow in different environments. In general, the level of N-fixation is thought to be moderate and could be improved by inoculating the species. In farmers' fields in Nigeria, biomass and N yields in *Mucuna* increased by more than 40% after inoculation (Hougnandan, 2000).

In this study, biomass production by the cover crops varied between agro-ecological zones. For instance, *Pueraria phaseoloides* accumulated high biomass in the bimodal forest zone and performed poorly in the derived savanna zone. In addition to cover crop performance in the different zones, residue management options showed that residue incorporation was the best option in the savanna zone while in the forest area the practice of residue burning produced the highest rice yield in the subsequent year. A positive effect of burning over mulching on cereal grain yield has also been reported for humid forest environments in South Asia (Beri *et al.*, 1995), South-east Asia (Roder *et al.*, 1998) and South America (Luna-Orea and Wagger, 1996). Fallow management studies by Tonye *et al.* (1997) concluded that residue burning appears to be the best management strategy for forest environments in Central Africa. Similarly in West Africa, van Reuler and Janssen (1996) observed an increase in rice yield in response to ash after burning, as a result of an increase in nutrient uptake (N, P, K and Mg). This could partly be explained by the limitation of phosphorus in the forest environment. However, there is evidence that by burning, much of the N (and S) in the biomass is lost to the atmosphere (60-85%; Sanchez, 1976). This may explain the low yield in the savanna zone, where the main limitation in soil nutrient is N. Another positive effect of burning could be the reduction of viable weed seeds in the topsoil layer (de Rouw, 1995). In this study, it was found that regardless of management, the percentage increase in rice yield following the legume fallow was about 20 to 30% compared to the natural fallow. Rice responded linearly to incorporated residue N and nitrogen use efficiency was about 10 kg of rice grain per kg N applied. In a previous study in the same area, Becker and Johnson (1998) found similar rice yield increases following a six-month-old fallow. In Chapter 4, where the after-effect of *C. cajan* and *Stylosanthes hamata* was evaluated, no clear relation between N-accumulation and subsequent rice grain yield was observed. In this experiment legumes were grown at a range of growth durations, resulting in clear differences in residue quality. This indicates that besides the amount of N, residue quality may determine net N-release as pointed out by Fox *et al.* (1990) and Palm and Sanchez (1991).

The observations imply that using cover crops to replace natural fallow can increase yield of a subsequent crop and could play a role in intensification of land use. Low yield response following a legume fallow can be compensated by supplementing the crop with mineral N-fertilizer along with organic material and N from the legume. This strategy appears appropriate to meet the N-requirement of the crop. Positive effects of improved fallow and supplemental N fertilization have been observed in the Central Africa country of Cameroon (Adesina and Coulibaly, 1998). Studies have shown that matching the N-release from green manure with nutrient demand of the food crop is important. This synchrony depends on several characteristics including residue quality (age and composition) and residue management (Tian, 1992; Kuo and Jellum, 2000).

Advantages and disadvantages of various management options may justify farmers' practices across different agro-ecological zones. In addition, weed suppression is an essential factor for viability of improved fallow management practices, which could be attractive to farmers with limited resources. While direct planting into the mulch without tilling the soil reduces the risks of soil erosion and involves less labour (Kannegieter, 1968), termites may become hazardous mainly in savanna areas.

From this analysis, it appears that selection of cover crops that may fit into a defined cropping system necessitates good knowledge not only on the management of the residue, but also on the morphology and physiology of the species. In most studies, selection is still based on general descriptive and empirical information (Weber *et al.*, 1997; Kiff *et al.*, 1996). As cultivation of legume cover crops is being promoted in many tropical regions, there is a need to select suitable species that fit into the environment and meet farmers' objectives for adoption.

The prolonged rainy season in the West Africa savanna zone can be used to establish cover crops either as relay crop or as sole crop for short-fallow improvement. Characterization of *Cajanus cajan*, *Stylosanthes hamata*, *Calopogonium mucunoides*, *Mucuna pruriens*, *Crotalaria juncea*, *Aeschynomene histrix* revealed differences in morphology and in biomass production. Differences in competitive ability, as measured by the early relative growth rate of leaf area, the rate of height increase and maximum height, were also found. These characteristics are frequently used to characterize competitive species (Kropff and van Laar, 1993; Bastiaans *et al.*, 1997). A combination of these characteristics was used to group the species on the basis of their productivity and competitivity. The most productive species were also potentially more competitive. *C. cajan* and *C. juncea* combined high biomass production and high N-accumulation. *S. hamata* and *A. histrix* were less competitive and accumulated the lowest amount of N. In the present study, the amount of N found in the leaf material ranged between 70 and 100 kg N ha^{-1}. However, the large variability observed between fields suggested that N-fixation might be linked to other factors (Becker and Johnson, 1998), such as soil conditions.

Competition in relay intercropping systems

In rice–cover crop relay intercropping, both components of the system may not have equal importance for farmers. For producers the main importance of the system would be to obtain legume biomass at a low cost of rice in terms of yield loss, which implies that a balance must be found to obtain optimum yield of both species. More importantly yield loss in rice grain yield should justify the use of cover crops in the system. Based on results obtained in Chapter 3, the performance of the competitive legume species *C. cajan* and the less competitive *S. hamata*, were studied in a relay cropping system.

In Chapter 4, the effects of rice and legumes on each other were quantified. It was found that logistic functions described the relationship between final yield of both species in dependence of the relative sowing date of the cover crop reasonably well. The results show that the highest yield loss in rice was caused when both crops were established at the same time. When the time of legume introduction was delayed, less competition from the legume was exerted on rice, thus leading to a gradual decline in rice yield reduction. Similar observations were found in maize–*Crotalaria* intercropping systems, where a yield reduction of 40% was observed when both species were sown at the same time, and yield reduction was only 22%, when the legume species was established three weeks later (Fischler, 1997). However, with the delay in legume introduction time, less legume biomass was produced. The derived rice yield loss–legume biomass relationship basically comprises three different phases. The first phase represents high levels of legume biomass production combined with a complete or a nearly complete loss in rice grain yield. This was only found with early introduction of a competitive legume. A second phase represents a 'sensitive phase', corresponding to the linear phase of the logistic function. In that phase, a slight advancement of the sowing date of the legume results in a considerable increase in yield loss of the rice crop. For farmers, however, these two phases are not of interest, since yield loss in rice will be too high. The third phase encompasses the relationship between rice yield loss and legume biomass at low levels of yield reduction in rice. To obtain these low levels of yield loss, the competitive *C. cajan* had to be introduced 10-14 days later than the weakly competitive *S. hamata*. Still, introduction of *C. cajan* led to higher amounts of legume biomass for comparable rice yield losses. Rice cultivar V4, classified as a competitive cultivar against weeds, seemed to tolerate the presence of the legumes better than did WAB56-50. These results show that selection of the intercrop components establishes the range of potential outcomes of an intercropping system. Setting the relative introduction time of the legume then determines the actual result.

In Chapter 5, the eco-physiological model INTERCOM was parameterized and validated using two years of experimentation. Results indicated that the monoculture model for *C. cajan* was more robust because the parameterized model could be used for simulation of growth at different sowing dates (14, 28, 56 DAS) using stable parameters across years. Growth of *S. hamata*, however, was variable and the model parameters needed adaptation to simulate legume biomass adequately at the different sowing dates by introducing year-specific data. In competition with rice a shading index was introduced and a lower boundary of the leaf area density function was set to improve competitiveness of *S. hamata* as the model underestimated biomass production in mixture. This study showed that plant morphological processes are often not stable when plants experience sub-optimal growth conditions, which was the case for *S. hamata*. This species had a slow growth rate and, therefore, grew continuously underneath the rice canopy throughout the entire growing period. Adaptation of plants to shading and its consequences for crop–weed interactions were analysed in maize–weed competition studies (Cavero *et al.*, 2000). Dingkuhn and Kropff (1996) observed that N-limitation in rice affects partitioning of dry matter to shoot and root as well as the fraction of assimilates in the leaves.

To satisfy the double objective of accumulating sufficient legume biomass and at the same time minimize competition effects of the cover crops on rice, an analysis of the complex interaction of the rice–cover crop relay system was conducted in Chapter 6. A descriptive model was used to summarize and analyse the results of a mechanistic simulation model of the intercropping system under study, a principle earlier applied for a leek-celery intercropping system (Baumann, 2001). Given a certain yield loss in rice, identical amounts of legume biomass at rice maturity were obtained, irrespective of the use of a competitive or a less competitive legume species. This could be explained as a direct result of competition between rice cultivars and legume species, where the capture and utilization of resources by one crop is at the cost of the other crop. The competitive ability of the two intercrop components largely determines the time of legume establishment required for obtaining a specific yield reduction in rice. At the same time, this moment of introduction will determine the physiological age of the cover crop at rice maturity. This study indicated that in relay intercropping of rice and cover crops, the physiological age of the cover crop at rice maturity is important to achieve significant recovery of the species. *C. cajan* was able to increase biomass more rapidly than *S. hamata* after rice maturity at the same yield loss because it was sown later and thus younger. The poor performance of *S. hamata* in the period following rice maturity was attributed to the difference in phenology, combined with the short-duration characteristic of this species. Based on the gained insight in the rice–legume intercropping system in the savanna zone of West Africa, it can be concluded that this system would benefit most from rapid-growing, drought-tolerant legume species.

Relay cropping systems are the most widely used cropping systems in food production in developing countries. Farmers generally find a good balance between the crops to maximize their production. In the rice–cover crop systems, although no direct benefit is obtained from the legume species, it is generally suggested that the cover crops accumulate large amounts of shoot biomass at rice maturity for the survival of the species during the dry season. This study demonstrated that biomass accumulation in relay systems depends on the combined effects of the competitive ability of the cover crop species and the rice cultivar, and the relative sowing time of the cover crop. A further analysis of this system suggested that options for improving legume biomass production in upland rice-legume intercropping systems in the savanna zone of West Africa should strongly focus on maximizing legume biomass production in the period following rice maturity. The amount of residual soil moisture determines the length of this growing period. The modelling approach developed in this thesis provided a better understanding of the system and resulted in clear recommendations for further improvement.

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Summary

Upland rice in West Africa is mainly cultivated in rotation with extended periods of natural fallow. Demographic pressure and land shortage are leading to increasingly shorter fallow periods which, in turn, result in declining soil fertility, increased weed infestation and lower yields. A promising option for stabilizing such land-use is to improve the quality of the fallow vegetation through the use of nitrogen-fixing legume cover crops. As nitrogen (N) is the most deficient nutrient in upland soils in West Africa, the biologically fixed N is an important aspect of this system, as it helps meeting the N-demand of subsequent crops. Sequential cropping of sole legumes with the main crop was investigated in three agro-ecological zones of Ivory Coast, which encompassed the Guinea savanna zone in the North, the forest zone in the South and the forest-savanna transition – or derived savanna – zone in between. In this study, various legumes and different residue management practices were compared. Special attention was given to N-accumulation and weed suppression of the legumes and the productivity of the rice crop following the legumes. For the savanna zones with a unimodal rainfall pattern, combining the growth of a rice crop with an improved short-season fallow necessitates relay establishment of cover crops into the rice crop. In the second part of this study competitive relations within such relay-cropping systems of rice and legumes were more closely investigated, and suggestions for further improvement of this system were made.

In Chapter 2, four or five pre-selected legume species were grown in each of the three agro-ecological zones under study. The effects of the legume species on fallow biomass, N-accumulation, weed biomass, the yield response of upland rice and a range of soil physical and chemical parameters were evaluated. Furthermore, the effect of different residue management practices was determined. Replacing the natural fallow in short-fallow rotation systems by legumes increased yield of subsequent upland rice crops in forest as well as in savanna agro-ecological zones and tended to reduce weed growth. Rice grain yield was about 20 to 30% higher irrespective of fallow management. In the savanna environments, residue incorporation was superior to farmers' practice of residue removal. Increases in rice yield were related to the amount of fallow N returned to the soil. In the forest zone, farmers' practice of residue burning not only produced highest yields but also resulted in lowest weed biomass. Residue mulching generally hindered rice crop establishment and tended to increase termite damage on rice roots. No short-term effects of fallow species or residue management on soil parameters, like pH, C:N ratio and penetration resistance were apparent.

In Chapter 3, biomass production and N-accumulation of six different cover legumes was

determined in monoculture. In addition, various characteristics indicative for competitive ability were determined, as this trait is particularly relevant when plants are used in intercropping systems. A wide variability in productivity and competitive ability of the selected legume species was observed. Based on morpho-physiological characteristics, *Crotalaria juncea*, *Cajanus cajan* and the short-lived *Mucuna pruriens* were identified as potentially most competitive compared to *Aeschynomene histrix* and *Stylosanthes hamata*. Based on these results, two contrasting cover crop species (*C. cajan* and *S. hamata*) were chosen as intercrop for a relay cropping system with two rice cultivars (WAB56-50 and V4) that differed in competitiveness.

In two years of experimentation, cover crops were introduced into the rice crop between 0 to 84 days after rice sowing (DARS) (Chapter 4). Logistic functions adequately described rice grain yield, final rice biomass and legume biomass at one week after rice harvest as a function of relative sowing date of the legume. Rice biomass and grain yield were significantly ($p<0.001$) reduced when legumes were established between 0 and 28 DARS. Beyond 56 DARS no significant competition effects on rice were observed. At these late sowing dates only relatively small amounts of legume biomass were obtained, due to a combined effect of a more severe competition by the rice crop and a shorter growing period. If introduced at the same time, *C. cajan* produced significantly higher amounts of biomass than *S. hamata*, but this was at the cost of rice grain yield. To allow a good comparison of the performance of the two legume species, rice grain yield loss and legume biomass were directly related. The derived yield loss–legume biomass relationship showed that *C. cajan* was the most appropriate legume species of the two, as it produced reasonable amounts of biomass at low levels of rice grain yield loss. The choice of rice cultivar seemed far less important for the performance of the relay intercropping system.

Although descriptive models could reasonably quantify the outcome of relay-intercropping rice and cover crops, a better understanding of the system was required to identify options for improvement. An eco-physiological model for interplant competition was used for that purpose. In Chapter 5, the model was parameterized and calibrated for the two legume species in monoculture. Model performance was evaluated with independent experimental data for monoculture crops sown at different dates. Results indicated that the performance of the model still needs to be further enhanced, as some processes could not be adequately simulated for *S. hamata*. This was particularly the case for environmental effects on morpho-physiological traits such as early leaf area development, dry matter partitioning and leaf thickness. A better understanding of these processes followed by model improvement will be necessary to enable simulation of growth under a wide range of conditions.

The monoculture models were combined into the competition model INTERCOM for simulation of the relay intercropping system of rice with a leguminous cover crop (Chapter 6). The performance of the competition model was evaluated using data from two years of experimentation. Model analysis revealed, that differences in produced legume biomass at a specified level of rice yield loss were mainly created in the growth period following rice maturity. In this period water supply completely relies on the availability of water in the soil profile, restricting the duration of this additional growth period to an estimated average of 3-4 weeks. The inferior performance of *S. hamata* was indirectly caused by its weak competitiveness, which required a relatively early introduction of this legume. This early introduction combined with the short growth duration of this species prevented a rapid leaf canopy development after rice harvest, resulting in the relatively poor biomass production. This analysis was done by simulating legume biomass both at rice maturity and at three weeks thereafter, corresponding to a conservative estimate of the length of the period in which water availability still allows for a period of extended growth. It was concluded that options to improve legume biomass production in upland rice–legume intercropping systems in the savanna zone of West Africa should strongly focus on maximization of legume biomass production in the period following rice maturity, when residual soil moisture still allows for additional growth. The use of rapidly growing, competitive, legume species that also possess a certain level of drought-tolerance is considered a suitable option. Using short-duration rice cultivars that would extend the rice-free period is another option that deserves further investigation.

In Chapter 7, all the results presented in the previous Chapters are integrated and further discussed. In this study main focus was put on the contribution of cover crops in maintaining soil fertility and productivity of upland rice. Other advantages of integrating cover crops in cropping systems comprise the possibility to introduce minimum or no-till systems, to control weeds, to reduce the negative side effects of heavy rainfall on surface erosion and to serve as fodder banks for animals. Consequently, the choice of legume species should not only fit the cropping system, but should also meet the production objectives of the farmer. The current study revealed that cover crops as a short fallow and the management practices of the residue must be considered within the farming system in which they are cultivated. A successful design of a relay system of upland rice with cover crops should be based on the competitive ability of the components, which in turn will determine the optimum sowing time of the cover crop. The attainable legume biomass will be achieved essentially after rice harvest.

Résumé

Le riz de plateau en Afrique de l'Ouest est essentiellement cultivé en rotation avec des périodes prolongées de jachère naturelle. La pression démographique et la pénurie des terres conduisent à des périodes de jachère de plus en plus courtes, qui en retour, provoquent une baisse de fertilité des sols, une augmentation de l'infestation par les mauvaises herbes et une réduction des rendements. Une des options prometteuses de la stabilisation d'une telle utilisation des terres, est d'améliorer la qualité de la végétation de la jachère par l'emploi des légumineuses de couverture fixatrice d'azote. L'azote fixée biologiquement, qui est libérée pendant la décomposition des résidus, peut réduire considérablement les besoins en engrais azoté d'une récolte subséquente. L'azote constitue l'élément le plus déficient dans les terres de plateau en Afrique de l'Ouest. Les autres avantages de l'intégration des plantes de couverture dans les systèmes de culture comprennent la possibilité de semer dans le paillis mort ou vivant avec un travail minimum du sol ou en zéro labour, la conservation en eau du sol pendant la culture suivante, le contrôle des mauvaises herbes, la réduction des effets secondaires négatifs des lourdes précipitations sur l'érosion de surface et l'utilisation de ces plantes de couverture comme stock de fourrage pour des animaux. Donc, le choix d'espèces des légumineuses doit être judicieusement fait afin d'adapter celles-ci aux systèmes de culture et aux objectifs de production des agriculteurs.

Dans le Chapitre 2, une gamme de quatre à cinq espèces de légumineuses a été sélectionnée dans trois zones agroécologiques sur la base de leur taux d'accumulation en N, leur capacité à supprimer les mauvaises herbes et leur survie en période sèche. Les effets des espèces de légumineuses et de la jachère naturelle ainsi que ceux d'un certain nombre de pratiques de gestion des résidus sur la biomasse de jachère, l'accumulation en N, la biomasse des mauvaises herbes, la réponse du rendement du riz de plateau et des caractéristiques chimiques et physiques ont été évalués dans toutes les trois zones agroécologiques. Remplacer les repousses de la jachère naturelle dans un système de rotation de courte durée par des espèces de légumineuses augmente les rendements du riz de plateau dans la zone de forêt ainsi que dans la zone agroécologique de savane et tendrait à réduire la croissance des mauvaises herbes. Indépendamment de la gestion de la jachère, le rendement grain en riz est à peut près de 20 à 30% supérieur au témoin. Dans l'environnement de savane, l'incorporation des résidus était supérieure à la pratique des paysans qui consiste à exporter les résidus. Les accroissements de rendement riz sont dus à la quantité de N retournée au sol. Dans la zone forestière, la pratique des paysans de brûlis des résidus donne non seulement les rendements les plus élevés, mais aussi résulte à la plus basse biomasse des mauvaises herbes. Le paillage des résidus généralement entrave l'établissement du riz et tend à augmenter les dommages causés par les termites sur les racines de riz. Aucun effet à court terme des espèces de légumineuses ou de la gestion des résidus sur les paramètres physiques ou chimiques du sol n'étaient apparents.

Dans le Chapitre 3, la production de biomasse et l'accumulation d'azote de six différentes légumineuses de couverture ont été déterminées en monoculture. En plus, diverses caractéristiques physiologiques, morphologiques et phenologiques qui indiqueraient leur aptitude potentielle à la compétition ont été déterminées. Une large variabilité en productivité et en aptitude à la compétition des espèces de légumineuses sélectionnées qui pourraient intégrer les systèmes de culture de riz de plateau ont été identifiées. Sur la base des caractéristiques morpho-physiologiques, *Crotalaria juncea*, *Cajanus cajan* et *Mucuna pruriens* de cycle court ont été identifiés comme potentiellement plus compétitifs comparés à *Aeschynomene histrix* et *Stylosanthes hamata*. En conséquence, pour concevoir un système de culture relais avec le riz, on peut s'attendre qu'une période optimum spécifique d'introduction des légumineuses existe pour chaque combinaison légumineuse–riz. Les résultats indiquent que le temps d'introduction des légumineuses est aussi bien un paramètre important dans les systèmes de culture relais. Sur la base de ces résultats deux espèces contrastant de plantes de couverture, *Cajanus cajan* et *Stylosanthes hamata* ont été sélectionnées comme intercrop pour une culture relais avec deux cultivars de riz (WAB56-50 et V4) de compétitivité différente.

Dans le Chapitre 4, une fonction logistique a été utilisée pour décrire, le rendement en grain du riz, la biomasse finale du riz et la biomasse des légumineuses à une semaine après la récolte riz en fonction de la date de semis des légumineuses. La biomasse du riz et les rendements grain étaient considérablement réduits ($p<0.001$) quand les légumineuses étaient semées entre 0 et 28 jours après semis du riz (JASR). Au-delà de 56 JASR aucun effet significatif de la compétition des légumineuses sur le riz n'a été observé. A ces dates de semis tardifs, seules relativement de faibles biomasses de légumineuse étaient obtenues, à cause de l'effet combiné d'une compétition plus sévère par le riz et d'une période de croissance plus courte des légumineuses. La relation pertes de rendement en riz – quantité de biomasse de légumineuses a montré que *C. cajan* était l'espèce de légumineuse la plus appropriée dans cette étude qui peut convenir à un système de culture relais avec le riz de plateau, parce que des quantités raisonnables de biomasse étaient produites pour de bas niveaux de perte de rendement en grain de riz.
Bien que des modèles descriptifs peuvent raisonnablement quantifier les résultats de

culture relais de riz et de légumineuses de couverture, une meilleure compréhension du mécanisme était requise. A cet effet, un modèle éco-physiologique pour la compétition entre les plantes a été utilisé.

Dans le Chapitre 5, le modèle a été paramétrisé et calibré pour les deux espèces de légumineuses cultivées en monoculture. La performance du modèle a été évaluée avec des données expérimentales indépendantes obtenues avec des espèces semées en monoculture à différentes dates. Les résultats indiquent que la performance du modèle peut être améliorée davantage parce que certains processus n'ont pas été simulés de façon adéquate pour une des espèces. Il a été observé que cette amélioration du modèle serait nécessaire pour expliquer les effets de l'environnement sur des traits tels que la surface foliaire spécifique (SLA), la répartition de la matière sèche et le taux de croissance relative des feuilles (RGRL) pour permettre la simulation de la croissance sous une large gamme de conditions, particulièrement pour *S. hamata*.

Dans le Chapitre 6, les modèles de croissance des plants en monoculture ont été combinés dans le modèle de compétition INTERCOM pour la simulation de la culture relais des plantes de couverture avec le riz. La performance du modèle de compétition a été aussi évaluée avec des données expérimentales sur deux années. L'analyse des résultats du modèle révèle que les différences de production de biomasse des légumineuses à un niveau précis de perte de rendement en riz apparaît essentiellement pendant la période de croissance suivant la maturité du riz, qui est limitée par la disponibilité en eau et qui généralement dure 3-4 semaines. La performance faible de *S. hamata* est indirectement causée par sa compétitivité faible, qui nécessite un semis relativement précoce de cette légumineuse. La combinaison semis précoce et courte durée de croissance de cette espèce empêche un développement rapide de la surface foliaire après la récolte du riz, résultant en une production de biomasse relativement faible. Cette analyse a été faite en simulant la biomasse des légumineuses à la fois à la maturité du riz et trois semaines plus tard, ce qui correspond à une estimation raisonnable de la longueur de la période pendant laquelle les disponibilités en eau permettent encore une période de croissance additionnelle. Il a été conclu que les options proposées pour améliorer la production en biomasse des légumineuses dans un système d'association avec le riz de plateau dans la zone savane de l'Afrique de l'Ouest mettent l'accent sur la maximisation de la production de biomasse des légumineuses pendant la période suivant la maturité du riz, quand l'humidité résiduelle du sol permet encore une croissance supplémentaire.

Dans le Chapitre 7, tous les résultats présentés dans les chapitres précédents sont intégrés et discutés davantage. Les plantes de couverture utilisées comme jachères de courte durée et les pratiques de gestion des résidus doivent être considérées dans le système de culture dans lequel ils sont cultivés. La conception d'un dispositif performant de système de culture relais des plantes de couverture avec le riz de plateau devra se baser sur l'aptitude à la compétition des différentes composantes en association, qui en retour déterminera la période optimum de semis des plantes de couverture. La quantité de biomasse qu'on peut obtenir sera réalisée essentiellement après la récolte du riz.

Samenvatting

In West Afrika wordt rijst voornamelijk verbouwd in rotatie met lange 'groene' braakperiodes. Deze worden steeds korter vanwege de toenemende bevolkingsdruk en een tekort aan grond. Kortere braak resulteert in een afnemende bodemvruchtbaarheid, een toename van de onkruiddruk en afnemende gewasopbrengsten. Een veelbelovende methode om de productiviteit en de kwaliteit van de natuurlijke vegetatie in de braakperiode te verbeteren is het gebruik van vlinderbloemige groenbemesters. De biologisch gebonden stikstof (N), die weer vrijkomt door mineralisatie van het organisch materiaal, voorziet deels in de N behoefte van het volgende (rijst)gewas in de rotatie. Dat is van belang, omdat in West Afrika stikstof de belangrijkste groeibeperkende factor voor de droge rijstteelt is. De verbouw van groenbemesters in rotatie met rijst werd onderzocht in drie agro-ecologische zones in Ivoorkust, te weten de Guinea savannezone in het Noorden, de boszone in het Zuiden en de overgangszone daar tussenin. Verschillende vinderbloemige soorten en verschillende methoden om de braakvegetatie te bewerken werden vergeleken. Hierbij werd vooral gelet op stikstofophoping, onkruidonderdrukking en de opbrengst van het volggewas. Voor de savanne- en de overgangszone met één regenperiode, kunnen de verbouw van een rijstgewas en de verbetering van de braakvegetatie slechts gerealiseerd worden door de bodembedekker te introduceren tijdens de groei van het rijstgewas. Om deze reden zijn de concurrentieverhoudingen tussen rijst en vlinderbloemige aan een nadere analyse onderworpen, wat geleid heeft tot aanbevelingen voor verdere verbetering van dit systeem.

In Hoofdstuk 2 zijn op grond van een aantal eigenschappen (N ophoping, onkruidonderdrukkend vermogen, en mogelijkheid tot het overleven in het droge seizoen), voor elk van de drie agro-ecologische zones, vier tot vijf vlinderbloemige soorten geselecteerd. De effecten van deze vlinderbloemigen op de biomassa van de braakvegetatie, de N ophoping, de onkruidbiomassa, de opbrengst van rijst en een groot aantal bodemfysische en -chemische eigenschappen zijn bepaald en vergeleken met de resultaten van een natuurlijke braak. Daarnaast werd het effect van de verwerking van de vegetatieresten op de opbrengst van de rijst onderzocht. Het vervangen van de natuurlijke vegetatie in rotaties met een korte braakperiode door vlinderbloemigen verhoogde de opbrengst van rijst en verminderde de onkruidgroei in alle drie de zones. De toename in rijstopbrengst was 20 tot 30%. In de savanne- en de overgangszone sorteerde het inwerken van de braakvegetatie meer effect dan de gangbare boerenpraktijk, waarin de resten van de braakvegetatie worden verwijderd. De toename in opbrengst was gecorreleerd met de hoeveelheid N die via de vegetatie werd ingebracht. In de boszone was de standaardpraktijk, waarbij de vegetatie wordt verbrand, superieur met betrekking tot het effect op rijstopbrengst en onkruidbiomassa. Het achterblijven van de vegetatie als strooisellaag belemmerde de vestiging van de rijstplanten en verhoogde de schade aan wortels door termieten. Zowel de verwerkingwijze van de vegetatieresten, als de keuze van de vlinderbloemige bleek geen aantoonbare invloed uit te oefenen op een brede reeks fysische en chemische bodemkenmerken, waaronder pH, C:N-ratio en penetratieweerstand.

In Hoofdstuk 3 zijn studies beschreven waarin de biomassatoename en N ophoping van zes verschillende vlinderbloemige soorten in monocultuur werd bepaald. Om de geschiktheid van de soorten voor gebruik als ondergroei in een rijstgewas te bepalen werden verder een aantal fysiologische, morfologische en fenologische karakteristieken, gerelateerd aan de concurrentiekracht van een soort, bepaald. Er werd een grote variabiliteit in deze eigenschappen waargenomen binnen de groep van soorten die was geselecteerd voor dit systeem. De soorten *Crotalaria juncea*, *Cajanus cajan* en *Mucuna pruriens* bleken meer concurrentiekrachtig te zijn dan *Aeschynomene histrix* en *Stylosanthes hamata*. Op basis van deze resultaten werd besloten om twee uiteenlopende soorten (*C. cajan* en *S. hamata*) te selecteren voor gebruik als ondergroei in twee rijstvariëteiten (WAB56-50 en V4), met een uiteenlopend concurrentievermogen. In experimenten werden de bodembedekkers op verschillende momenten, variërend van 0 tot 84 dagen na het zaaien van de rijst, aan het hoofdgewas toegevoegd (Hoofdstuk 4). De relatie tussen datum van introductie van de bodembedekker en de biomassa van de bodembedekker, rijstopbrengst en -biomassa bleken met een logistische curve goed te worden beschreven. Rijstopbrengst en -biomassa werden significant gereduceerd als de vlinderbloemigen werden geïntroduceerd tussen 0 en 28 dagen na het zaaien van de rijst. Introducties later dan 56 dagen leidden niet tot significante opbrengstreducties in het rijstgewas. Bij dit soort late introducties was de biomassa van de vlinderbloemigen zeer laag door de concurrentiekracht van het rijstgewas en door het korte groeiseizoen. Bij introductie op hetzelfde moment bleek *C. cajan* beduidend meer biomassa te produceren dan *S. hamata*, maar dit ging wel ten koste van de opbrengst van het rijstgewas. Voor een goede vergelijking tussen de twee vlinderbloemigen werden daarom opbrengstverlies en biomassa van de vlinderbloemigen rechtstreeks tegen elkaar uitgezet. Uit deze analyse kwam naar voren dat uitgaande van een gering opbrengstverlies in rijst de concurrentiekrachtige *C. cajan* duidelijk meer biomassa wist te produceren. De keuze van de rijstvariëteit bleek beduidend minder invloed te hebben op de resultaten van het systeem.

Hoewel logistische vergelijkingen de gevonden relaties goed beschreven was een beter inzicht in het systeem nodig teneinde de gevonden verschillen te kunnen verklaren en aanbevelingen voor verbetering van het systeem te formuleren. Een ecofysiologisch model voor de concurrentie tussen planten werd hiertoe geparameteriseerd en gecalibreerd voor de twee vlinderbloemige soorten in monoculturen (Hoofdstuk 5). Het model werd getest met onafhankelijke datasets waarbij monoculturen van de vlinderbloemigen op verschillende tijdstippen werden gezaaid. De resultaten gaven aan dat het model verbeterd dient te worden, omdat voor *S. hamata* sommige processen niet goed konden worden gesimuleerd. Vooral het effect van milieufactoren op het verloop van enkele morfo-fysiologische kenmerken, zoals de vroege bladoppervlakte-ontwikkeling, de droge stofverdeling en de bladdikte bleek nog onvoldoende begrepen.

In Hoofdstuk 6 werden de groeimodellen voor de vlinderbloemigen en de twee rijstrassen ingebouwd in het concurrentiemodel INTERCOM. Simulaties met dit model werden getest op basis van gegevens verzameld in twee veldproeven. Modelanalyse maakte duidelijk, dat verschillen in geproduceerde biomassa van de vlinderbloemigen vooral het gevolg waren van verschillen in de groei in de periode na de oogst van de rijst. Het gewas is in deze periode voor z'n watervoorziening volledig afhankelijk van restwater voorradig in het bodemprofiel, waardoor de lengte van deze groeiperiode gemiddeld genomen slechts 3-4 weken bedraagt. De lagere biomassa productie van *S. hamata* bij een gegeven opbrengstverlies bleek veroorzaakt te worden door de geringe concurrentiekracht van deze soort, waardoor een vroege onderzaai in de rijst nodig was. Deze vroege introductie gecombineerd met de korte groeiduur van de soort verhinderde een sterke bladgroei na oogst van de rijst, waardoor er relatief weinig biomassa werd geproduceerd. Op basis van deze modelanalyse werd geconcludeerd dat in de West Afrikaanse savanne inspanningen tot verbetering van het beschreven systeem vooral gericht moeten zijn op het maximaliseren van de biomassa productie van de vlinderbloemige in de korte periode na de oogst van het rijstgewas. Opties die hiervoor het meest in aanmerking lijken te komen zijn het gebruik van snelgroeiende en concurrentiekrachtige vlinderbloemigen, welke daarnaast over een zekere mate van droogt-tolerantie beschikken. Ook het gebruik van rijstrassen met een kortere ontwikkelingsduur verdient nader onderzoek.

In Hoofdstuk 7 zijn alle resultaten geïntegreerd en bediscussieerd. Bodembedekkers voor korte braakperiodes en de bewerking van de vegetatie bij de zaaibedbereiding voor het daaropvolgende seizoen moeten worden afgestemd op de doelstellingen van de boeren. In het beschreven onderzoek is vooral aandacht besteed aan de bijdrage van de groenbemesters aan het in stand houden van de bodemvruchtbaarheid en de productiviteit van de droge rijst. Andere voordelen van de integratie van bodembedekkers in de rotatie zijn: de mogelijkheid tot introductie van teeltsystemen met minimale of geen grondbewerking, de onderdrukking van onkruiden, het reduceren van erosie door zware regenval en de productie van veevoeder. Het is van belang deze aspecten in de keuze van de vlinderbloemige te betrekken. Een succesvol ontwerp voor een mengteeltsysteem van rijst en een groenbemester moet gebaseerd zijn op de concurrentiekracht van de soorten Het tijdstip van onderzaai van het vlinderbloemige gewas moet hierop afgestemd zijn; hetgeen betekent dat vlinderbloemigen met een zwakke concurrentie eerder gezaaid dienen te worden. Zonder noemenswaardige verliezen in rijstopbrengst bleek een biomassa van de braakvegetatie van *ca.* 4 ton droge stof haalbaar, waarbij aangetekend dat deze biomassa vooral geproduceerd werd in de korte groeiperiode na de oogst van de rijst. De studie maakt aannemelijk dat deze periode dan ook centraal zou moeten staan bij inspanningen gericht op een verdere verhoging van de biomassa productie van de braakvegetatie.

Curriculum vitae

Akanvou René Kouacou was born on October 1st 1959 in Ivory Coast. After completing basic and technical studies in Biochemistry and Microbiology, he was admitted at the University of Abidjan where he graduated in 1984 with a Maîtrise en Genetique. The same year, he was awarded a Government scholarship for graduate studies in the United States. In 1987 he graduated from West Virginia University with an MSc in Genetics and Developmental Biology. Back to Ivory Coast he started his professional carrier as a Research Scientist at the former Institut des Savanes (IDESSA) in Bouaké where he served as a cropping systems specialist in an FAO project. A year later, he was based at Ferkessedougou in the northern part of the country where he continued his work for 7 years. During that period, he attended several training courses on various aspects of agronomy and on technology transfer to farmers. He was also involved in regional network activities on cropping systems and sustainable food production. From 1995 to 2000, he served as member of the Steering Committee of the West and Central Africa Millet Network (ROCAFREMI). In 1996, a joint research activity was started that involved Wageningen University, the West Africa Rice Development Association (WARDA) and his home institute IDESSA. This offered him the opportunity to pursue a PhD study on improving fallow in upland rice cropping systems, of which this thesis is the final result. In 1998, the Centre National de Recherche Agronomique (CNRA) was created where he still maintains his position. Since 1999 his main focus has been on analysing and improving production systems in the moist savanna zone of Ivory Coast. Beside his professional carrier, he became member of the Junior Chamber International (JCI) since 1992.