Explorative Modelling of Development Opportunities and Challenges of Biofuel Production for Smallholders in Manica Province, Mozambique

By : Igor Milosavljević
September 2012
Supervisors: Gerrie van de Ven, Linus Franke
Plant Production Systems, Wageningen University and Research Center

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- Summary -

The current extent of dependence on fossil sources for energy needs will have to be reduced to address depleting stocks, serious environmental concerns, address adverse economic effects, and security considerations. Biomass, widespread and abundant, is a potential option to become a major source material for energy in the near future. With preferential productive conditions occurring in tropical countries, increased use of biofuels on a global scale may have developmental potential for rural areas of the developing world. This study examines possibilities for smallholder benefits from production of biofuel feedstock in Manica Province of Mozambique, an area with good agricultural conditions for feedstock production. The farm level model FARMSIM was used to examine intensification options for inclusion of biofuel feedstocks and income improvement from agricultural production. A representation of local practices was included in the field-level submodel FIELD: relay cropping, and a module tracking the chemical effects on soil following slash and burn of fallow. Socio-economic modules LabourSIM and FinanSIM were also included in FARMSIM to show socio-economic performance of the farm. FARMSIM was run for several scenarios involving different application of fertilizer in different amounts to maize, the staple crop, and soybean, biofuel feedstock crop, in a relay system and as a monoculture for one category of households of an identified typology, one type of identified soil. Results show that use of fertilizer increases household income when used for both maize and soybean cultivation and is more effective when used on a monoculture. In comparison, nutrient regimes from fallows are comparable and offer several advantages but require long periods of land use dedicated to fallow. Labour saving technologies seem a promising intensification option considering the low productivity of labour. Further use of this model should be conducted for other household types and for other soils in the region to identify differences in intensification strategies that can be employed to improve household income.

Preface

This masters thesis was formed as a part of the research within NWO's project *Biomass for fuel: Opportunity or threat to food and feed security, Case studies for farms in Brazil and Mozambique* (http://www.nwo.nl/nwohome.nsf/pages /NWOP_876G74_Eng) coordinated by M.K. van Ittersum of Wageningen University and Research Center. Data were collected by Wilson Leonardo, a PhD candidate of Wageningen University, for the NWO project. This work was supervised and proposed by Gerrie van de Ven. Linus Franke acted as supportive supervisor.

- 1 - Introduction -

Biofuel production has appeared in Manica. So far, it has taken the form of export-oriented plantation production initiated by foreign capital seeking financial return. On the other hand, smallholder feedstock production is considered pro-poor (Arndt et al., 2010) by offering rural smallholders larger returns on resources, which, through reinvestment in the productive process, could potentially serve as a *stepping-stone* for development. To examine the promise of this claim, an exploratory study has been conducted using a modelling approach.

1.1 – Introduction to Mozambique

Mozambique covers a land area of 786,380 km^2 (IBRD, 2012; Arndt et al., 2010) between 26° S to 10° S (Google Earth), containing a range of agro ecological conditions. The country's population was 23.9 million in 2011, of which 62% was rural (IBRD, 2012). Total population grew 2.3% in 2011, with 1.0% growth for the rural population in 2010 (IBRD, 2012). Density was 29.7 people per km^2 in 2010 (IBRD, 2012).

As Newitt (1995) contends, the modern territory is representative of the historical evolution of the region, with economic clusters of hub-points and their hinterlands largely respected. Trade from the interior would conflate on en-route regional centers and eventually into coastal entrepôts connecting Mozambique with the Indian Ocean and the wider world. The history of the land confined in the borders of modern Mozambique is one of coexistence in interaction with regional and international trade, small scale coercion, and influence.

The 20th century was one of turbulence for Mozambique. At its dawn, the Portuguese Crown sought coercive consolidation of a colony; in response, FRELIMO formed in 1962 seeking independence. Their success in 1974 was followed in three years by a brutal civil war. 1992 brought a fresh gasp of peace and the chance to construct a nation battered to a state of underdevelopment below the regional average for sub-Saharan Africa (IBRD, 2012).

Mozambique is considered a low income country by The World Bank with a GDP per capita PPP of $982 current international dollars in 2011 (IBRD, 2012). As of 2008, 60% of the population lived on $1.25 USD PPP or less, with 57% of rural population considered impoverished (IBRD, 2012). GDP per capita PPP has been growing strongly, averaging 5.1 % for the decade up to 2011 (IBRD, 2012). Poverty rates have been dropping.

As of 2009, 62.7% of total area is agricultural land, with little over a tenth, 6.4% of total land, is arable land (IBRD, 2012). In 2003, 80.5% of total employment was in the agricultural sector, 90% for women (IBRD, 2012). Value added from agriculture represented 32% of GDP, growing an average of 8.6% per year since 2001, 6.6% since 1992.

Agriculture has a pronounced dominance in national employment. It also is a means of sustenance for rural populations, typically poorer than their urban counterparts.

See FAOSTAT glossary for definitions of terms (FAO, 2012). For more history of Mozambique and Manica, see *appendix 2*.

1.2 – Biofuels

1.2.1 - Introduction to Biofuels

Industrialization's heavy forward movement has been fuelled by the burning of fossil fuels. Negative environmental consequences, as epitomized by global climate change, and inevitable physical limitations of supply are driving the desire for divergent diversification in the context of recent dire developments. Fossil fuel prices, driven by economic expansion of developing countries and geopolitical instability of major oil producers, have reached and maintained high price levels quivering with volatility. With these drivers unlikely to abate in the medium run, development of alternatives is economically and socially attractive. Biofuels are one such option; of a renewable nature, supply structure constructs offer possibilities to sequester and cycle carbon in a shorter time scale (Pacala et al., 2004), and galvanize rural development (Arndt et al., 2010; de Vries et al., 2012; Schut et al., 2010).

In a broad sense, biofuels are any energy-containing material which offers easy release of energy, made from materials of biological origin (Demirbas, 2009). The term as it is used commonly nowadays refers to liquid forms produced by intentionally transforming biological material using biochemical and thermochemical conversion technologies (Belat, 2009) to replace petroleum derived liquid fuels. First generation biofuels are technologically simple and already being made. Bioethanol is produced by fermenting sugars into ethanol. Biodiesel is produced from oily substances like vegetable oil or animal fat through transesterification into fatty acid methyl esters. The previous is a replacement for petroleum and the latter is a replacement for diesel, both often being blended with their corresponding substance. Second generation biofuels use lignocellulosic feedstocks, as of yet uneconomic for production (Naik, 2010). Third and fourth generation fuels are also being developed.

Bioethanol trade volumes swelled from 1 billion liters in 2000 to 7 billion liters in 2007 (Oosterveer, 2010). Although there is a difference in regulations between consumer markets that may constitute technical barriers to trade, Oosterveer et al. (2010) conclude that market access is not a major obstacle for most poor tropical countries. The International Energy Agency (2011) projects biofuel supply tripling by 2035.

Under tropical conditions, production of biomass can be cost efficient representing a major comparative advantage in global trade (Oosterveer et al., 2010). Africa has a large part of its vast landmass in the tropics, and with proper infrastructure and adequate policies (Oosterveer et al., 2010), the emerging biofuel trade can offer tropical countries the opportunity to develop an industrial export industry fed by agricultural production.

The rise of biofuels has encountered criticism for adverse effects it can have for the poor and for sustainability. In the case of plantation production, encroachment on smallholder resources (land, water, etc.) have been reported (Alonso, 2012; Oakland Institute, 2011; Ribeiro et al. 2009). First generation biofuels mostly use food crops as feedstock and have been linked to rising commodity prices (Babcock, 2011; Ecofys, 2011). Greenhouse gas emissions are lower if cropping does not replace virgin/unused land or pastures. As such, biofuel production is not without danger. High-profile investments into biofuel plantations have the danger of being unsustainable and socially undesirable, like other market oriented agricultural investments (van der Ploeg, 1990), particularly if resources are limited.

The rise of biofuels represents an opportunity on a large-scale with rewards and perils for economic development in the tropics.

1.2.2 –Biofuels in Mozambique

Within Africa, Mozambique is in certain respects well positioned to produce biofuel for the world market: an abundance of relatively fertile lands of low population density, available water, and abundant labour (Arndt et al., 2010; Jumbe, 2009; Batidzirai et al., 2006). It has two deepwater ports, one in Maputo and one in Beira (see *Figure 1*) (Schut et al., 2010).

Mozambique's exports have preferential market access to two major markets and the world's largest ethanol importers, the EU and the USA, and to the regional market through the Southern African Development Community (Schut et al., 2010). Biofuel production in Mozambique is profitable for world oil prices over $70 USD per barrel (Ecoenergy, 2008). IEA (2011) predicts that continued demand and supply pressures on prices *confirm the end of cheap oil*. Nonetheless, volatility must not be forgotten; in the 2008 global recession, crude oil submerged below this threshold in late 2008, not to surpass it till mid 2009 (Tradingcharts.com, 2012) with the consequence of a pause in biofuel investments in Mozambique (Schut et al., 2010).

The Government of Mozambique (2009) has recognized the country's suitability for biofuel production in the National Biofuel Policy and Strategy, an outline of the aims (e.g. sustainability, promotion of rural socio-economic development, development of local biofuels market) and limitations (e.g. feedstocks allowed for processing) of the nascent national biofuel industry.

The industry is supported by construction and modernization of infrastructure (Schut et al. 2010). With all land in Mozambique owned by the government, land concessions have been coordinated with investments to allow biofuel investors easier land access. Regulations have been approved by Mozambique's Council of Ministers for mandatory blends of biofuels with petroleum (1:9) and diesel (3:97) (Allafrica.com, 2011). Blending will benefit macroeconomic considerations by reducing the national trade deficit, USD $500 million of which comes from fossil fuel imports (Allafrica.com, 2011).

So far, Mozambique has attracted large biofuel plantation investments of sugar cane and Jatropha amounting to US$1.3 billion as of 2010 (Schut et al., 2010), unmatched by smallholders. Structural development to support the manifestation of a biofuel market is necessary: e.g. fostering market connectivity, agronomic support outreach, establishment of quality parameters, etc. Recent optimism for Jatropha witnessed a failed campaign to promote smallholder cultivation of the crop. Bad seeds with poor germination, failure to follow-up by authorities, lack of agronomic knowledge and its dissemination amongst farmers, poor understanding of smallholder farming systems, and lack of a market structure for Jatropha lead to cessation of production and dissipation of farmer's enthusiasm (pers. comm.: Leonardo; Schut et al., 2010).

1.3 – Smallholder Agriculture in Manica Province

1.3.1 – Farm Layout

Land is bountiful for smallholders in Manica. A farm has both cultivated and fallow areas chronologically non-static; farmers abandon cultivated areas when yields drop and move cropping to cleared fallow. Differing lengths of fallows were reported by farmers during interviews, from 4-8 years. They use sensory indications (e.g. "soft on the feet", colour of the topsoil) of soil organic matter build up to judge when the fallow is ripe for cultivation again.

To switch from fallow vegetation to cropping, slash and burn is used. It is an accessible, economical and efficient tool (pers. comm.: Leffelaar) not requiring more than a machete. The process is similar throughout the world and in different tropical forest ecosystems (pers. comm.: Janssen) (see: Jaramillo et al., 2003; Hughes et al., 1999; Kaufman et al., 1995; van Reuler et al., 1996). Fallow vegetation is cut, left to dry, and incinerated on a hot, dry, and windy day, usually at midday when it is the hottest. In dry forests, the slashing occurs at the onset of the dry season, and the burning occurs at the end. Leaching can occur during the drying if there is precipitation as for wet or moist tropical forests (Mackensen et al., 1996).

1.3.2 – Cropping System

Smallholder agricultural systems in Manica focus on the production of staple foods for home consumption and the market. The farmers practice relay cropping to a large degree.

Maize plays a central role in the farming system as the staple crop. Farmers say sorghum was previously grown as a staple with maize sold as a cash crop, but that they prefer to eat maize. Maize enjoys high market desirability as it is preferred by rural and urban populations, with Manica's maize transported around Mozambique (pers. comm.: Leonardo). Maize is a reliable calorie source, 3700 kcal kg^{-1} (USDA, 2012), and a liquid commodity that, through market exchange, can be converted into a good (soap, oil, etc.) or service (medical expenses, school fees, etc.) with ease at a short physical distance. Maize is the first crop in a relay cropping system or largely the only one where relay cropping systems are not practiced. Maize is dried and ground down to flour, which is used to make porridge called xima. Average maize grain yields in Manica are 1400 kg ha^{-1}, with attainable yields at 5000-6500 kg ha^{-1} (Zavale et al., 2006).

Cash crops are grown as a relay crop after maize and are variable throughout the regions of Manica Province, such as sesame or sunflower, and are widespread as they represent an accessible source of cash for farmers.

Smallholders rely on manual labour for production, with some utilization of traction during land preparation. Seeds are planted randomly, not in rows, and are not managed according to best technical means (pers. comm.: Leonardo). Weeding is done with hoes or hands. Potentially, weeding could be done using traction; although the machinery is not locally available (pers. comm.: Leonardo), simple mechanical solutions exist. Production is rudimentary allowing for a great deal of improvement.

In field margins, pumpkins, cucumbers, melons, water melons, cassava, pigeon pea, okra, banana, papaya, guava, sugar cane, mango and avocado are grown to provide essential nutrients and vitamins for household diet; sometimes they are sold or, in the case of banana, brewed into alcoholic beverages for sale. Households have at least one fruit-bearing tree/plant in the homestead.

Vegetable production occurs on riverbanks with alluvial deposits; this land is scarcer and plots tend to be small, separated from the farm proper. Production is distinctly more intensive, hand irrigation and fertilizers are used, and steered towards supplying the market. Not every farmer is engaged in horticulture.

1.3.3 – Annual Cropping Schedule

Land preparation, sowing, first weeding, second weeding, and harvest are performed for a crop throughout the growing season. In a relay system there is some overlap between the two crops (e.g. weeding the first crop while sowing the second crop) allowing for better utilization of limited labour to some degree; indicatively, land does not need to be prepared twice on the same area.

The most critical activity during the cropping season is the first weeding of the first crop. It occurs during the initial stages of crop growth when crops are the most susceptible to damage from competition with weeds; ideally, it should be performed in a week although periods up to 3 weeks were found by Leonardo (in prep.). It also requires a hefty quantity of labour input.

1.3.4 – Off-Farm Activities

Off-farm activities supplant cash for smallholders. There is a wide range of them including:

- Reed mat production
- Baked sweets production
- Casual employment on other farms
- Employment out of the agricultural sector (including remittances)
- Charcoal production is a popular option, practiced by both wealthy and poor households. The popularity could be due to the fact that production occurs during the dry season when labour does not compete with agricultural production and the easy access of willing farmers to this arduous activity; as opposed to limited wage work opportunities.

As incomes, defined by access to cash, increase, dependence on the market for provision of goods and services does as well. For example, with housing, traditional housing use adobe bricks, clay-based plastering and straw roofs; richer farmers install tin roofs, purchased bricks, concrete plaster, windows, locks. Arzadun (pers. comm.: 2012) observed farmers moving away from food production as they are able to generate sufficient cash to purchase it on the market.

1.4 – Farm Typologies

A farm typology based on labour dynamics and farm size was developed by Leonardo (in prep.) for Manica Province based on data collection in 2 Manica villages, Dombe and Zembe (see 2.1). The farm typology includes:

- type 1, farms with a larger cultivated area that only hire in labour;
- type 2, farms with medium sized cultivated area which hire in and out labour;
- type 3a, farms with small cultivated areas that exchange labour through a traditional mechanism locally called *gumuè*;
- and type 3b, farms with small cultivated areas that only hire out their labour and are paid in cash or kind, mechanisms traditionally called *mutrakita*;

A quantitative summary is presented in *Table 1*.

Tab. 1. Household, cultivation, yield and labour input data for different Farm types in two study locations: Dombe and Zembe, Manica Province, Mozambique. Cash crop = sesame for Dombe and sunflower for Zembe.

Location	Dombe				Zembe			
Farm types	1	2	3a	3b	1	2	3a	3b
Household								
Size* (# of people)	10	7	5	6	6	7	7	6
Maize need (kg DM/yr)	860	880	650	880	720	830	770	650
Cultivated area (ha)								
Relay (maize / cash-crop)	0	.6	.4	.4	1.4	1	.7	.4
Maize monocrop	3.6	1.3	.9	.9	.7	.5	.1	.4
Cash crop monocrop	1.1	0	0	0	0	0	0	0
Yield (kg/ha)								
Maize	2500	1890	1770	1680	1720	1750	1280	1040
Cash crop**	1390	1170	1080	1000	240	240	170	250
Labour (hrs)								
Total*** for maize	3780	1690	1150	1640	1570	1590	1000	1010
Cash crop	660	170	130	140	240	200	170	130
Hired Labour	200	10	0	0	160	30	0	0

*Individuals, adults and children, residing on farm.

**Cash crop is sesame for Dombe and sunflower for Zembe.

***Total includes hired labour.

All farms are self-sufficient for calorie provision if production volumes are examined, not counting bad years (Leonardo, in prep.). However, the need for cash leads some households to sell maize and buy it back later on. Farm types 2, 3a, and 3b sell maize when the market is flush for seasonal low prices (3.5 Meticais) and purchase maize back later in the year when prices are higher due to inverse market conditions (9 Meticais). 1 Euro is approximately 38 Meticais in March, 2012.

The different farm households pursue different survival strategies. Farm type 1 is focused on agricultural production during the season while the other Farm types display diversified use of labour; e.g. employees of SunBiofuel Jatropha plantation near Manica Province's capital Chimoio are from Farm types 2 and 3 rather than Farm type 1.

Farm type 1 are the best-off farmers, with the best material standing, social position and with a better education (e.g. able to speak Portuguese, the language of schooling). Young farmers are not type 1 (see 4.1). Type 1 farmers are able and willing to take risk. They are the most interested in innovation, as evidenced by their enthusiasm for soybean not matched by other Farm types (pers. comm.: Leonardo). They represent potential pioneers, a conduit through which to encourage farm scale alterations in Manica deemed beneficial in an explorative study.

1.5 – Study Aims

Energy crops directly compete with food crops for farm resources and are thus entwined with food security considerations. The relationship need not be competitive; biofuels offer opportunity for larger financial surplus from smallholder production, possibly allowing exit from the low productivity of rudimentary production through investment and use of market-available inputs.

Modelling will allow for an ex-ante exploration of options for smallholder production intensification. At the field-scale, an exploration will be conducted to understand nutrient dynamics of relay cropping in the context of a fallow and cropping rotation, and compare them to intensification options. Intensification will be scaled up to the farm level to help identify entry points for future initiatives.

The methodology is intended to serve as a connection between modelling and the Manica context. The first part of the project consisted of literature review and a location visit for observation. The second part consisted of reshaping the FARMSIM model and calibrating component modules to reflect Manica's conditions. Finally, simulations derived from the aims of this thesis were conducted.

According to the study of biofuel feedstock by de Vries et al. (2010), maize is a poor performer in terms of resource use efficiency and environmental performance, soybean was considered intermediate and sweet sorghum performed moderately well. Out of these, only sweet sorghum is approved in Mozambique as a biofuel feedstock (Conselho de Ministros, 2009). Soybean is in high demand (Hanlon et al., 2012), has a high price, fixes N, and can alternately be used as food or feed. Sweet sorghum is familiar to farmers (pers. comm.: Leonardo). Soybean was used as a potential biofuel feedstock in this study, with the established framework representing a starting point for modelling in the *Biomass for Food, Feed or Fuel* project in Manica, Mozambique. Although sweet sorghum crop parameters were calibrated, it was not used (see 2.3.1).

The aim of this thesis is to adapt and use the FARMSIM modelling framework to compare and judge different options for intensification by:

-operationalizing the FIELD model for maize, soybean and sweet sorghum using available data from Wilson Leonardo,
-adapting the FIELD model to account for relay cropping,
-adapting the FARMSIM framework to account for the role of labour availability on farm,
-adapting the FARMSIM framework to observe effects on income,

for Farm type 1 in Manica province, Mozambique.

- 2 - Methodology -

2.1 – Introduction and Study Area

Manica Province is located in the central region of Mozambique, on the Manica plateau rising behind the coastal low veld of Sofala, up to the Chimanimani and Inyanga mountains. The climate is tropical, with rainfall between 1000 and 1200 mm per year (Maria et al., 2006). Manica is located on the crossroads between major roads to the African interior, Zambia and Zimbabwe, and the deepwater port of Beira. Data from Dombe (19°58’30”S, 33°23’52”E) and Zembe (19°16’16”S, 33°20’52”E) was used, see *Figure 1*; Matsinho (19°02’34”S, 33°24’29”E) was also visited during the field visits (Google Earth). The study area corresponds to medium elevation Manica Province, 200-1000m above sea level, as defined by Maria et al. (2006) and is probably predominated by Oxisol soil types. Manica, alongside Sofala and Maputo, is where biofuel investments in Mozambique have concentrated thus far, for bio-physical, technical and socio-economic reasons (see Schut et al., 2010).

Fig. 1. Manica Province (highlighted in red) showing the Provincial capital, Chimoio, and the study locations; the national capital and the nearby deepwater port, Beira, are shown on the larger map. Source: Google Earth. Edited with Adobe Photoshop CS3.

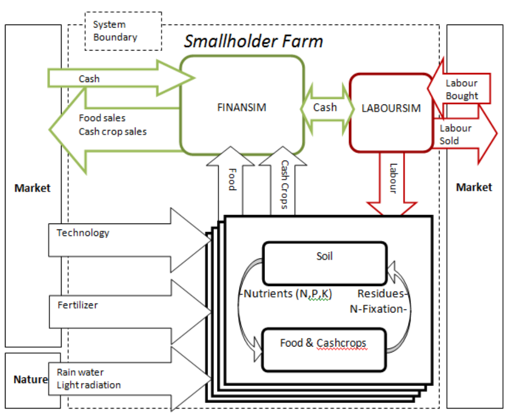


Fig.2. Diagram of a smallholder farm using NUANCES-FARMSIM framework for application in Manica, Mozambique.

2.2 – The FARMSIM Framework

The NUANCES-FARMSIM model combines several sub-level components on a farm and has been used for numerous case studies to examine farm scale strategic decisions. FARMSIM was used by van Wijk et al. (2009) applied to a case in Western Kenya: crop and soil module (FIELD) + manure module (HEAPSIM) + labour module (LABOURSIM) + livestock module (LIVSIM). This approach allows for explorative studies with interacting farm components (van Wijk et al., 2009). FARMSIM has been used to model farm scale decision processes (Tittonell et al. 2010; Giller et al. 2011; van Wijk et al. 2009).

FARMSIM was recommended by Gerrie van de Ven (see *Preface*) and adopted for this work. FIELD models soil-crop interaction. LabourSIM models labour flows and FinanSIM models financial flows. See *Figure 2*. Data from and consultation with Wilson Leonardo was used to construct a representative farm for Farm type 1 using average values.

Using the FARMSIM model, Farm type 1 in Dombe was run through the following scenarios:

- A relay setup with soybean as a relay crop (*Simulation 1*)
- A separation of maize and soybean, with both in a monoculture (*Simulation 2*)
- Use of fertilizer in a relay cropping system, at two different intensities: 12-24-12 NPK kg ha^{-1} and 24-48-12 NPK kg ha^{-1} (*Simulation 3 & Simulation 4*)
- Use of fertilizer for maize monoculture, with and without application on soybean monoculture, 12-24-12 NPK kg ha^{-1} for both crops (*Simulation 5 & Simulation 6*)
- Use of fertilizer in the relay setup: 12-24-12 NPK kg ha^{-1} applied at the beginning of the season (*Simulation 7*)
- Different areas for production of monocrop soybean without maize production, fertilized with 12-24-12 NPK kg ha^{-1} (*Commercial Simulation 1*, *Commercial Simulation 2*, *Commercial Simulation 3*)

Simulation 1 represents a baseline. It demonstrates a farm with a relay system. Simulation 1 has 1.1 ha under maize-soybean relay and 2.5 ha of maize monoculture, the average for Dombe Farm type 1. Simulations 2-6 separate maize and soybean into mono cultures, resulting in 3.6 ha of maize monoculture and 1.1 ha of soybean monoculture. Simulation 7 reintegrates the relay, as in Simulation 1. The Commercial Simulations (CS) do not cultivate maize. CS 1 dedicated all the area Simulations 2-6 cultivates to soybean production, 4.7 ha. CS 2 cultivates 2.6 ha of maize, the area at which 0 labour input is necessary. CS 3 is the midpoint between CS 1 and CS 2, with 3.7 ha of soybean monoculture.

A setup of a 5 year fallow followed by a 12 year cropping cycle was used to determine crop yields, an average was taken of the 12 years. Labour and fertilizer were assumed to be limitlessly available without price changing with demand. 50 kg of 12-24-12 blend NPK fertilizer was priced at 1400 Meticais. Labour was priced at 8 Meticais per hour. Soybean was priced at 15 Meticais kg^{-1}. Maize was priced at high, medium and low prices: 9, 6.5, 3.5 Meticais kg^{-1} respectively. Farm type 1 in Dombe sells 30% of its maize at the high price, and 70% at the medium price; it does not buy maize.

Please see below for module input parameters.

2.3 - FIELD

2.3.1 - Introduction to FIELD

FIELD QUEFTS version 1.0, translated into R (http://www.r-project.org/) by Mink Zijlstra was used; authors: Mark van Wijk, Linus Franke, and Mink Zijlstra.

FIELD is a *summary model* of the dynamic response of crops on per ha basis using few parameters to avoid the complexity of process-based models (Tittonel et al., 2010); this allows for integration into a farm scale model. The time step of FIELD is one season.

Flows of C, N and P between soil and crops are simulated through sequential seasons. The availability of K from soil to crops is calculated annually, but without a turnover to the next year. Three soil C pools of increasing resistance to decomposition are used: active organic matter C, stable organic matter C, and inert C; respectively. The inert C pool is disabled in the received version. Using predefined CN and CP ratios, soil N and soil P mineralization rates are calculated from changes in the C pools.

The model allows for additions of organic amendments, manure and mineral fertilizer. The first two contain labile and resistant fractions with different decomposition rates. Crop residues are included from the previous season, also having two pools. Residual crop roots have decompose at one rate. Different rates of leaching are taken into account for these pools.

Crop growth is a function of photosynthetically active radiation, water availability and available nutrients from the soil modelled in CropSIM. CropSIM in the current version is based on the QUEFTS algorithm developed by Janssen et al. (1990). Resource limited yield account for the interaction between the uptake of different nutrients and water.

The number of seasons can be changed. A period of 50 years was used initially for the FIELD level to examine fallow/cropping cycle, generalized to 5/12 years respectively in consultation with Wilson Leonardo. The first 12 year average yield values were used to scale up to the farm level.

The following data was available for calibration and validation of FIELD:

- Soil data from composite sampling of farms in Dombe and Zembe from Wilson Leonardo
- NPK response farm trials for maize in Dombe and Zembe from Wilson Leonardo
- Inoculation and PK response farm trials for soybean in Dombe and Zembe from Wilson Leonardo
- Farm trials for sweet sorghum in Dombe from Wilson Leonardo

FIELD's soil parameters were calibrated using the soil data and previous calibrations of FIELD obtained from Linus Franke and Mink Zijlstra.

Calibration of maize is well developed in FIELD (pers. comm.: Zijlstra). Maize crop parameters from FIELD versions received from Linus Franke and Mink Zijlstra were identical and performed better than an independent attempt at calibration. The received parameters were validated using the maize data.

Soybean parameters were adopted from the FIELD version received from Linus Franke and validated using Wilson Leonardo's and Linus Franke's soybean data from N2Africa station trials in Sussundenga.

Sweet sorghum was calibrated for the first time in FIELD using available data. Because its marketable product is juice, sweet sorghum in FIELD was calibrated for fresh weight rather than dry weight. Data were insufficient for validation (pers. comm.: Franke). Sweet sorghum was not used for this work.

Rainfall was set at 1000 mm for all years, variation in precipitation was not examined. The amount of rainfall available for the first crop was set at the relative value of .75 for all seasons. This can be changed in future calculations.

Linus Franke and Mink Zijlstra were consulted during calibration. For the FIELD parameter values used, see *appendix 2*, *Table 2* and *Table 3*.

Four soil types were recognized by Wilson Leonardo to be included in FIELD, two in Dombe and two in Zembe. They are distinguished through different soil properties parameters, see *Table 2*, without changes to soil properties, see *Appendix 2*. The parameters were judged to be a good representation of yield differences between location and soil types in consultation with Gerrie van de Ven and Wilson Leonardo.

Tab. 2. Soil properties parameters used in FIELD for four different soil types as found in Dombe and Zembe, Manica Province and the results of relay cropping maize followed by soybean found in FIELD.

	Dombe 1	Dombe 2	Zembe 1	Zembe 2
SOC (%)	1.58	1.41	1.41	1.35
pH (H2O)	5.57	5.67	5.78	5.91
Olsen P (mg kg^{-1})	46.16	18.38	25.36	2.48
Clay (%)	23.63	21.47	24.00	26.10
Silt (%)	33.29	14.74	12.48	12.30
Soil Type	Loam	Sandy clay loam	Sandy clay loam	Sandy clay loam
Soil Local Name	Djiho djetcha	Djiho	Djiho djetcha	Djiho
Maize Relay Yield*	2210 kg/ha	1830 kg/ha	1940 kg/ha	1570 kg/ha
Soybean Relay Yield*	430 kg/ha	340 kg/ha	360 kg/ha	340 kg/ha

*average of year 6 through 17 (after initialization), maize is the first crop in relay, soybean is the second.

Soil properties show the largest difference in silt content and Olsen P, with clay content, SOC and pH similar throughout. Differences in yields between soils, shown in *Table 2*, are explained by Olsen P differences. Soil Dombe 1 has been used for this work.

2.3.2 Additions to FIELD

Additions were made using Notepad++ v5.9.8 from (http://notepad-plus-plus.org/), RStudio 2.14.2 (http://rstudio.org/) and RTools 2.14 (http://cran.r-project.org/bin/windows/Rtools) on Windows Vista Home Premium operating system.

Relay Cropping

FIELD was adapted to allow for relay cropping as practiced in Manica province. A second crop was added within the one season time step. Decomposition calculations were left unaltered, with residues of the two crops combined for the next season.

In Manica, direct competition between crops is small. By the time the second crop germinates, the first crop is mature and does not take up nutrients or water from the soil. Maize is currently the first crop; the shading effect of dry maize on the successive crop is small. Parameters for mutual competition effects were created and parameterized at 0.

A sequential split between crops was added for soil mineralization of nutrients between the two crops: .75 for the first crop, .25 for the second crop loosely based on number of growing days. The proportion of mineralized nutrients is defined at the beginning of the run for all seasons.

During one loop with FIELD:

1. soil available nutrients are calculated for the first crop,
2. CROPSIM is run for the first crop,
3. the nutrient pools are updated,
4. CROPSIM is run for the second crop,
5. crop residues quantities and contents are determined for the next season.

At the end of a run in one season, the two crop residue dry matters are added together and their nutrient contents are averaged together with weights to account for their relative share. A second initial crop residue parameter set was added.

First Crop Leaf Decomposition

During the leaf senescence that coincides with grain filling, plant translocates nutrients from its leaves, roots and stems into grain (pers. comm.: Janssen). This translocation is not a complete process and nutrients remain in the non-grain organs of the plant (Hanway, 1962; Cliquet, 1990) and some can leak out (pers. comm.: Janssen). In the temporal construct of relay cropping, a certain portion of decomposition from the first crop should become available to the second crop.

To explore whether this amount would be significant, a simple equation was used in Microsoft Excel 97. The model assumed that first crop's leaves will decompose completely in the season to offer nutrients for the relay crop, though stems will not.

An equation on a per ha basis was derived from Ramachandra Prasad's (1992) equation for maize leaf biomass as a portion of total biomass, applicable from 15 days of age till maturity. A mathematically simpler version shown in *equation 1* was calibrated and validated by changing *B.plant* values, and adopted.

Equation 1.

$$B.leaves = 9998.06155 * e^{\ln(B.plant/Plants.ha)/1.25} / e^{\ln(1.645)/1.25}$$

Where:
B.leaves = *Biomass of leaves in dry matter kg* ha^{-1}
B.plant = *Biomass of plants in dry matter kg* ha^{-1}
Plant.ha = *amount of plant per ha*

Maize leaf biomass, and leaf N and P concentration, .43% and .28%, respectively come from averages of the control treatments of Wilson Leonardo's experimental data. K concentration was not available. Concentration multiplied with biomass yields equals total N and P available for the relay crop from the first crop's leaf biomass within a season. All N was assumed to be available. Available P as a portion of total P was calculated using an equation from Hanway (1962):

Equation 2.

$$P_{sol} = .67\,(P_{tot} - .03)$$

Where:
P_{sol} = *H_2O soluble P in maize leaves in kg* ha^{-1}
P_{tot} = *Total P of maize leaves in kg* ha^{-1}

A total maize biomass of 5600 kg ha^{-1}, with a leaf biomass of 1400 kg ha^{-1}, contains 5.6 kg ha^{-1} of N and 2.4 kg ha^{-1} of H_2O soluble P is made available for the relay crop, non-soluble P is kept in the crop residues. Decomposition of first-crop fine-roots was not considered.

Fallow and Burn Module

The fallow and burn modules are summary models which were integrated into the FARMSIM framework. Together, they aim to model (a) the changes in aboveground and belowground nutrients during fallow over time, FALLOWSIM; (b) model the effects on aboveground and belowground nutrients during slash and burn, BURNSIM.

The aboveground portion of the fallow module for growth uses a generalized logistic function (shown in *Figure 3*), or Richard's function (Richards, 1959), as modified by Hughes et al. (1999):

Equation 3.

$$TAGB_t = TAGB_{max} \left(1 - e^{(\alpha * t)}\right)^{\beta}$$

Where:

$TAGB_t$	*= **T**otal **A**bove**G**round **B**iomass at time t in dry matter kg ha^{-1}*
t	*= time in years since beginning of fallow*
$TAGB_{max}$	*= Total AboveGround Biomass when the system is at carrying capacity in dry matter kg ha^{-1}, alternatively this should approach the TAGB of a primary forest in the same ecosystem*
α	*=a relative parameter related to the rate of biomass accumulation per year*
β	*=a relative parameter relating to the inflection point of the curve*

Hughes et al. (1999) and Jepsen (2006) used a generalized logistic function to model secondary forest growth in wet tropical forests and deemed it representative; it has three general stages:

- An initial increasing growth rate granting a concave TAGB curve shape (not easily visible on *figure 3*) as vegetation is increasingly able to utilize spatial resources through vegetative expansion of canopy and roots;
- An inflection point is reached at which the rate of TAGB growth is at a maximum and the growth curve starts to increase at a slower rate, granting a convex TAGB curve shape; higher plant density results in root and canopy competition and species with slower growth rates begin to take over in succession;
- The curve levels off at $TAGB_{max}$, the climax vegetation that can be supported given spatial resources, also referred to as carrying capacity in ecology.

Equation 3 was chosen for simplicity, it has few variables but is still dynamic. A drawback is that parameters α and β are relative with no conceptual value unlike other versions of the generalized logistic function (Richards, 1959) or the Gompertz curve.

Wood elements are calculated by multiplying $TAGB_t$ by a ratio representing the portion of woody elements in total aboveground biomass; non-wood elements are a product of the TAGB and the said ratio subtract from one. Wood includes standing tree biomass, rotting wood, stumps and palms; non-wood includes leaves from standing trees and floor litter; as recorded by Kauffman et al. (1993) for dry tropical forests. The use of this distinction is based on the combustibility of the categories, with wood being more resistant; as used by Kauffman et al. (1993), Kauffman et al. (1995), Guild et al. (1998), Kauffman et al. (2003), and Kauffman et al. (2009).

Belowground biomass is a function of living aboveground biomass multiplied by a ratio, see *Figure 2*:

Equation 4.

$$TBGB_t = TAGB_t * TAGB^{ratio}{}_{alive} * P$$

Where:

$TBGB_t$	*= **T**otal **B**elow**G**round **B**iomass at time t in dry matter kg ha^{-1}*
$TAGB_t$	*= **T**otal **A**bove**G**round **B**iomass at time t in dry matter kg ha^{-1}*
$TAGB^{ratio}{}_{alive}$	*= Portion of **T**otal **A**bove**G**round **B**iomass that is part of living organisms*
t	*= time in years since beginning of fallow*
P	*= ratio of belowground biomass to aboveground biomass*

During the fallow stage, soil C pools in FIELD are kept at the value they had during their last cropping cycle.

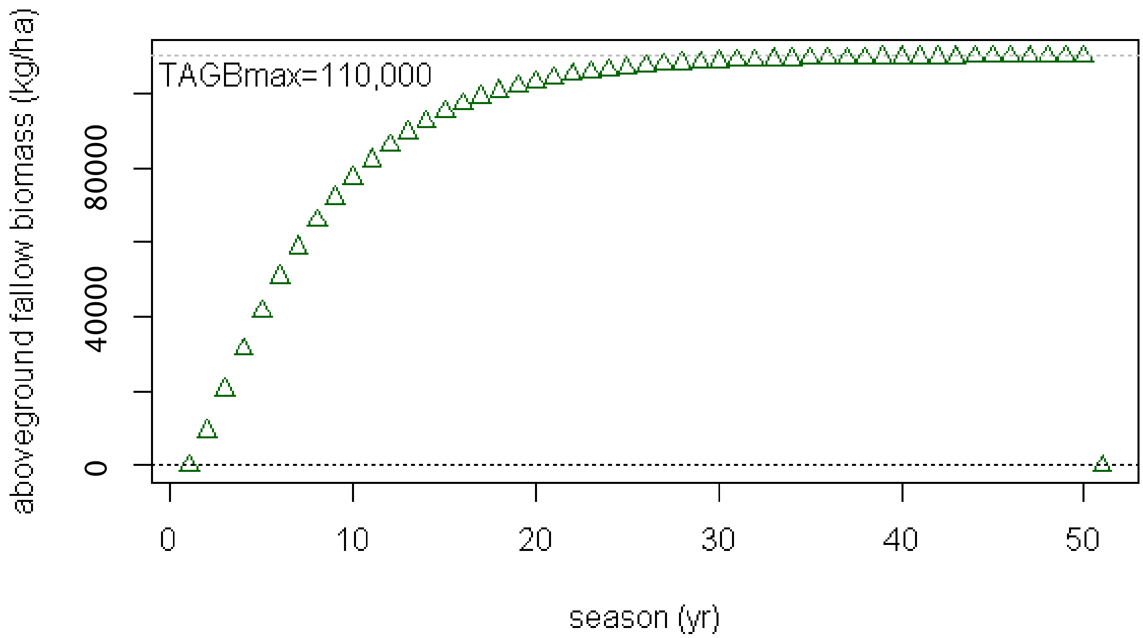


Fig. 3. Total aboveground fallow biomass modeled by *equation 3*, $TAGB_t = TAGB_{max} * (1 - e^{(\alpha * t)})^{\beta}$, with α = .16, β = 1.3, $TAGB_{max}$ = 110,000, as used in this work.

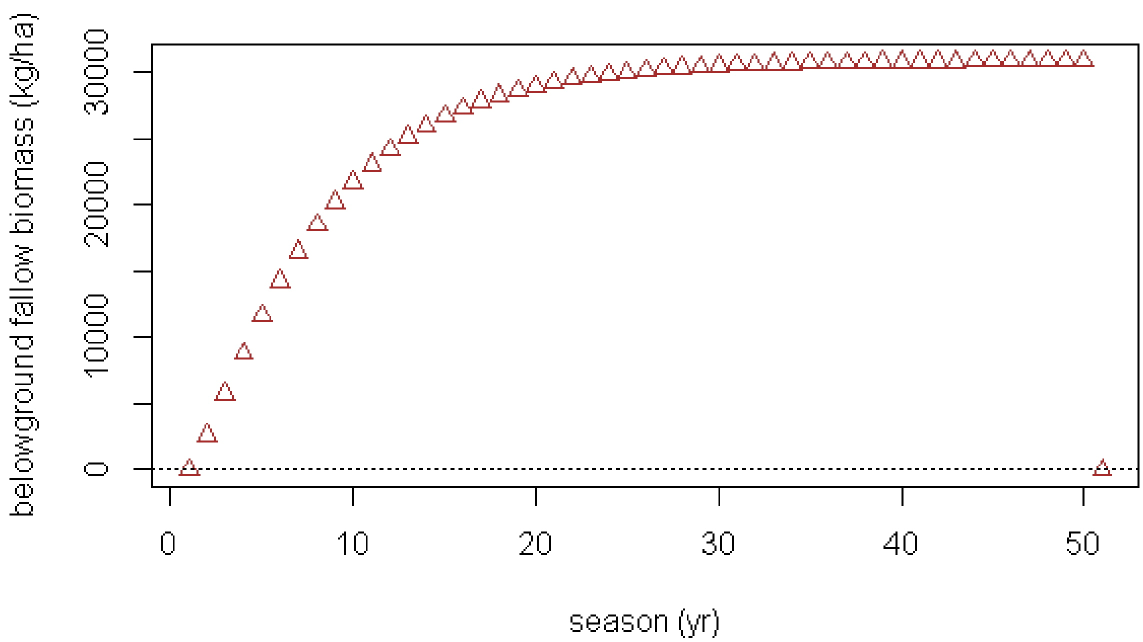


Fig. 4. Total belowground fallow biomass modeled by *equation 4*, $TBGB_t = TAGB_{max} * (1 - e^{(\alpha * t)})^{\beta} * TAGB^{ratio}_{alive} * P$, with α = .16, β = 1.3, $TAGB_{max}$ = 110,000, $TAGB^{ratio}_{alive}$ = .85, P = .33, as used in this work.

The model was parameterized from literature. Because of comparative paucity of data for tropical dry forests compared to tropical wet forests, values for the latter were used when unavailable for the former; see *Table 3*. The parameters *forest growth parameter* and *inception point parameter* were chosen to construct an estimated forest growth curve of secondary forests in Manica Province. To estimate this, literature for dry tropical forests was surveyed (Uhl et al., 1987; Andiresse et al., 1987; Hughes et al., 1999; UNESCO et al., 1978) and parameters were chosen to reflect this ecosystem as deemed acceptable for Manica. For the parameters adopted, biomass accumulation was 9870 kg ha^{-1} for the first year and 10554 kg ha^{-1} for the second year. Rapid growth was kept for approximately 10-15 years, in accordance with Brown et al. (1990), dropping to 4317 kg ha^{-1} in year 10.

Tab. 3. Fallow parameters adopted for tropical dry forests of Manica used in FallowSIM and BurnSIM and their sources from literature.

Parameter	Value	Source
Forest Growth Param	0.16	*See text*
Inception Point Param	1.3	*See text*
Carrying capacity of ecosystem (aboveground biomass of primary forest can be used as an estimate) (kg/ha)	110000	Estimated with reference to: Hughes et al., 1999; Brown et al. 1990; Jaramillo et al. 2003; Kauffman et al., 2003; Kauffman et al., 1993; Ryan et al., 2011; Murphy et al., 1986
Portion of aboveground biomass combusted	0.8	Rough estimate for tropical dry forests based on Kauffman et al., 2003; Kauffman et al. 1993
Portion of Aboveground biomass still alive	0.85	Brown et al., 1990 *(not used in final version)*; Kauffman et al., 2009
Root to Shoot Ratio	0.33	Used by Brown, 1997; Crow, 1978. Function of rainfall; referred to: Brown et al. 1990; Murphy et al., 1986; Castellanos et al., 1991; Ryan et al., 2011; Jaramillo et al. 2003; Kauffman et al., 2003; Kauffman et al., 1993; Uhl, 1987.
Portion of Woody elements in Aboveground Biomass	0.89	For secondary dry tropical forest: Kauffman et al., 1993; Uhl, 1987
Portion of Fine Roots in total roots	0.1	Jaramillo et al., 2003
Portion of ash mass to pre burn aboveground biomass	0.05	Calculated ratio found for wet tropical forests and tropical dry forests using data from Kauffman et al., 2003; Kauffman et al., 1993; Guild et al., 1998; Kauffman et al., 1995
Portion of woody elements removed before fire	0	*(not used in final version)*
C Content of Ash	0.3	Calculated ratio found for tropical dry forests using data from Kauffman et al., 2003; Kauffman et al., 1993
N Content of Ash	0.004	Calculated ratio found for tropical dry forests using data from Kauffman et al., 2003; Kauffman et al., 1993
P Content of Ash	0.005	Calculated ratio found for tropical dry forests using data from Kauffman et al., 2003; Kauffman et al., 1993
K Content of Ash	0.044	Calculated ratio found for tropical dry forests using data from Kauffman et al., 2003; Kauffman et al., 1993
Portion of ash carried away by wind	0.57	Kauffman et al, 1995; function of wind and surrounding vegetation (pers. comm.: Leffelaar)
Woody elements C Concentration	0.46	Different values for different thicknesses, calculated weighted average using data from Kaufmann et al., 1993 and Kauffman et al. 2003.
Woody elements N Concentration	0.0051	Different values for different thicknesses, calculated weighted average using data from Kaufmann et al., 1993 and Kauffman et al. 2003.

Woody elements P Concentration	0.00038	Different values for different thicknesses, calculated weighted average using data from Kaufmann et al., 1993 and Kauffman et al. 2003.
Woody elements K Concentration	0.000024	Different values for different thicknesses, calculated weighted average using data from Kaufmann et al., 1993 and Kauffman et al. 2003.
Nonwoody elements C Concentration	0.43	Different values for litter and foliage, calculated using weighted average from Kauffman et al., 1993
Nonwoody elements N Concentration	0.021	Different values for litter and foliage, calculated using weighted average from Kauffman et al., 1993
Nonwoody elements P Concentration	0.0012	Different values for litter and foliage, calculated using weighted average from Kauffman et al., 1993
Nonwoody elements K Concentration	0.0054	Different values for litter and foliage, calculated using weighted average from Kauffman et al., 1995 (wet tropical forest)
Coarse roots C concentration	0.39	Jaramillo et al., 2003
Coarse roots N concentration	0.006	Jaramillo et al., 2003
Coarse roots P concentration	0.00038	Noij et al., 1993 (for wet tropical forest)
Coarse roots K concentration	0.000024	Noij et al., 1993 (for wet tropical forest)
Fine roots C concentration	0.375	Jaramillo et al., 2003
Fine roots N concentration	0.008	Jaramillo et al., 2003
Fine roots P concentration	0.00038	Noij et al., 1993 (for wet tropical forest)
Fine roots K concentration	0.000024	Noij et al., 1993 (for wet tropical forest)

Pioneer fallow species are non-woody mostly grasses and forbs. 1 to 2 year fallows have the aboveground woody elements to TAGB ratio set to.333 for the first year of fallow and .733 for the second year. Parameters are from Uhl (1987).

BurnSIM channels nutrients in fallow biomass into FIELD, accounting for losses related to the burn event. Non-wood is completely combusted and wood is combusted as a function of total aboveground biomass combustion (Hughes et al., 1999; Kaufman et al., 1995; van Reuler et al., 1996; Kauffman et al. 1993; Kauffman et al. 2009; Kauffman et al., 2003; Mackensen et al., 1996; Hölscher et al., 1997; Guimarães, 1993). Aboveground, nutrients are either lost from the system, through volatization or particle transport, contained in remaining ash, or in woody residues. Belowground, roots decompose and their nutrients are returned to the soil; leaching losses are not considered as most roots are located in the upper layers of the soil for dry forests: 88% in the top 40 cm and 51-69% in the top 20 cm (Jaramillo et al., 2003; Castellanos et al., 1991).

C and N are volatized at low temperatures, and the losses are a function of total biomass loss. P is volatized at a higher temperature (Kauffman et al., 2009); as such, a low constant level is maintained until a threshold after which an increasing linear function is used. K volatizes at very high temperatures, which cannot be reached in fallow burns (Kauffman et al., 2009), and a small constant amount is lost from all burn intensities. Ash is 5% of total biomass (Kauffman et al. 2003; Kauffman et al., 1993; Guild et al., 1998; Kauffman et al., 1995) and is subject to wind erosion (Kauffman et al., 1995).

The nutrient contents of unburned wood is equal to those for pre-fire wood. Nutrient losses in wood require the lignocellulosic structure of which wood is constructed to be destroyed, rendering loss of wood. Wan et al. (2001) found N concentration of biomass does not change in fire, other less volatile elements should not be affected either.

Nutrient losses from combustion relate to the combustion coefficient of aboveground biomass, a proxy of fire intensity. A good linear fit was found for C and N. P volatilizes in fallow during very intense fires, which reach a sufficiently high temperature; hence, a piecewise function was used to reflect this threshold. K is not related to combustion coefficient, the linear model only had a significant intercept confirming the high temperatures needed to volatize this nutrient are not reached in fallow fires. Models in *equation 5* are based on data from Kauffman et al. (2003); Kauffman et al. (1993), Guild et al. (1998) including both dry and wet tropical forests, Kauffman et al. (1995); equations were verified with data from Mackensen et al. (1996) and van Reueler et al. (1996).

Equations 5.

$$
\begin{aligned}
C_{losses} &= Comb^{coef}{}_{TAGB} * .952655 \\
N_{losses} &= Comb^{coef}{}_{TAGB} * .831260 \\
P_{losses} &= .147133, & \text{if } Comb^{coef}{}_{TAGB} \leq .8 \\
&= Comb^{coef}{}_{TAGB} * 3.356 - 2.537, & \text{if } Comb^{coef}{}_{TAGB} > .8 \\
K_{losses} &= .07
\end{aligned}
$$

Where:

$Comb^{coef}{}_{TAGB}$ *= Combustion Coefficient of **T**otal **A**bove**G**round **B**iomass, or the portion combusted*

C_{losses} *= Amount of C lost during combustion kg ha^{-1}*

N_{losses} *= Amount of N lost during combustion kg ha^{-1}*

P_{losses} *= Amount of P lost during combustion kg ha^{-1}*

K_{losses} *= Amount of K lost during combustion kg ha^{-1}*

Ash contents are related to the extent of the burn (Jaramillo et al., 2003; van Reuler et al., 1996; Mackensen et al., 1996) and the vegetation being burned (Gray et al., 2006; van Reuler et al., 1996). BurnSIM asks for these values beforehand as a model could not be established due to the high variability and weakness of fit between combustion and ash content with the data obtained from literature, also noticed by van Reuler (1996). See *Table 3* for details on values used.

Root contents, course and fined, are pre-defined from values found in literature. Models for component contents based on leaf contents were developed by Noij et al. (1993); they were not included in the model as they are based on data for wet tropical forests. Calculated values do concur with data found for tropical dry forests to some degree; a more intensive comparison should be made to explore the option of including these models into FallowSIM to lower parameter inputs.

The effect of combustion on the chemical forms N, P and K is important to channel fallow nutrients into FIELD in an appropriate way. In general, combustion breaks down organically bound nutrients into inorganic forms, which have high solubility and are accessible for plants. However, the transformation of fuel material during combustion is guided by both chemical and physical properties that differ between species, and depends on fire properties as well. The model assumes N and P in ash are completely in soluble form as FIELD does with manure and organic amendments to *keep it as simple as possible* (pers. comm.: Zijlstra).

BurnSIM channels nutrients into FIELD. Ash N and P are treated like fertilizer, prone to the same losses and considered completely in soluble form. Ash C is added to the stable organic matter pool as Kauffman et al. (1995) states combustion renders C into recalcitrant forms. Woody components are channeled into the crop residue pool, with their CN and CP ratios calculated from content parameters. Fine roots are treated as organic amendments due to their rapid decomposition, on advice from Gerrie van de Ven. Coarse roots are treated as a special pool. FIELD's root residues have only one C pool prone to rapid mineralization, 80%, like that of C labile from crop residues resulting in very rapid mineralization. This is not representative for thick and woody coarse roots. The special pool has a decomposition rate of 8% per year like that of resistant C that applies to fallow wood residues. This approach was discussed with Mink Zijlstra and deemed appropriate.

K's treatment in FIELD is not equal to that of N and P; K is simplified (pers. comm.: Zijlstra) and is not included in the feedback loop between crops and soil. K fallow contents are not added to FIELD.

2.4 – LabourSIM

LabourSIM was based on a model used by van Wijk (pers. comm.) before data was received, see *appendix 3*. However, differing labour productivities between Farm types did not allow for this set-up to be used. A statistical analysis was conducted to seek casual mechanics relating yield and labour, for which an analysis of labour data was conducted which will be presented in 3.1.

The new LabourSIM was constructed in Excel 2007 to determine labour input for a cropping regime (monocrop/relay) using *equation 6*:

Equation 6.

$$Lb^{a}_{demand} = \Sigma_c Area_c * Lb.req^{a}_{c}$$

Where:

c = crop including relay combinations as single values
a = FIELD related activity
Lb^{a}_{demand} = Labour input required for activity a (hrs)
$Area_c$ = Area within which crop c is cultivated
$Lb.req^{a}_{c}$ = Labour input for activity a for crop c

Labour available for each activity was determined as a product of maximum labour available per week and weeks spent on the activity, as in *Table 4*. Maximum labour available is the amount of labour that a farm can muster in different periods; this value is higher for first weeding as more child labour is utilized. It was formed based on labour input values and judgment of labour organization in consultation with Wilson Leonardo; that is, Farm type 1 does not use 210 hours per week for harvesting but it is assumed that it can.

With supply and demand values, a labour differential is obtained. This is fed into FinanSIM to determine the cost of hiring labour.

Tab. 4. Farm type 1 labour demand and supply parameters in h ha^{-1}, and labour demand schedule for different FIELD combinations as used in LabourSIM and FinanSIM. LP = land preparation, S = sowing, W1 = first weeding, W2 = second weeding, H = harvesting, Relay = relay setup, Mono = monoculture, Fert = Fertilized option. Periods refer to chronologically separated ranges of time.

LABOUR DEMAND								
Period	1	2	3	4	5	6	7	8
FIELD types								
Relay: Maize	190	61	265	212	0	211	0	0
Relay: Soybean (w/ Mz)	0	0	0	33	108	0	26	32
Mono: Maize	190	61	265	212	0	211	0	0
Mono: Soybean	270	0	0	36	235	0	51	59
Fert: Soybean (12-24-12)	270	0	0	41	235	0	51	59
Fert: Soybean (24-48-24)	270	0	0	46	235	0	51	59
Fert Relay (12-24-12)	190	66	265	245	108	211	26	32
Fert Mono Maize (12-24-12)	190	66	265	212	0	211	0	0
Schedule								
Maize	LP	S	W1	W2		H		
Soybean	LP*			S	W1		W2	H

LABOUR SUPPLY								
Periods	1	2	3	4	5	6	7	8
Hrs per week per period	150	260	250	210	210	210	210	210
Weeks in period	10	1	3	4	3	4	3	2
Total Supply	1500	260	750	840	630	840	630	420

*No separate land preparation for relay crop in relay system.

2.5 – FinanSIM

FINANSIM calculates household income from agricultural activities. Revenue is calculated from cash crop sales, maize sales, and labour sales. Maize purchases, fertilizer costs and labour costs are calculated. The result is an indication of farm income from agricultural production.

For household need of maize, the average value for Dombe Farm type 1 (860 kg yr^{-1}) from data was used because attempted generalized equations rendered estimates far from observed value (see *Appendix 4*). FAO (2001) provides the means to develop more sophisticated age group dependent models for future improvement of FinanSIM, if need be.

2.6 – Sensitivity Analysis

Sensitivity is defined as the change in a state variable due to a change in a parameter variable (pers. comm.: Leffelaar). A sensitivity analysis of FallowSIM-BurnSIM was conducted using an R script created for this purpose. Parameters were adjusted 1% in both directions for fallows of different ages, 1-19 years, and the proportion effect on the chosen state variables (*Table 5*) was recorded. The state variables were chosen to track burn effects and nutrient additions to cropping into consequent FIELD runs.

K related state variables were not included as K does not hold the central role that the other nutrients do in FIELD (see 2.3).

Tab. 5. State variables chosen for the sensitivity analysis and what they include from FallowSIM.

Name	Includes
Total AboveGround Biomass	*Total AboveGround Biomass*
Total Biomass	*Total AboveGround Biomass* and *Total BelowGround Biomass*
C losses	C lost from combustion event (kg ha^{-1})
Total C pool post-burn	C in *ash*, unburned *woody residue*, *fine roots*, *coarse roots*
C losses	N lost from combustion event (kg ha^{-1})
Total N pool post-burn	N in *ash*, unburned *woody residue*, *fine roots*, *coarse roots*
C losses	P lost from combustion event (kg ha^{-1})
Total P pool post-burn	P in *ash*, unburned *woody residue*, *fine roots*, *coarse roots*

2.7 – Data and Statistical Analysis

Wilson Leonardo's farm trials of maize and soybean were conducted for during 2010-2011 and 2011-2012 seasons by volunteer farmers. Five 10 m X 2 m plots were placed alongside each other with the following treatments: control, NP, NK, PK, NPK. Yields and nutrient concentrations were determined after discounting plot border plants. A couple of plots failed due to heavy rain damage and decomposition of plants that were knocked down to the ground.

Soil data did not completely correspond to farm trials. Composite sampling of a farm was used.

Farm data were obtained from a detailed survey carried out by Wilson Leonardo for different Farm types in Dombe and Zembe; n=3 per category with N=24. Data included size of farms, cultivation areas, household size, household maize need, labour input. The data could be segregated between location and Farm types.

R with RStudio interface was used for ANOVAs, linear models, and arithmetic calculations, as needed.

- 3 - Results -

3.1 – Labour Data Analysis

As labour productivities differ between Farm types, the amount of labour input does not account for differences in yield observed (visualized in *figure 5*, see *Appendix 5* for greater detail).

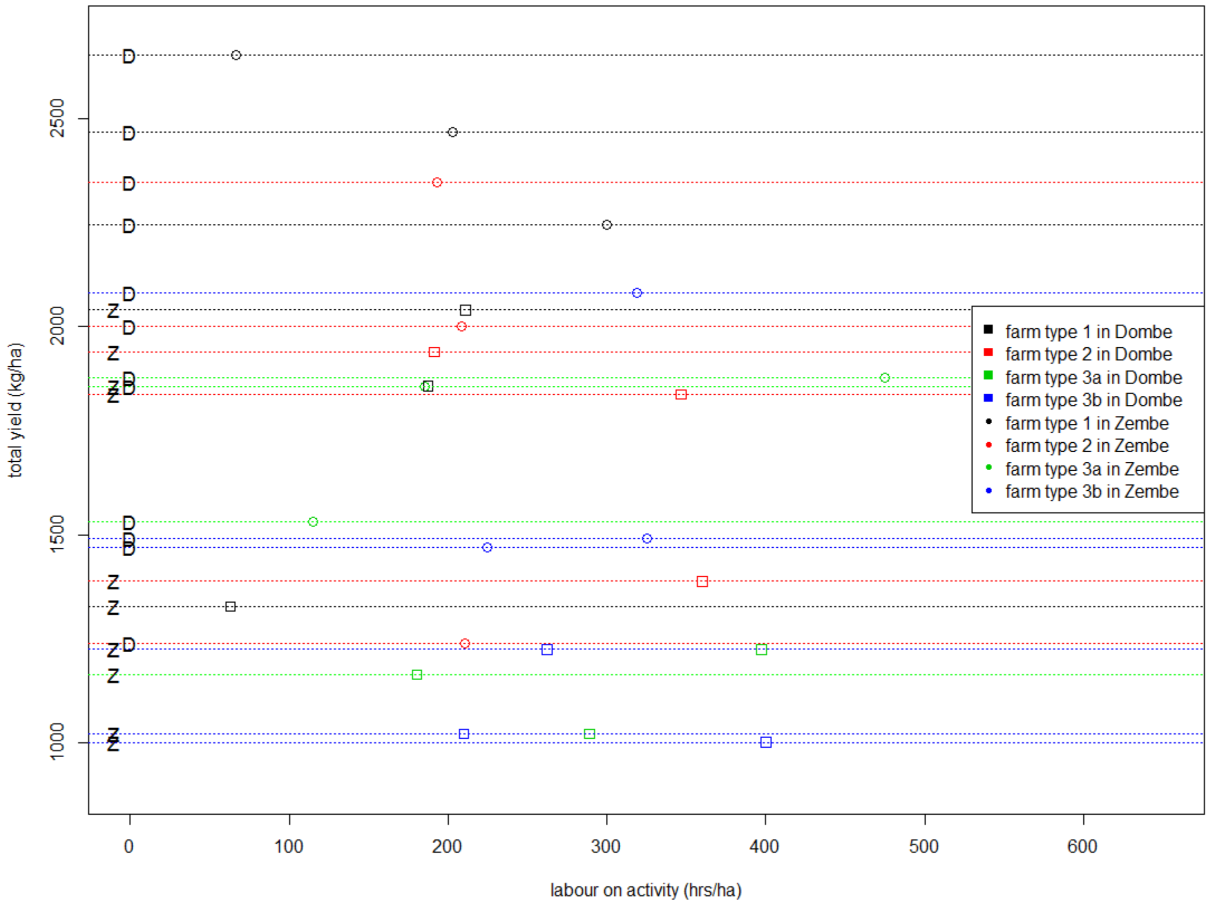


Fig. 5. Labour hours input for first weeding, the most critical activity, and corresponding maize yields for farms in Dombe (D) and Zembe (Z). Lines represent a surveyed farm. See *Appendix 5A* for linear model.

In field visits, certain areas of all Farm types were observed to have been sown with maize and overgrown with weeds; indicating a failure to perform the first, particularly, or second weeding on this area. Due to aggressive competition, the grain of maize cultivated under these conditions has not developed suitably to be fit for consumption. In this way, labour availability during the critical first weeding restricts the amount of area that is successfully cultivated.

Deductively, differing labour input quantities should influence yield, with more time allowing for more complete performance of a task. However, labour input was found to not correlate with yields in the data due to differences in farm type productivities; as such, labour input is not a reliable predictor of yields.

Differences of productivity between farm type is probably due to several reasons. As observed during farm visits, Farm types 3a and 3b tend to be more involved in off-farm activities, such as wage labour. With larger competition for limited labour hours, larger farms are able to seize upon good opportunities in thin time slots, such as weeding during good weather, which other Farm types have to make up for, driving productivity apart. Moreover, Farm types 1 and 2 show a larger propensity for risk, such as planting earlier to benefit from early rains, and have the potential to reap greater benefit through higher yield. Moreover, Dombe overall has higher yields (see 3.2) and productivities than Zembe for all Farm types.

With the desire to relate yield to labour to allow for modelling, a quantitative relationship was sought between measured variables and yield in the data. Although this exercise did not meet its goal, it did yield some interesting results to be addressed in the discussion:

- Of all the available variables in the data, area was found to correlate the strongest with maize yields, as can be seen in *Figure 6*. Area is a very good proxy for the combination farm type and location as they relate to maize yields (*Appendix 4E*).

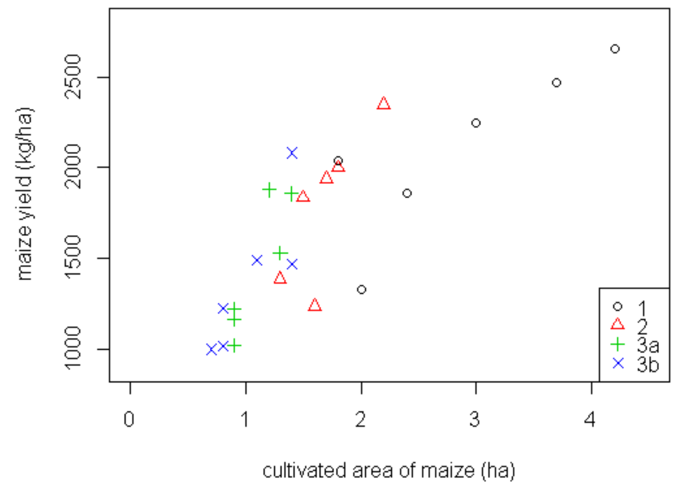


Fig. 6. Maize yield as it is related to the area used for cultivation for different Farm types (see legend).

- As shown in *Figure* 7, type 1 farmers show a positive correlation between household size and area; however, with only six points for this Farm type, a firm conclusion cannot be obtained. No correlation is apparent for the other Farm types.

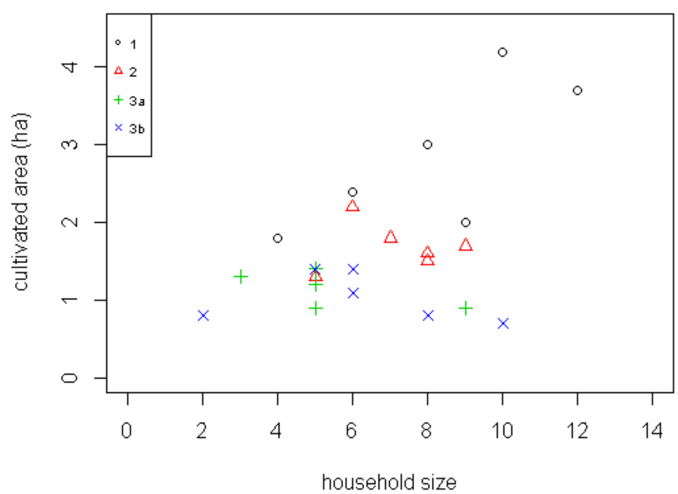


Fig. 7. Cultivated area for household size showing different Farm types (see legend).

3.2 – FIELD level

Average maize grain yields are 714 kg/ha lower in Zembe than Dombe.

After calibration was deemed successful, light determined (LDY), water determined (WDY) and nutrient determined (NDY) grain yields of maize and soybean for Dombe 1 soil from *Table 2* were obtained, presented in *figure 8*. LDY was obtained by setting rain and nutrients (through fertilizer inputs) to very high values: 10^9. NDY was obtained by resetting Manica rain levels and keeping nutrients (through fertilizer inputs) very high. The soybean yields in *Figure 8* are calculated with the crop as a relay crop. Values of LDY and WDY in *Figure 8* are realistic: farmers in South Africa obtain 10-14 t maize grain ha^{-1} and commercial farmers in Zimbabwe obtain 4-5 t soy grain ha^{-1} (pers. comm.: Franke). The first five years can be considered an initialization period (pers. comm.: Zijlstra) and are not included for runs not starting with fallow; no seasons are omitted after fallow. All soils from *Table 1* were validated by data of field trials and consultation with Wilson Leonardo (not shown).

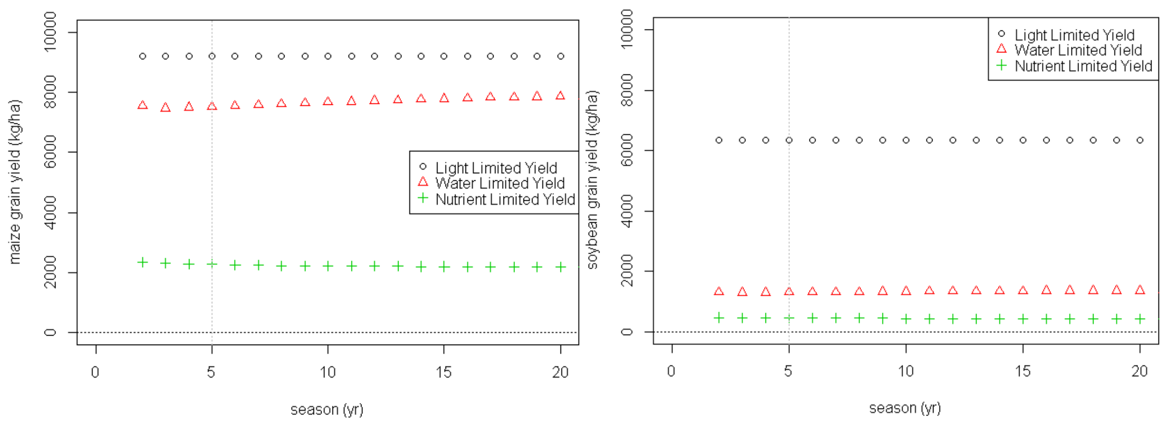


Fig. 8. Grain yields at light, water and nutrient limitations calculated in FIELD for maize (left) and soybean (right), Dombe 1 soil properties were used from *table 2*. Some change in yield occurs overtime for WDY due to changes in soil C.

For maize, the WDY is not much lower than its LDY, implying that the rainfall levels used as input are sufficient. On the other hand, NDYs are much lower, at a level slightly above 2000 kg/ha, representing approximately 25% of the crops WDY in FIELD. Maize yields promise to be increased through an increase in nutrient supply through practice of fallow or mineral fertilization.

On the other hand, soybean's WDY is a small portion of its LDY implying that response to greater nutrient availability will not have the same response as with maize and will not be able to surpass a doubling of grain yields without addressing water supply.

The present results are based on constant rainfall and distribution, variation of these two will change WDYs. The current model parameters demonstrate that the first crop has a greater access to water than its successor.

FallowSIM-BurnSIM were used to examine nutrient provision by fallows for successive cropping. Since the baseline is taken after 5 years to allow for stabilization of FIELD, the same period was used before a fallow; that is, a fallow of 5 years has an initiation of 5 years (cropping), followed by 5 years fallow, followed by cropping. *Figure 9* shows the effect of different lengths of fallow on successive maize cropping. The largest increase occurs for the longest fallow period, 25 years. The largest rate of increase in yields occurs after a two year fallow. This time period coincides with the fastest growth of fallow vegetation and hence the fastest accumulation of nutrients which are consecutively made available for cropping (see *figure 3* and *4*). This has important economic consequences for a farmer. If land becomes more scarce in the future, fast rates of nutrient accumulation would bring the most total benefit. However, if land is abundant, shifting to cropping when fallow biomass is near climax vegetation will yield the largest total benefit: approximately 20 years (see *Figure 9*). In Manica, fallow periods of 4-6 years are observed coinciding with a period of fast biomass and nutrient accumulation as modeled by BurnSIM.

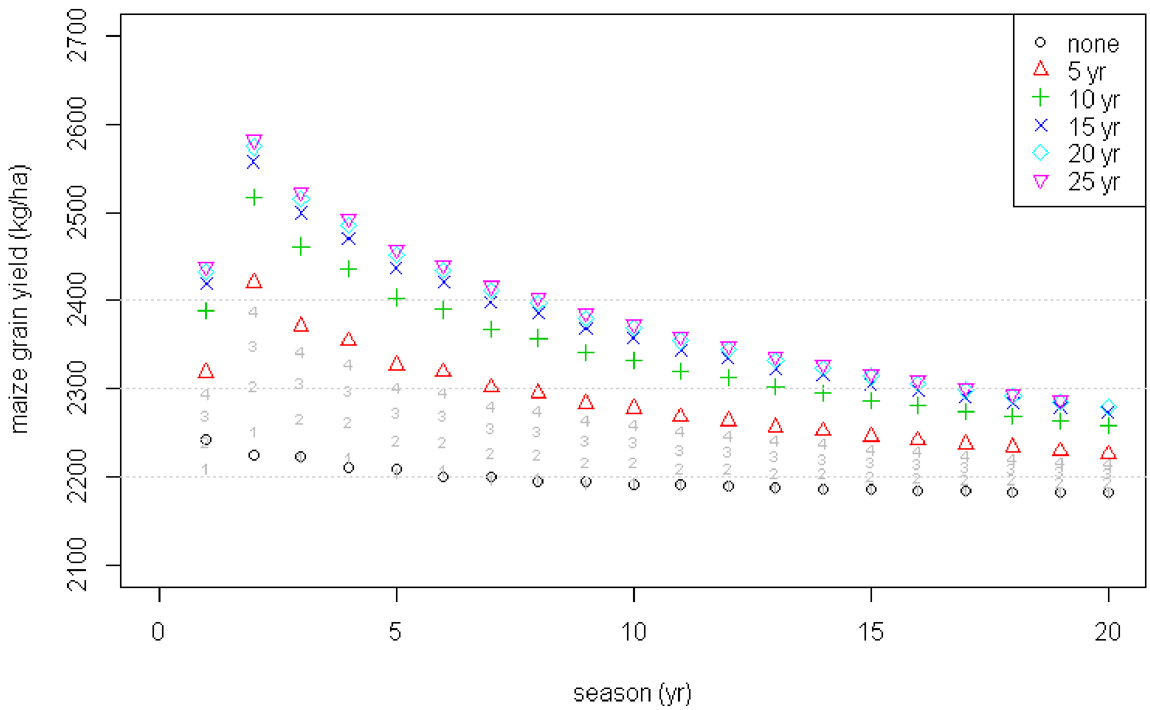


Fig. 9. Maize grain yields calculated in FIELD after different lengths of fallow. Fallow lengths 1-4 years are grey and labeled by a corresponding number, increments of 5 are labeled with different symbols and colors (see legend).

Fallow has a significant positive and prolonged effect on successive cropping of maize. Values of the first year after fallow were not used, as will be explained shortly. The largest increase, 356 kg/ha, occurs in the second year following a switch to cropping from a 25 years fallow. Fallow lengths of 1 year, 2 years, 3 years, 4 years, and 5 years demonstrates yield increases of 1.2%, 3.4%, 5.3%, 6.8% and 8.1% compared the no fallow run in the second season following fallow, respectively. The increase is rather moderate but the boost on yields continues for an extended period. In *Figure 9*, maize yields following a 5 year fallow stay above 2300 kg/ha for 10 years, 100 kg/ha higher than the long-term value for the baseline maize run. As an exception, the first year only demonstrates higher yields in the second season after fallow; this is due to changes in water capture efficiency in FIELD calculations and is unlikely to reflect reality.

A similar pattern is found for soybean as a relay crop in *Figure 10*, however with much smaller magnitude of effect (notice legend compared to *figure 9*): the largest increases occurs for the longest fallows and largest rate increase per year occurs for the 2 year fallow. Higher yields due to fallow are maintained for over 30 years for fallow length of 5 years.

The fallow curves show a kink (sudden change) at different times, with yields dropping at a faster rate. After the kink, decrease in yield is of a similar magnitude to that noticed in the initial stages of the no fallow run implying the increasing role of a nutrient's limitation on yields. This pattern was not noticed in the maize yield curves from *Figure 10*, implying unequal ability to uptake nutrients due to one crop following the other, an issue discussed later on. In *Figures 12* and *13*, the supply of N and P available to the first crop and the relay crop are shown. The kink seems to coincide with the end of P enrichment from fallow residues. However, the numerical significance of these rate changes is small and cannot stand as good evidence for any conclusion projected outside the FIELD algorithm.

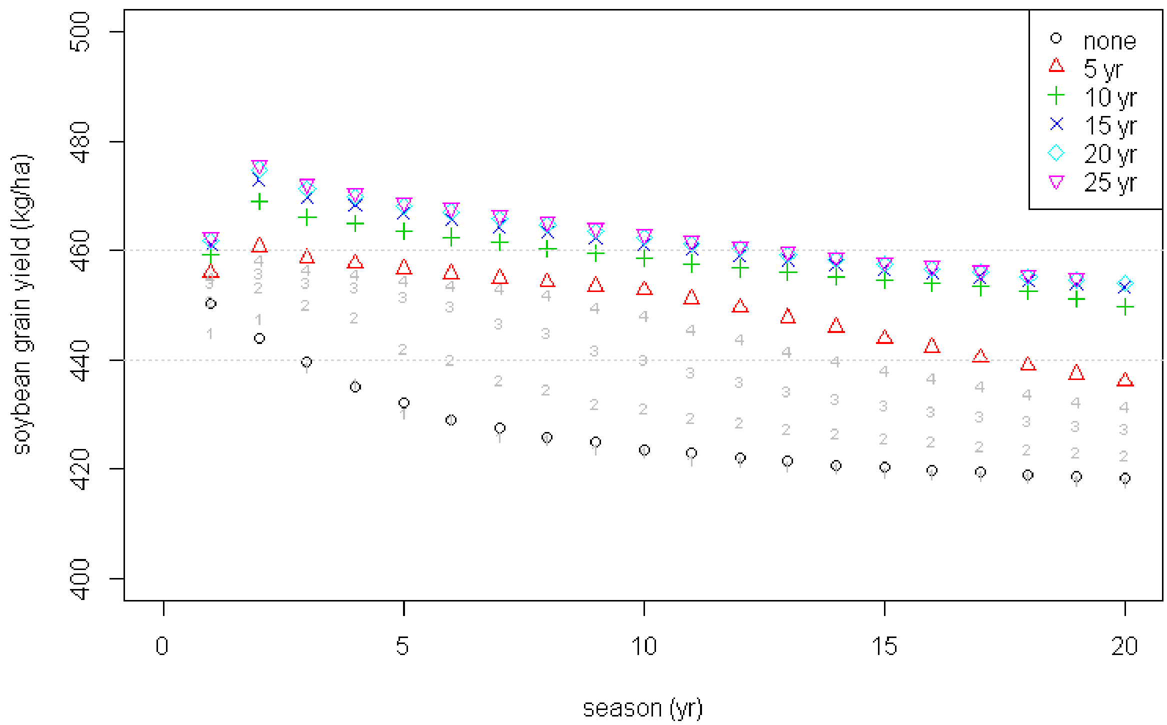


Fig. 10. Soybean grain yields calculated in FIELD for different lengths of fallow. Fallow lengths 1-4 years are grey and labeled by a corresponding number, increments of 5 are labeled with different symbols and colors (see legend).

Maize yields in the first year after fallow are lower than in successive years with a peak occurring in the second year after fallow. In *Figures 11* and *12*, organic N and P are shown to account for this observation. Fallow residues decompose but the N and P mineralized are not registered by FIELD, a initialization problem that could not be fixed; notice a 1 year fallow claims less yield than no fallow in the first year after fallow. An interpolated point from the yield curves in *Figures 9* and *10* would be a better estimate of grain yields in year 1; alternately the first year can be removed but the nutrients from ash should be applied in the second year.

Figure 11 shows that longer periods of fallow result in a higher amount of N supply in successive cropping. Larger amounts of biomass accumulated during longer fallow result in larger N pools in fallow residue and higher quantities of mineralization from *N organic*. The higher supply of *N organic* persists after fallow biomass is largely decomposed; the higher crop yields brought about result in more crop residues and more N supply from mineralization. *Soil N* supply is also boosted in the model for longer fallow periods, as the C pool expands with the addition of biomass. N additions from ash are seen in *Table 6* following fallow. N resulting from ash is always very low: 9 kg/ha for the 25 year fallow run. In comparison, fine root decomposition provides 29 kg/ha N, coarse roots provide 13 kg/ha, wood component residue decomposition provides 21 kg/ha N in the second year after 25 year fallow. N addition to cropping from fallows is in large part from component decomposition not combusted by fire.

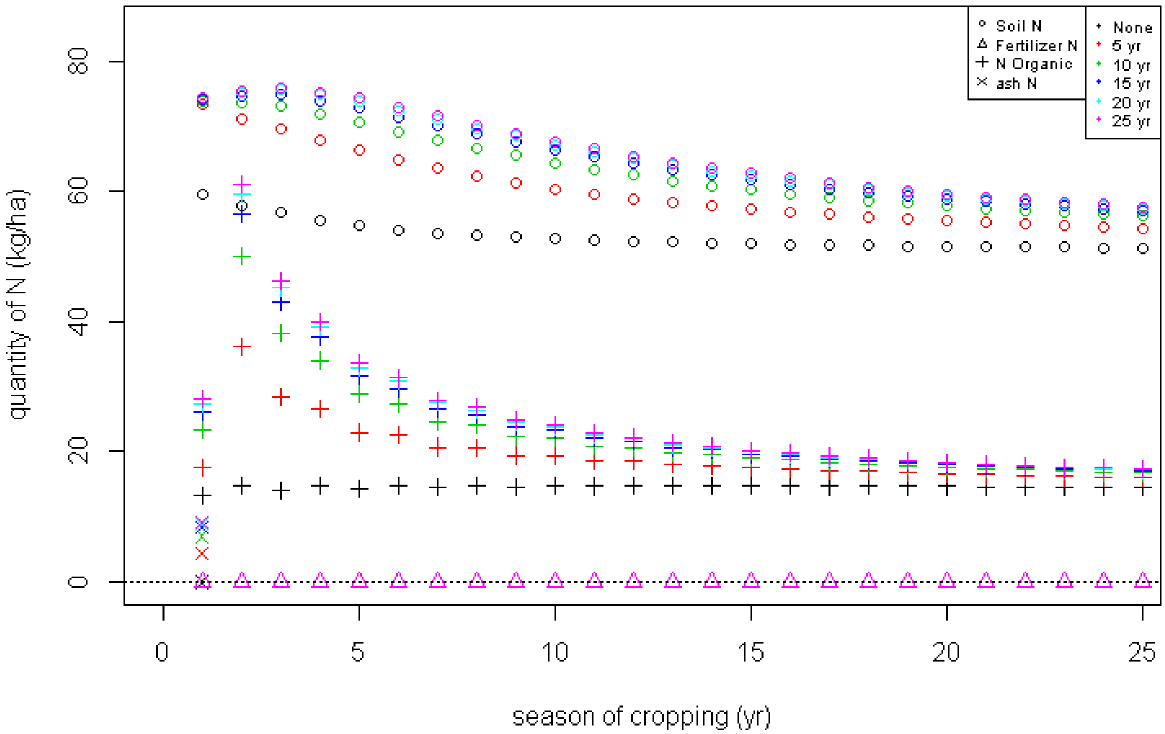


Fig. 11. Amount of N available to crops from different sources in FIELD following different lengths of fallow.

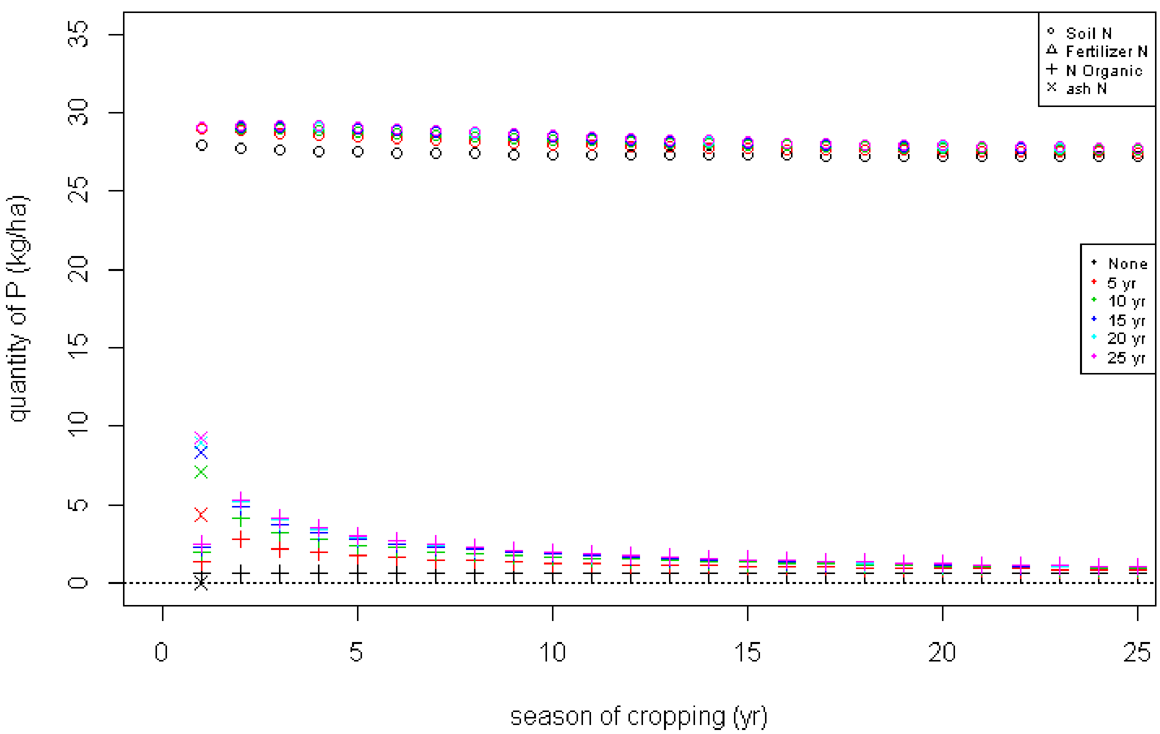


Fig. 12. Amount of P available to crops from different sources in FIELD following different lengths of fallow.

Figure 12 shows that longer periods of fallow result in a higher amount of P supply in successive cropping for the same reasons mentioned for N. Effects on soil P are not very pronounced for longer lengths of fallow, or even compared to no fallow. As such, P from fallows is channeled to crops mostly through fallow residues and ashes. In contrast to N, quantity of P in ashes are relatively high, 11.5 kg/ha for 25 years of fallow, amounting to 27.6% of the P mineralized from crop residues in the second year after 25 years fallow, as seen in *Table 6*. P additions from fallow are not as comparatively important as N additions when compared to soil mineralization values.

The occurrence of prolonged crop yield increases due to an extended increase in nutrient supply implies fallow will generate higher total yields in a shifting agriculture system compared to a continuous one. Indeed, this is the case for both crops in a relay, as seen in *Figure 13*. Average maize yields for continuous cropping are 2210 kg/ha during a 12 year period, below the shifting structure's value of 2370 kg/ha; a difference in yield of 7.2% compared to continuous cropping. Average soybean yields for continuous cropping are 430 kg/ha and 460 kg/ha during a 12 year period, with use of fallow representing an increase of 6.7%.

Tab. 6. N and P in ashes and sum of mineralization from all sources in successive years for different lengths of fallow.

Fallow Length (years)	N (kg/ha)				P (kg/ha)			
Years After Fallow	Ash	1	2	3	Ash	1	2	3
0	0	78.5	77.7	75.7	0	33.6	33.5	33.3
5	4.4	102.4	113.8	104.3	5.4	36.6	37.8	36.8
10	7.1	111.0	130.5	118.2	8.8	37.9	39.9	38.6
15	8.4	115.3	138.8	125.1	10.4	38.5	40.9	39.5
20	9.0	117.3	142.7	128.3	11.2	38.8	41.4	39.9
25	9.2	118.2	144.5	129.8	11.5	39.0	41.6	40.1

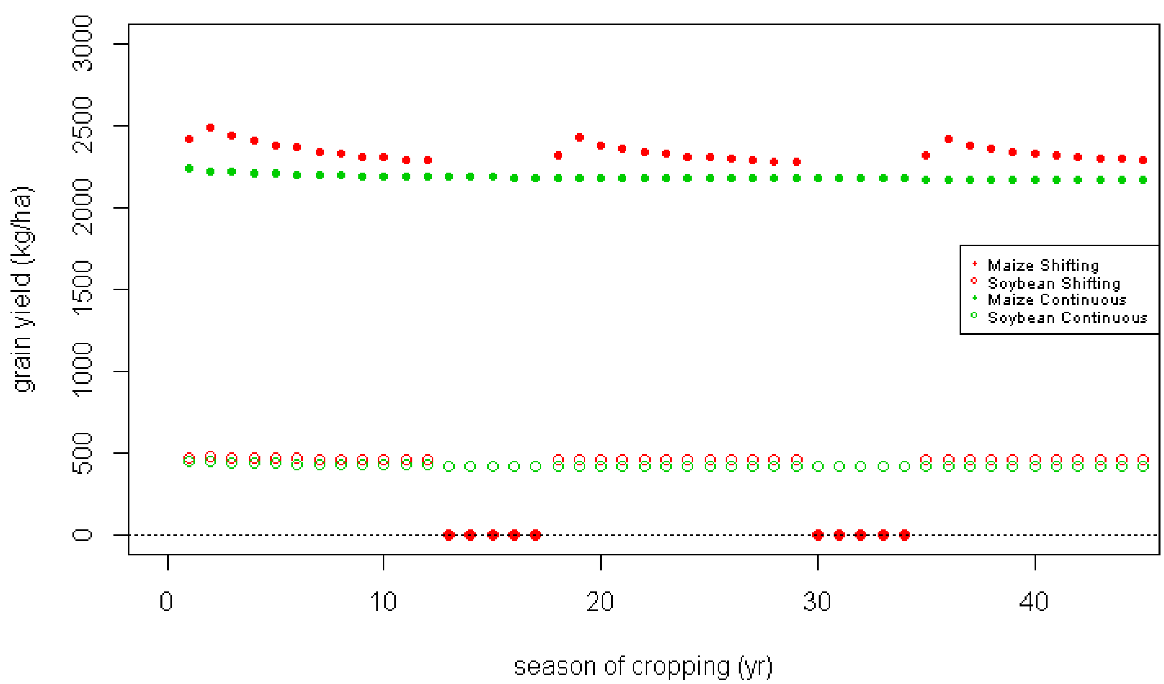


Fig. 13. Maize and soybean grain yields for continuous cropping and 5 year fallow-12 year cropping rotation.

To understand this in perspective, fallow can be compared to mineral fertilizer as in *Figure 14*. Fertilizing with 6-12-6 NPK kg/ha produces a yield of 2430 kg/ha similar to 2360 kg/ha achieved with a 5 year fallow, both averaged over 12 years. Higher applications of fertilizer move maize yields even closer to WDY from *figure 8*. Applying 12-24-12 NPK kg/ha of fertilizer results in 2644 kg/ha of maize, a 12.0% increase compared to shifting and a 20.2% increase compared to the baseline. Response of the relay crop is much lower with a yield increase from 430 kg/ha at the baseline to 490 kg/ha when 24-48-24 NPK kg/ha is applied, an increase of 14.0%. As seen in *Figure 14*, it must be noted that grain yields demonstrate decreasing marginal response to fertilizer (i.e. marginal input increases result in marginally lower response in maize yield).

The different response of the relay crops to mineral fertilizer suggests that the two crops compete for resources, with an advantage for the first crop. This is visualized in *Figures 15* and *16*; values of available nutrients are equal to the total sum each season from *Figures 11* and *12* split between the two relay crops. The burn event following fallow produces a windfall availability of N and P that manifests in a situation of plenty wherein utilization by the first crop does not drain availability for the second. In contrast, fertilizer options explored do demonstrate competition for N availability. Comparing a 5 year fallow with a fertilization regime of 6-12-6 NPK kg/ha, two options with similar average maize yields, that fallow increases N availability for the relay crop by 30.7% while mineral fertilizer only increases this value by 4.8%. Indeed, this is manifested in soybean grain yields. Fertilizing with 12-24-12 NPK kg/ha increases soybean yields from the baseline of 434 kg/ha to 476 kg/ha. Fertilizing with 40-20-20 NPK kg/ha increases yields further to 490 kg/ha. In comparison, a 5 year fallow already observes a soybean grain yield of 474 kg/ha, the value increasing to 481 kg/ha for a 10 year fallow.

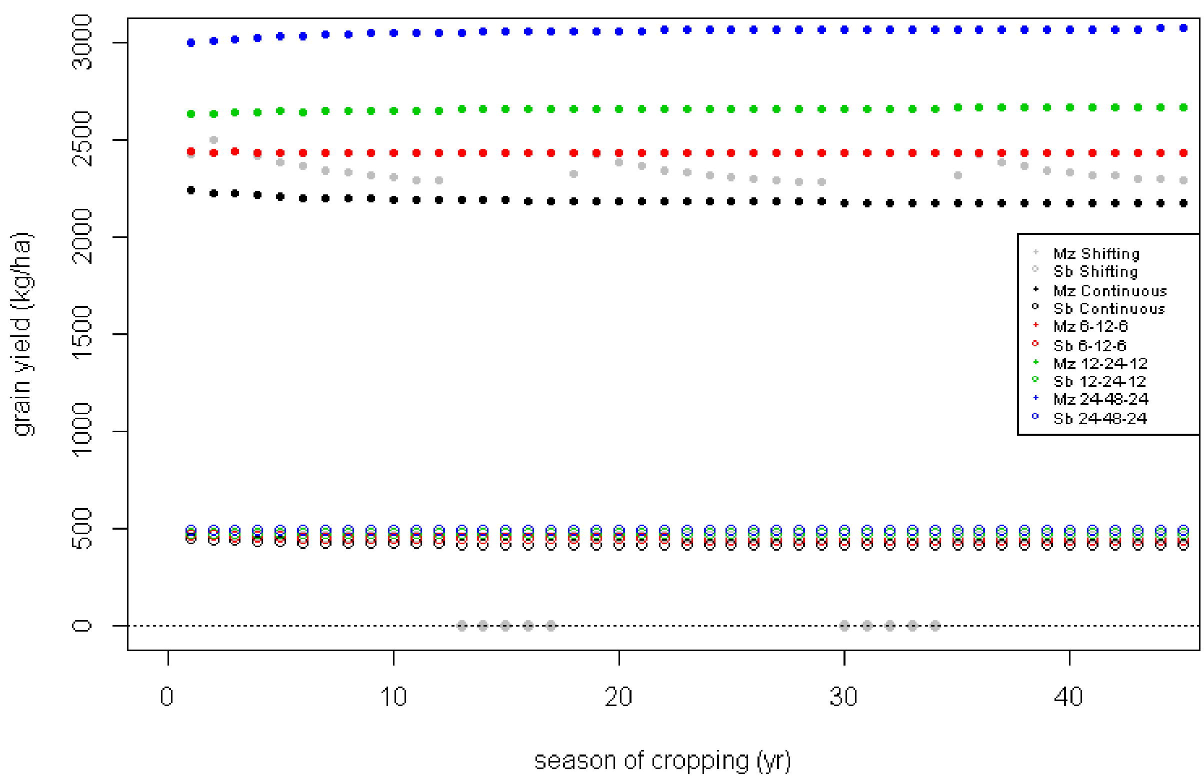
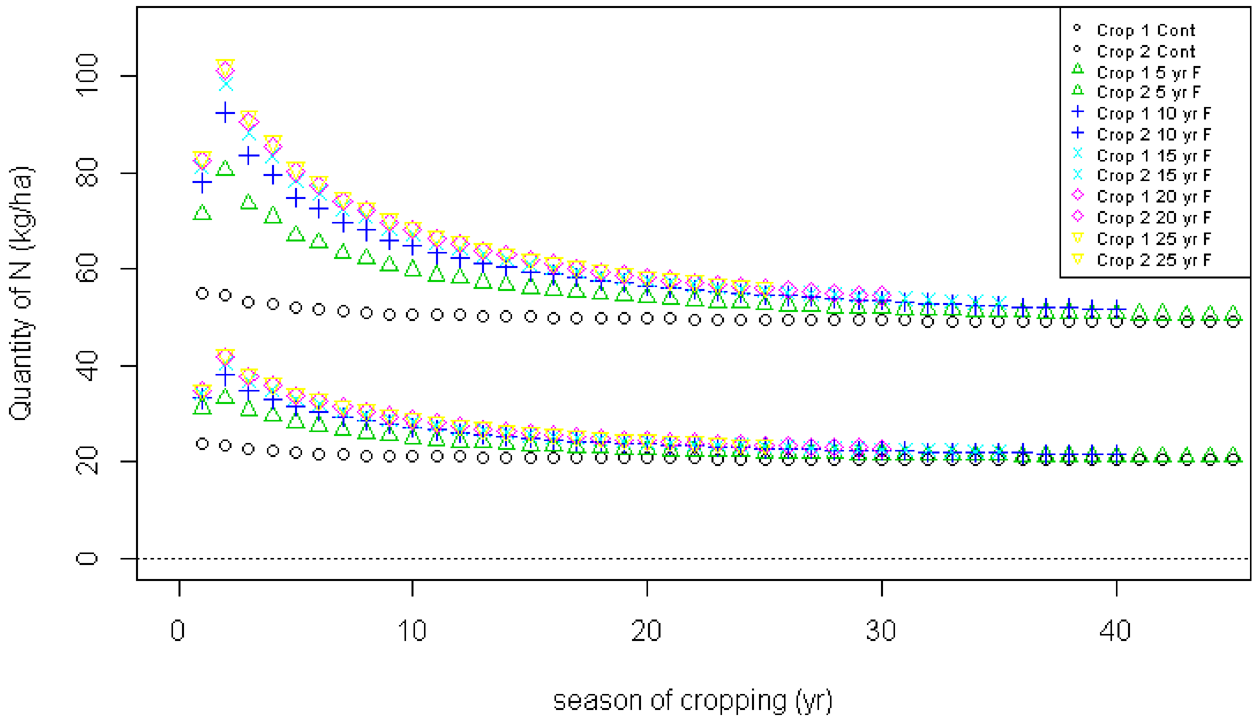


Fig. 14. Maize (Mz) and soybean (Sb) grain yields for different levels of mineral fertilizer application compared to shifting agriculture in FIELD; Dombe 1 soil properties were used from *Table 1*. #-#-# refers to amount in kg/ha of N-P-K fertilizers applied.



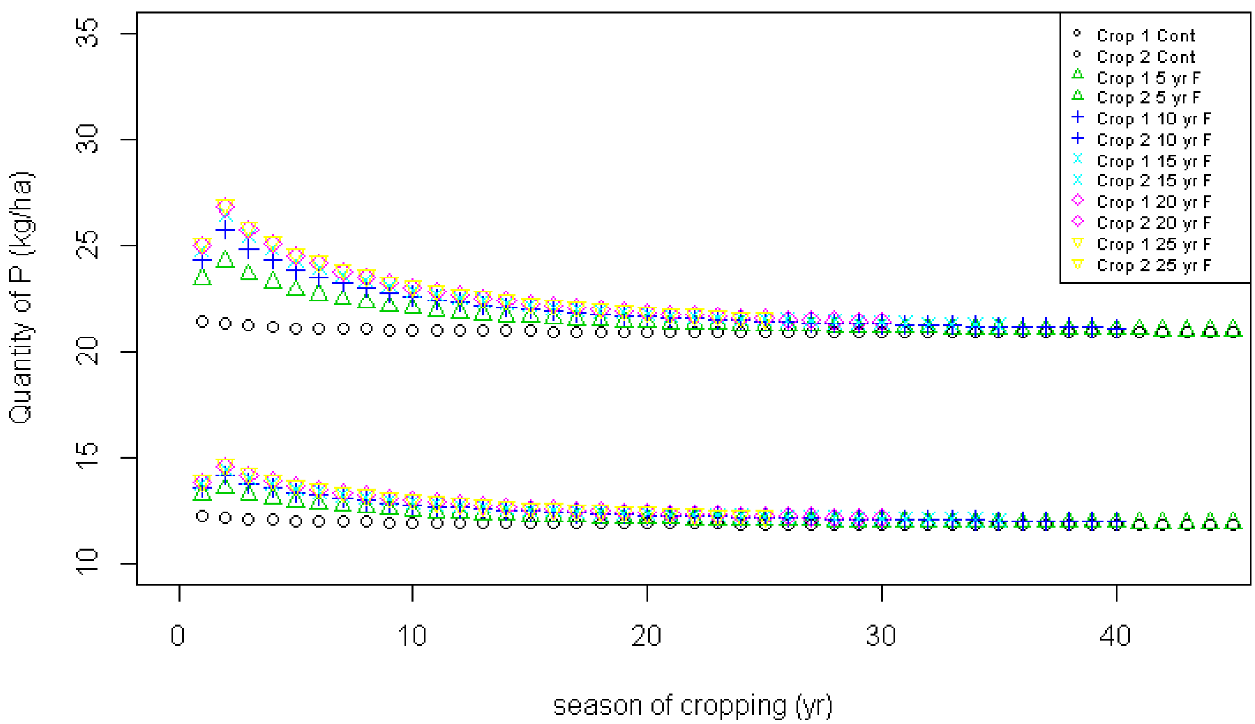
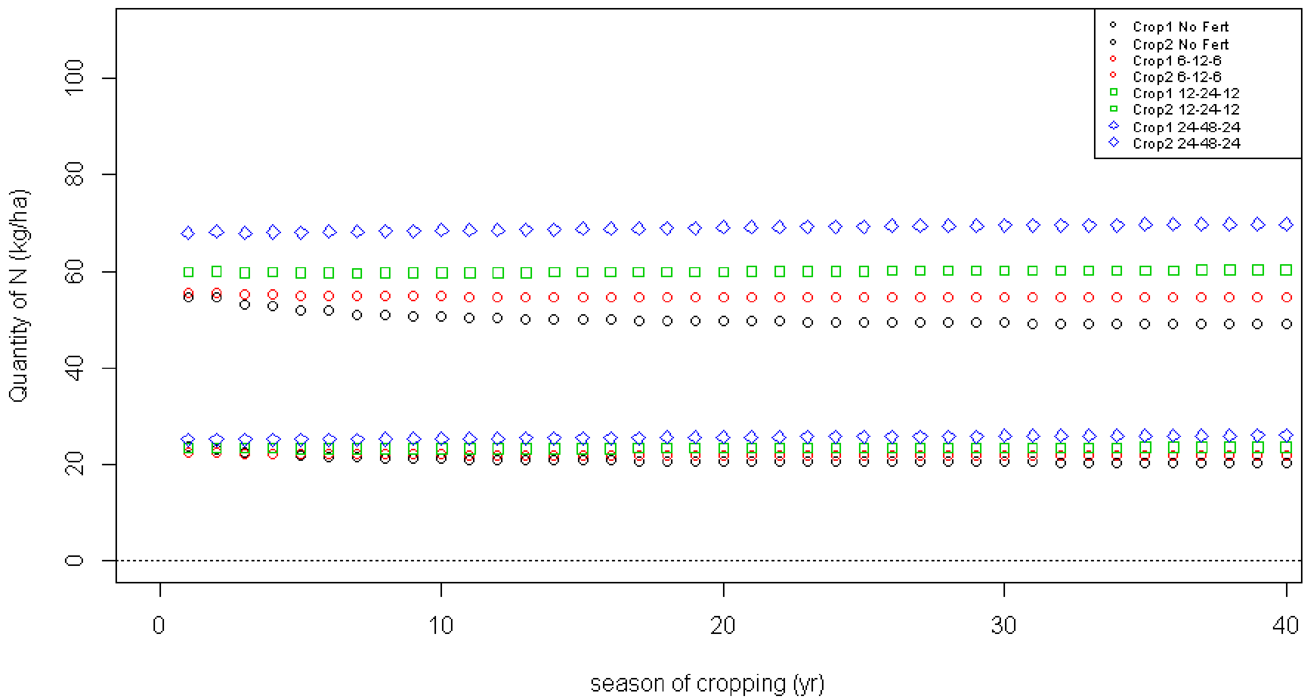


Fig. 15. N and P availabilities for the first crop and the relay crop for differing lengths of fallow. Cont = continous cropping, F = fallow. Top curves pertain to maize, bottom to soybean.



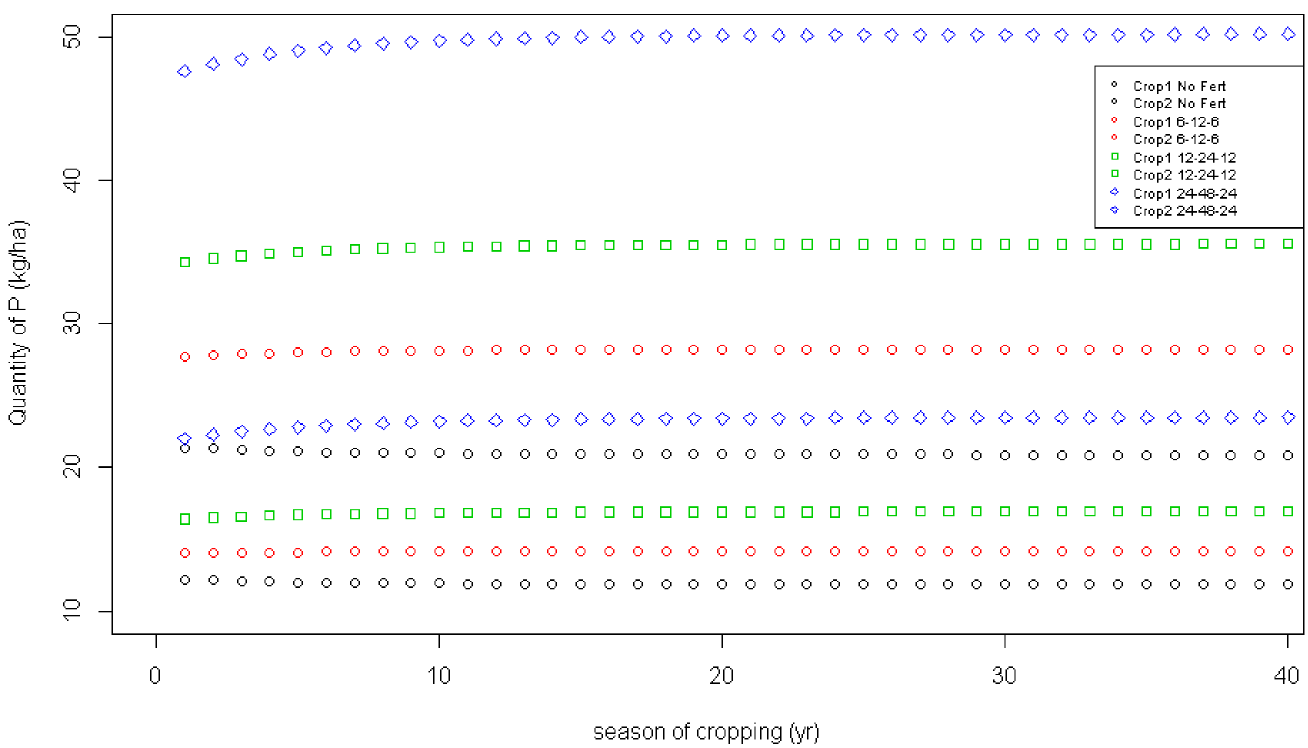


Fig. 16. N and P availabilities for the first crop and the relay crop for different fertilizer applications. #-#-# = quantities of NPK. Top curves pertain to maize, bottom to soybean.

Given the windfall gain of N and P, it is surprising that soybean yields are not responsive to the fallow runs, particularly since soybean is set obtain 70% of its N from fixation by rhizobium bacteria. The reason for this lies with K availability as it becomes limiting for the relay crop. K does not hold a paramount role in FIELD and is not as well represented. The effect of removing K from the QUEFTS calculations in FIELD on relay soybean grain yields raises the baseline yields to 500 kg/ha, at which point N and P become limiting.

Figure 17 shows maize and soybean yields if they are grown as a monocrop on Dombe 1 soils. Similar patterns emerge as discussed earlier. Significantly higher soybean grain yields are found, with the baseline alone achieving twice its value in a relay regime; moreover, soybean response to nutrient pool additions are much more pronounced than seen in *Figures 10, 13* and *14*. Comparatively, FIELD demonstrates that monoculture soybean is more appropriate for intensification than relay cropping on a field level; on the other hand, the problems with K must be taken into account.

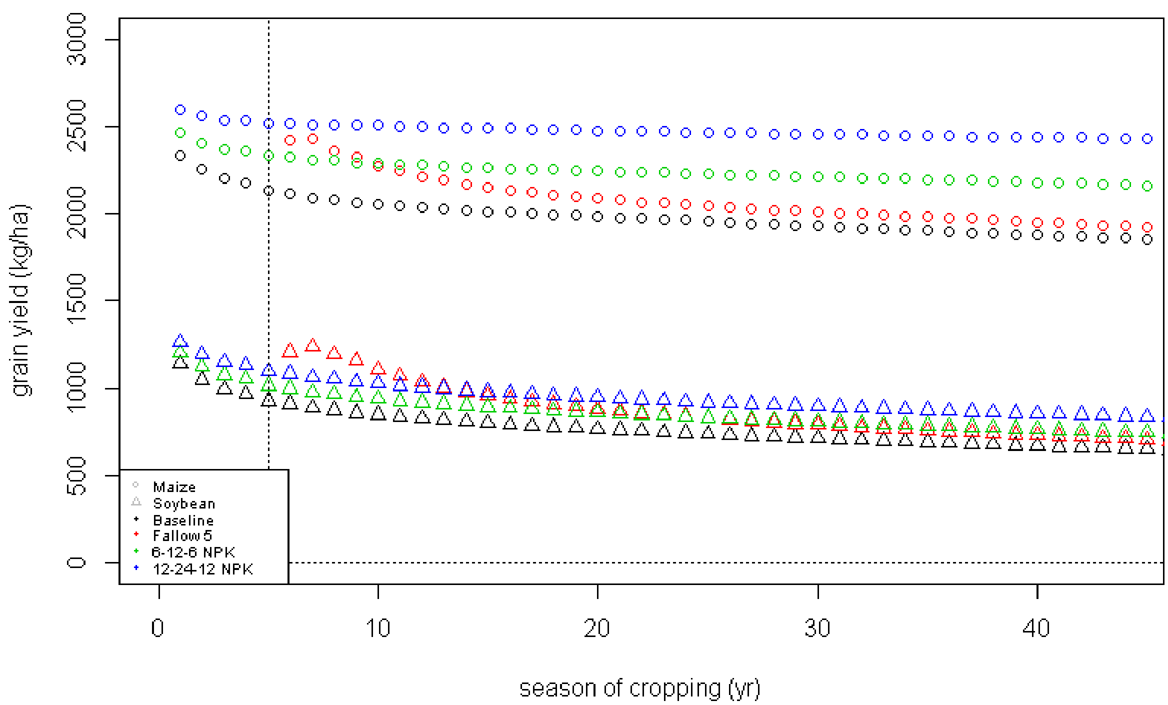


Fig. 17. Monocropped maize and soybean grain yields as generated by FIELD for a baseline continuous cropping, a fallow of 5 years (*Fallow 5*) and annual fertilizer applications of 10-5-5 NPK kg/ha and 20-10-10 NPK kg/ha. The initialization period is also shown, left of the vertical line at season=5.

FIELD shows diminishing yields for the monoculture baseline of both maize and soybean, which is not the case in the relay system. The reason for this is that soil C stocks are dropping in the monocrop regime, due to lower total additions each season, resulting in less mineral nutrients provided by the soil. However, weeds will grow after the first crop as long as there is precipitation and will contribute C to the soil in the next season, and this is not taken into account. For soybean, where C additions are smaller than for maize, the decline in grain yields is slightly steeper.

3.3 – Farm level

Different simulations were run as defined in 2.2. The results are presented in *Table 7*.

Tab. 7. LabourSIM and FinanSIM results for Farm type 1, with total yields, revenues, and costs. All monetary values are in Meticais. Simulation numbers pertain to codes from section 2.2. All values are expressed on a farm level. M= Maize, SB= Soybean, T=Total, S=Simulation.

	Area			Revenue				Costs		Totals			
				Maize		Soybean							
S	M (ha)	SB (ha)	T (ha)	Yield (kg)	Revenue	Yield (kg)	Revenue	Fertilizer	Labour	Revenue	Cost	Profit	Profit per ha
1	3.6	1.1	3.6	7556	48546	495	7425	0	1632	55971	1632	54339	15094
2	3.6	1.1	4.7	7380	47270	924	13860	0	1632	61130	1632	59498	12659
3	3.6	1.1	4.7	7380	47270	1133	16995	1540	1632	64265	3172	61093	12998
4	3.6	1.1	4.7	7380	47270	1309	19635	3080	1632	66905	4712	62193	13233
5	3.6	1.1	4.7	9000	59015	924	13860	5040	1632	72875	6672	66203	14086
6	3.6	1.1	4.7	9000	59015	1133	16995	6580	1632	76010	8212	67798	14425
7	3.6	1.1	3.6	8029	51975	528	7920	1540	1632	59895	3172	56723	15756
C1	0	4.7	4.7	0	0	4841	72615	6580	3796	72615	10376	62239	13242
C2	0	2.6	2.6	0	0	2678	40170	3640	0	40170	3640	36530	14050
C3	0	3.7	3.7	0	0	3811	57165	5180	1916	57165	7096	50069	13532

The fact that simulation 2 has a higher profit than simulation 1 shows that monocropping soybean is a better option for Farm type 1 than relaying with maize. Labour costs do not change, as hiring labour input is only required during maize's first weeding. At the same time, monocrop soybean has a higher yield than relay soybean, almost double from the same area: 924 kg ha^{-1} and 495 kg ha^{-1} respectively.

Simulations 3 and 4 show results of using 12-24-12 kg ha^{-1} NPK and 24-48-24 kg ha^{-1} NPK respectively for soybean. Soybean production increase by 200 kg in simulation 3 and 380 in simulation 4 compared to simulation 2, a 22% and 41% increase respectively. These increases are paralleled with higher profits over simulation 2, 1% and 2.6% respectively. Although doubling fertilizer from 3 to 4 already shows a smaller increase in profit than between 2 and 3. Profit will be maximized when the amount spent on fertilizer is equal to the additional revenue from maize's response to more fertilizer, for the model.

Simulations 5 shows the effect of fertilizer application on maize. 50 kg ha^{-1} of 12-24-12 NPK results in an 11% increase in profits compared to simulation 2; a 10 fold higher increase in total profit than in simulation 3.

Simulation 7 demonstrates the effect of fertilizer application on the relay system without the use of fallow. This is not the best option. Profits are slightly above the non-fertilized relay simulation (simulation 1) but below all other simulations mentioned so far. This implies that fertilizer should be used for monocrops by Farm type 1 on Dombe 1 soils.

The commercial simulation runs show the results of cultivating only soybean in the model. Only C1 generates higher profits than simulation 1 and 2.

Labour scarcity occurs when a large amount of land is dedicated to maize or soybean. Labour saved from relay cropping is not accentuated for Farm type 1. The use of fertilizer does not require additional labour inputs during this critical period. Higher yields and revenues justify fertilizer costs (at 50 kg ha^{-1} and 100 kg^{-1} 12-24-12 NPK). As such, fertilizer use promises increases in productivity in the simulations.

The results imply that fertilizing maize and soybean in a monoculture results in higher farm income. Maize shows higher response in Dombe 1 soil. Fertilizing both results in the higher total profit.

3.4 – Sensitivity Analysis

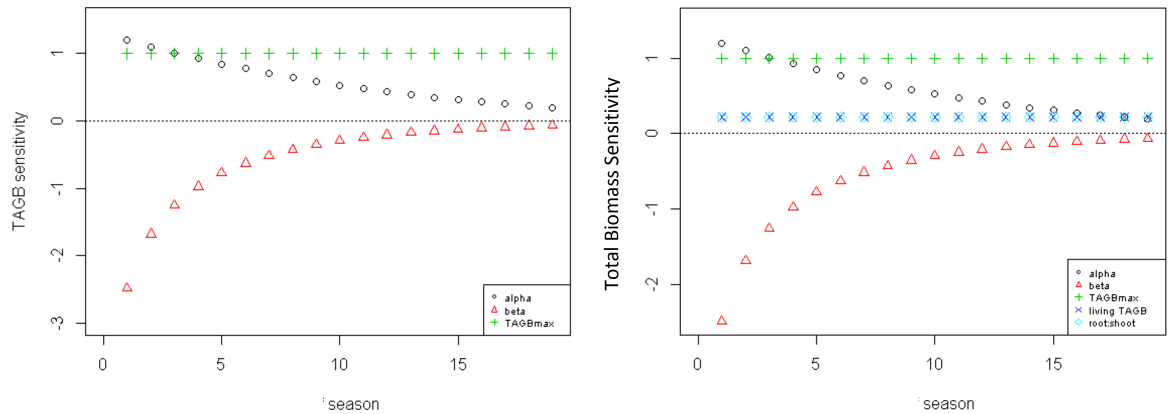


Fig. 19. Sensitivity of FallowSIM parameters on total aboveground biomass (left) and total biomass (right) for different lengths of fallow. Alpha = forest growth parameter; beta = inception point parameter; TAGBmax= carrying capacity; living TAGB = portion of aboveground biomass still alive; root:shoot = root to shoot ratio. See *Table 1*.

The sensitivity value relates to the degree to which a parameter's change affects the state variable, with negative or positive dictating whether this relationship is indirect or direct, respectively. An indirect relationship means increase in one variable causes a decrease in the other. A direct relationship means the increase in one variable causes an increase in the other.

As can be seen in *Figure 19*, aboveground biomass of a fallow is responsive to changes in parameters that form a part of its equation. The two growth parameters, forest growth parameter or α and inception point parameter or β as defined in *Table 1* and *equation 3*, demonstrate a high sensitivity in the first season, positive for the earlier and negative for the latter, which wanes for longer lengths of fallow. Parameter β sensitivity decreases at a faster rate, both approaching 0. Parameter $TAGB_{max}$ from *equation 3* has a constant sensitivity to TAGB throughout all seasons. After season 3, it demonstrates the largest magnitude of sensitivity for TAGB. For short fallows, growth parameters must also be parameterized carefully.

Total biomass, *Figure 19*, is a function of TAGB and therefore demonstrates the same values and pattern of sensitivity for α, β, and $TAGB_{max}$. Total biomass is also sensitive to two parameters, living biomass as a portion of total TAGB and root:shoot ratio, included in *equation 4* to calculate the belowground biomass. Their sensitivity is constant, positive, and comparatively not very high. $TAGB_{max}$ is the most deterministically significant parameter in the long-run for total biomass as well.

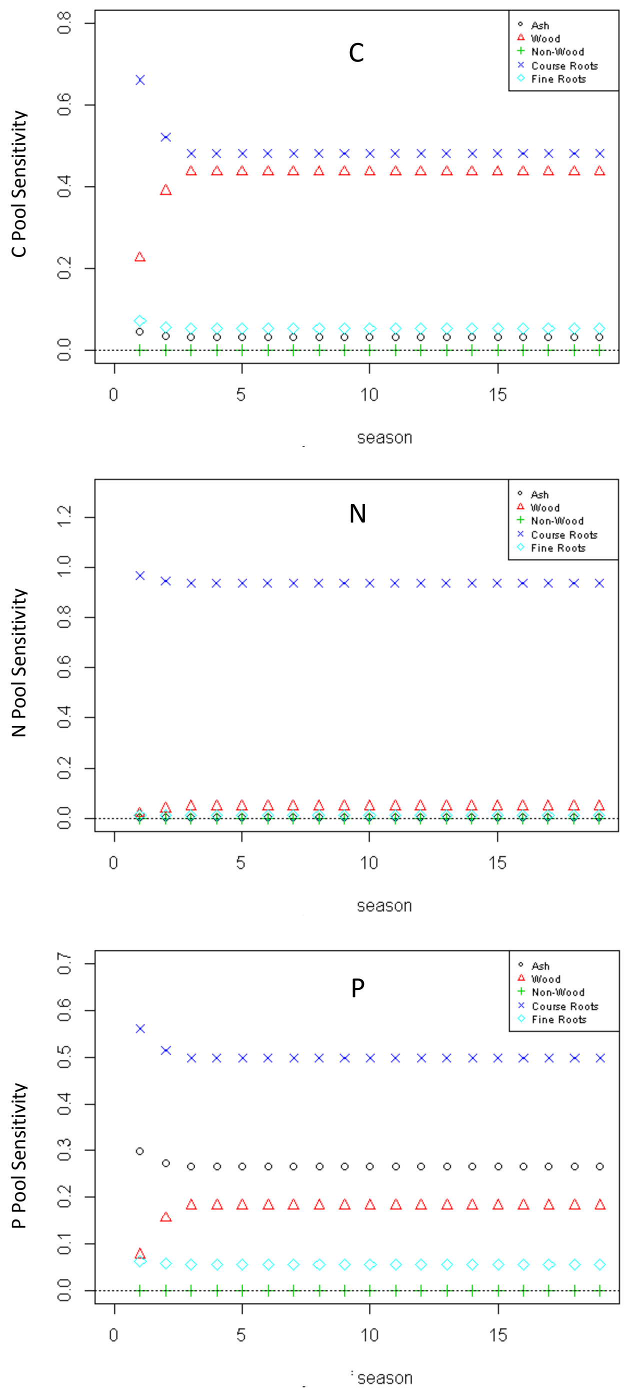


Fig. 20. The sensitivity of content parameters on their respective nutrient pool—C, N & P from top to bottom—for different fallow lengths. Ash = ash content of C, N and P, respectively; Wood = C, N and P contents of woody components, respectively; Non-wood = C, N and P contents of non-woody components, respectively; Coarse roots = C, N and P contents of coarse roots, respectively; Fine Roots = C, N and P contents of fine roots.

The size of C, N and P nutrient pools as state variables demonstrate sensitivity to their nutrient concentration parameters, *Figure 20*. The sensitivities are largely constant, except in the first two seasons where the allometric calculations are overridden between non-wood and wood components of TAGB (see 2.3.2, pg. 16). The ratio of woody elements to total TAGB is lowered, which increases the relative importance of non-wood component additions to the total nutrient pool. This can be seen where the sensitivity of wood content parameters is lower than their constant level, and the parameters of other components are higher. The size of this change in the first two years depends on the difference in nutrient concentrations between wood and non-wood elements; C is the nutrient with the largest difference between wood and non-wood and shows a larger change in these two years than N or P. Moreover, the individual parameter's change in sensitivity is greater for components with larger sensitivities; as with course root C content compared to fine root C content for the C pool state variable. Non-wood contents demonstrate no sensitivity for all fallow lengths and all nutrient pools.

Non-wood elements are completely combusted and do not show an effect on the post-fire nutrient pools. In theory, there should be a small effect as nutrients not volatized remain as ash but these parameters are exogenously defined in the model.

The sensitivity of content parameters reflect the share that the components they pertain to have in the post-burn nutrient pools. This is a function of the comparative size of the components (1), the effect of fire on the components (2), and the nutrient content values themselves (3). To illustrate this, an example will be examined. For the state variable P pool, the course root P content parameter has the largest sensitivity. Coarse roots have a relatively large mass, 90% of belowground biomass (1), are unaffected by fire (2), and have a content value higher than that of wood components and equal to that of fine roots (3); in comparison, the woody component size is diminished by fire (2), recording smaller sensitivity. The sensitivity of fine roots P content, a component also unaffected by fire and having the same value for its P concentration parameter, is one-ninth of the sensitivity for coarse roots, equal to the allometric ratio fine roots : coarse roots. The sum of all component sensitivities is 1 for all fallow lengths for all pools.

The pools are also sensitive to parameters determining and allocating biomass, α, β and $TAGB_{max}$. The parameters determining TAGB show the same magnitude and pattern of sensitivity as in *Figure 19* for all nutrient pools. The pools are sums of nutrient stored in all components, which are directly calculated from TAGB. The sensitivity of the allometric parameters for the different nutrient pools depends on the difference in content values between the components whose size the allometric parameter ascribes.

The combustion coefficient affects nutrient pools by determining how much of aboveground biomass is consumed in the fire. The sensitivity is negative and is larger for C than for the other nutrients. N and P, nutrients with low concentration in wood, are a lot less affected as they are predominantly found in non-wood components, which are completely combusted. Whether the sensitivity of the allometric ratios is positive or negative depends on whether the component to which the ratio primarily pertains (e.g. fine roots:total roots determines the proportion of fine roots primarily, and when this ratio is subtracted from 1 it determines to portion of coarse roots) has a higher concentration of the nutrient, in which case it is positive, or not, in which case it is negative.

The wind effect parameter has a negative sensitivity value as it lowers the quantity of ashes and the size of the nutrient pools contained within. For C and N, the magnitude is low as these nutrients are largely volatized during combustion; P is more present in ashes and is more affected by this parameter. Similarly, another parameter affecting the quantity of ash, ash:TAGB, has low sensitivity for C and N and a higher one for P. The deviation of sensitivities for the allometric ratios from constant values during fallow length periods of 1 and 2 years is seen for the nutrient pools, with the explanation being the same as before.

The sensitivity of FallowSIM parameters to the state variables of C, N and P losses from the burn event are shown in *Figures 21*, *22*, *23*.

A familiar pattern emerges for growth parameters α and β and $TAGB_{max}$ for all three nutrient pools. Of the allometric ratios, only woody:TAGB shows sensitivity due to the different effects of fire on woody and non-woody elements and the consequences for losses. The sensitivity is negative as a larger woody component signifies less total biomass combusted and less nutrients lost.

Ash parameters and wind effect also have a similar pattern. They also have switched quadrants, with ash:TAGB becoming negative and wind effect becoming positive. Both parameters show low sensitivities for nutrient losses of C and N, and a larger one for P for reasons already discussed.

Content parameters show sensitivity for the nutrient losses state variables. The sensitivity of a parameter for a nutrient depends on the relative share of the nutrients in the component. For example, ash contents for P losses shows high sensitivity while ash contents for C and N on their respective nutrient losses show low sensitivity.

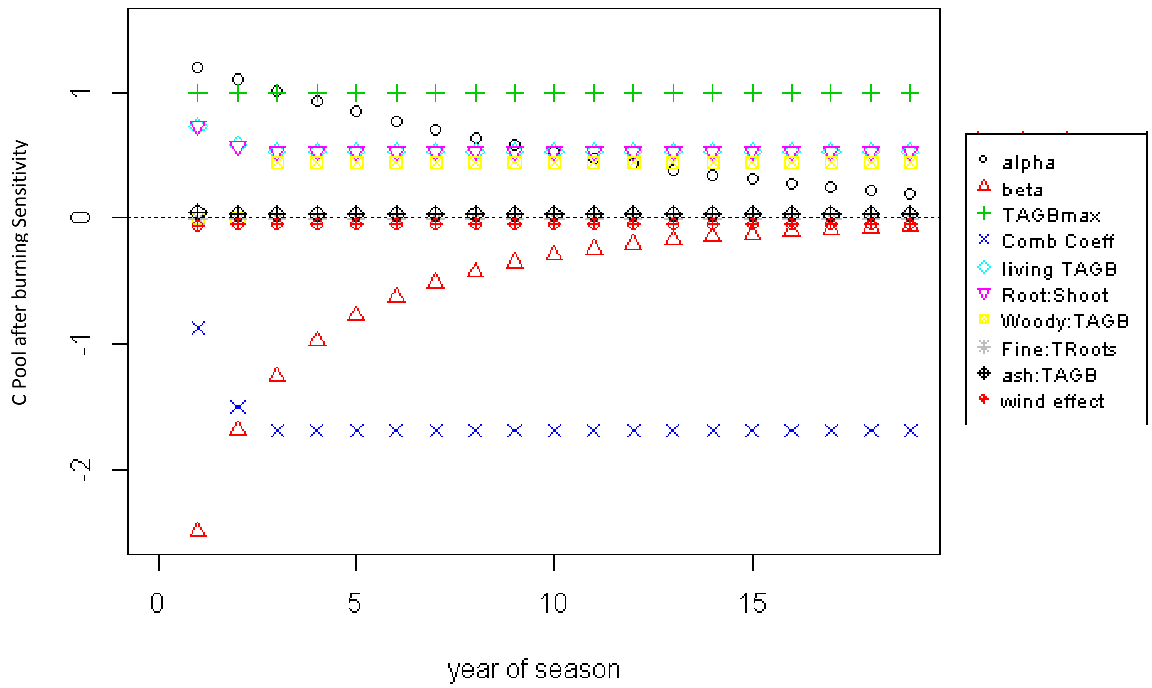


Fig. 21. Sensitivity of FallowSIM parameters on the post-burn C pool for different lengths of fallow. Alpha = forest growth parameter; beta = inception point parameter; Comb Coeff = portion of aboveground biomass combusted; root:shoot = root to shoot ratio; woody:TAGB = portion of total aboveground biomass that is woody; fine:TRoots = ratio of fine roots to total roots; ash:TAGB = ratio of ash mass to pre-burn total aboveground biomass; wind effect = portion of ash carried away by the wind. See *table 1*.

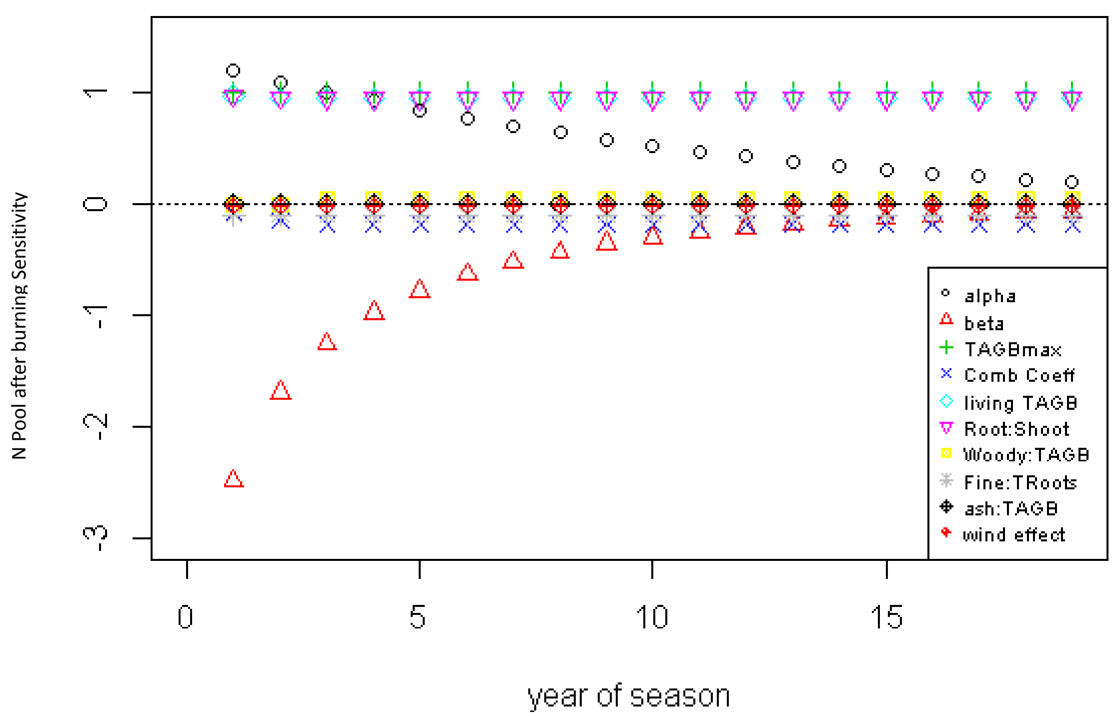


Fig. 22. Sensitivity of FallowSIM parameters on post-burn N pool for different lengths of fallow.

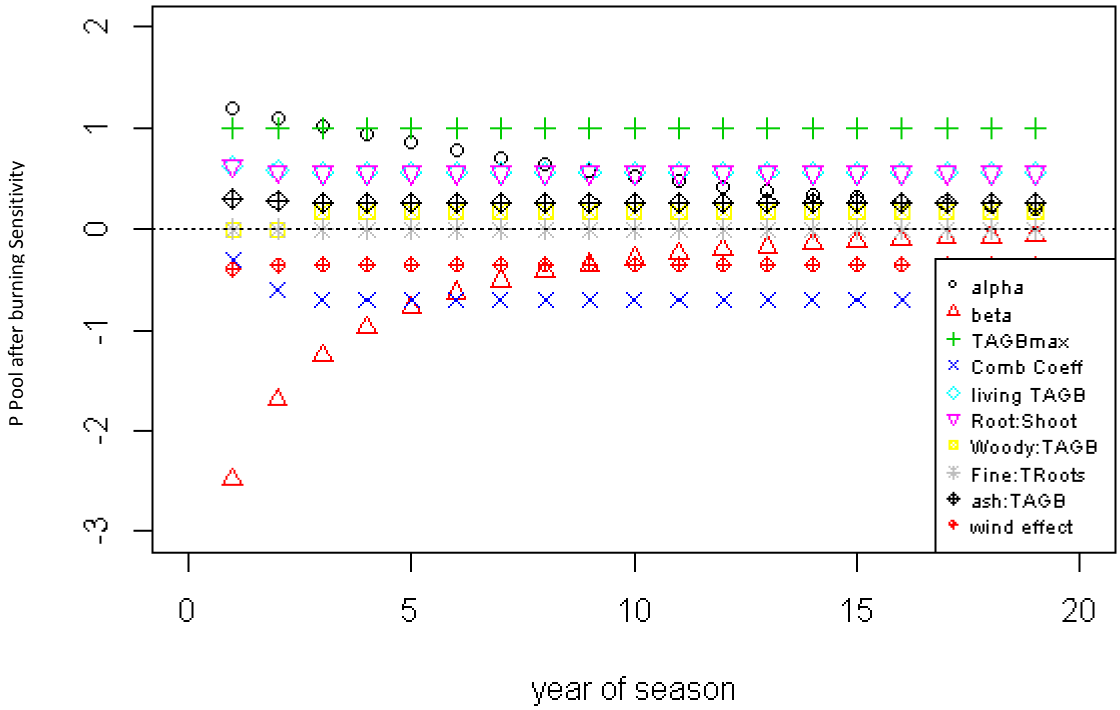


Fig. 23. Sensitivity of FallowSIM parameters on post-burn P pool for different lengths of fallow.

- 4 - Discussion -

4.1 – Labour

Labour availability is critical in Manica smallholder farming systems because of the reliance on labour for agricultural tasks; use of animal traction is limited.

Cropping activities have different labour restrictions. Land preparation, in particular, and harvesting are extensive activities. Sowing is not extensive but does not require much labour. The first weeding is the most critical activity in regards to labour demand, evidenced by the fact that household's rent labour predominantly for this activity. At this point, crops are in a critical phase of their growth and very sensitive to weed pressure; accounting for the inflexible timeframe observed. Arzarun (pers. comm.) also stated that first weeding is the most critical activity for cultivation and that labour restrictions appear in northern Mozambique. The second weeding occurs over a larger time frame than the first weeding when crops are more established and able to compete with weeds to a greater degree, and as such is not as critical.

As observed in field visits, different livelihood strategies are pursued by those engaged in agricultural production in Manica. Farming is an economic necessity for many, with farm type 2 and Farm types 3 diversifying labour utilization. In Matsinho, where Sunbiofuels offers employment, all except Farm type 1 were engaged (pers. comm.: Leonardo). As a result, the differences in productivity between Farm types reflect different prioritization of labour use and, consequentially, differential coordination between labour and the input demands of cropping. This is seen in *Figure 7* where only Farm type 1 demonstrates consistent increases in land utilization for larger household size.

The results indicate that cultivated area is a good predictor of productivity for the sample set. However, Dombe has both higher productivity and cultivates higher areas than Zembe and this generalization could not hold for other locations in Manica. On the other hand, productivity allows for larger cultivation areas, or drives them by offering larger returns to labour.

In *Figure 7*, it is interesting to note that an upper limit to cultivated area per person seems to be indicated, separating a point-free left with the right of the graph.

This picture can be projected in a dynamic way; a household size of two or three implies a new family that can evolve into a higher farm type; curiously, they are on the aforementioned frontier and can evolve to continue up the slope (towards Farm types 1 and 2) or keep their area as the household increases (types 3). For Farm types 1, there are different distances from the limit showing that farmers can also change Farm types the other way around (pers. comm.: Leonardo and van de Ven).

If this limit is indeed actual, then intensification options that raise labour productivity (such as use of pesticides), particularly in the limiting first weeding activity, could increase the slope of this line and lead to cultivation of larger areas. Since fallow land will be displaced, the carbon balance of the biofuel feedstock from type 1 smallholders would be negative and sustainability criteria would not be met.

4.2 – FallowSIM and BurnSIM

4.2.1 – FallowSIM FIELD runs

FALLOWSIM demonstrates use as a thinking model by indicating the relative importance and dynamics of different fallow components for nutrient provision during the successive cropping stage.

Burning results in high losses of N in the aboveground biomass, a fact well known and well recorded. The correlation with burn intensity implies that less intensive burning technique might avoid unnecessary losses, creating a trade-off between N loss and labour for land preparation. On the other hand, P residues in ashes are high in comparison to successive mineralization of fallow residue; although it is not efficiently utilized by the crop resulting in losses (Hölscher, 1997). Fallow residues were found to be an important source of nutrients with prolonged effects on the cropping cycle. This is in concurrence with Buschbacher (1988) who states that decomposition of unburned woody residue may provide one-half of the nutrients taken up for the next 8 years.

FALLOWSIM's most interesting questions stem from the belowground. Belowground nutrient pools and the annual mineralization are shown to be relatively large, particularly as this biomass is not affected by fire. As such, the question arises to the precise fate of nutrients mineralized from fallow belowground residues. To what extent do minerals leach? Are deeper rooted crops better able to mitigate this, and as such, what is the relationship with succession of cultivation of the given crop in terms of years and leaching loses? FALLOWSIM stands ready to explorative manipulations.

The use of FALLOWSIM in long-term rotation in FIELD as in *Figure 13* records equal regrowth patterns of secondary forests throughout time. Fallow secondary growth rates have been found to depend on land use intensity, duration of use and type of use, by depleting soil nutrients and physical soil changes (Hughes et al. 1999, Brown et al., 1990; Kauffman et al., 2009; McGrath et al., 2001). However, Buschbacher (1988) did not find this relationship, implying that there has to be conditional mechanisms determining this relationship. Indeed, the effect of nutrient limitation on secondary forest growth remains unclear, due to nutrient conservation mechanisms of tropical eco-systems (Noij et al., 1993). Nonetheless, N and P losses are very large during slash and burn and its aftermath and can become limiting for fallow growth in the long cycle of shifting-cultivation (Hölscher, 1997). Thus, less frequent cropping would allow for greater nutrient recovery through collection of deposition. Shifting agriculture has been in use for millennia by humanity and with traditional low intensity can have little effect on the ecosystem nutrient balance, even in sophisticated urban cultures like the Mayas (Brown, 1990). However, even small inferences should be made with caution as mechanisms largely remain a mystery; indicatively, Lawrence et al. (2005) that found higher C, N and P soil contents correlated with increasing number of prior cultivation cycles after accounting for inherent fertility differences in an Indonesia wet tropical rainforest. Thus, there is a need for local information to model fallow effects.

FARMSIM as it was used in this work included only a 5 year fallow and a 12 year cropping cycle in its run; as such, decreasing growth rates of fallow are not applicable. Inferences on the long-term sustainability of this system cannot be made without quantifying and accounting for the effects of land use on fallow growth. Nonetheless, it can be inferred that intensification and population growth will place a greater pressure on land resources; eventually, as uncultivated land becomes scarcer, fallow times will shorten affecting the ability of shifting cultivation to supply sufficient nutrients to cropping. As such, shifting agriculture should be abandoned but for places that will maintain low land pressure and the luxury of long and plentiful fallows.

Fertilization options compared to fallow show that replacing fallow will require significant additional costs. As such, it is unlikely to be used for low priced crops and preferred for cash crops. On the field level, fertilizing (in the given regime) at the beginning of a relay system showed little effect on the relay cash crop and gives evidence that fertilizing mono cultures might be more worthwhile.

4.2.2 – FallowSIM

The allometric calculations rely on constant ratios to calculate quantities of component biomass and the contained nutrient pool size. This approach assumes that biomass structure is constant overtime, which is not representative of reality (Brown et al., 1990; Long, 2012; Yamakura, 1986; Uhl, 1987; Johnson et al., 2001).

Succession follows a pattern of fast establishment of low wood-content forbs, grasses, and ferns followed by pioneer bushes, softwood trees, hardwood trees and eventual domination by the later as maturity is approached (Brown et al., 1990). As such, the non-wood portion of forest biomass increases overtime. Similarly, the high root:shoot of initial fallow years is not maintained (Brown et al., 1990; Ryan et al., 2011). FallowSIM has constant nutrient contents overtime, which is not precise (Uhl, 1987). As such, the allometric ratios and component nutrient content parameters should be calibrated to the secondary forests at the time they are slashed and burned, as this is when it is most important to reflect nutrient availability.

Further complexity would lower FallowSIM's parsimony, and is not necessary. The module serves to simulate nutrient additions from slash and burning fallow to cropping in FIELD, a summary model in itself. FallowSIM should be seen as a thinking model as well; the simplified representation of fallow nutrients dynamics allows for significant elements to be identified (e.g. leaching), and for the effect of fallow on cropping to be represented to an appropriate degree within FIELD, as will be discussed.

FallowSIM projects no changes in soil nutrients during fallow growth. This is contrary to the common assumption that fallow rest periods stimulate accumulation of nutrients in the soil. Soil nutrient dynamics are complex and depend on soil conditions which vary with location (pers. comm.: Janssen). Literature shows positive changes (Franke et al., 2008; Kauffman et al., 2009; Aweto, 1981) and no changes (Buschbacher, 1988; Kauffman et al., 1993; Hughes et al., 1999; Kauffman et al., 2009; McGrath et al., 2001; Williams et al., 2008) in soil nutrient pools for tropical soils as a result of fallow. Nhantumbo et al. (2009) found decreasing organic C and total N for the first 15 years in sandy soils under fallow in arid to sub-humid climates of Gaza Province, Mozambique followed by increases; although, this pattern is only apparent for average values and disappears if variation is taken into account, echoing Kauffman et al. (2009) that C changes could be so small that they are unnoticed with measurement error and variability. Juo et al. (1995) found a decrease in soil C in the first 7 years of fallow, followed by an increase. Johnson et al. (2001) also found long term decreases in soil C, N, P and K in secondary forests (20-60 years), to levels below primary forests, implying a possible future increase. Rusinamhodzi (pers. comm.) found no changes in soil C during fallow on the Manica plateau in Zimbabwe. Soil differences between secondary and primary forests (Johnson et al., 2001; McGrath et al., 2001) imply there must be a change in the long run, beyond the scope of FallowSIM's use.

Knops et al. (2000) found slow long-run increases in soil C and N in a Minnesota sand plain under fallow where soil C and N were depleted by cropping, with accumulation rate of soil C controlled by the rate of N accumulation and decreasing as C soil stocks increase. Weathered tropical soils do not seem to have the capacity for large accumulation of nutrients and instead accumulate it in aboveground biomass, developing an efficient uptake of nutrients in a rapid turnover and almost closed system (Brown et al., 1990). As such, FallowSIM's assumption that soil enrichment for cropping will come from the ashes and residues of the aboveground pool, as state by Juo et al. (1996), can be tested against available data sets.

Although effects on pH are well recorded (Mackensen et al., 1996; Juo et al., 1996), fallow pH was not measured in the study areas, hence pH is assumed constant during fallow, reflecting a return to the measured cropping pH once fallow is slashed and burned.

The difference in sensitivities imply that greater care should be taken in defining certain parameters for different lengths of fallow to be used.

4.2.2 – BurnSIM

The construct of BurnSIM was based primarily on data retrieved from: Kauffman et al., 2003; Kauffman et al., 1993; Guild et al., 1998; Kauffman et al., 1995. The papers come from the same group of researchers that employed similar methodology and provide a good amount of details, making it very handy for comparison. The equations for aboveground C, N, P and K losses as a function of TAGB loss were verified using data from Mackensen et al. (1996) and van Reuler (1996).

Evidence for ash N content varying negatively with a higher TAGB combustion coefficient was found, but variation is too high to establish. Ash quantity as 5% of TAGB combustion is a generalization and not without variation; van Reuler (1996) found the same quantity of ash resulting from different biomass.

The equation for the combustion coefficient of woody biomass could not be validated as these data were not reported. However, it is logical that it is closely related to that of TAGB, except a little lower, as woody parts represent the predominant portion of TAGB, and the more resistant pool to combustion.

Combustion of non-wood elements is assumed to be complete. This is a reasonable assumption for a dry tropical forest, with burning coming a couple of dry months after the slashing; Kauffman et al. (1993) found 92% combustion for non-woods for the lowest fire intensity and 100% for medium and severe burns. For moist forests, this assumption would be less appropriate (Kauffman et al., 1995; Guimarães, 1993; Mackensen et al., 1996). Gray et al. (2006) found 100% of leaf mass is lost at 400°C.

BurnSIM assumes that the fire has no effect on the soil during combustion. Indeed, heat changes physical and chemical properties of soil; increasingly so at higher temperatures and for longer exposure times. Organic compounds are broken down into inorganic forms; some of which remain in the soil and some of which volatize. Soil pH is increased by the release of soluble cations, which coincidently has effects on microbial activity. Heat from combustion lowers moisture (Wilbur et al., 1983), lowers OM, and increases bulk density (Ellis et al., 1983).

Mackensen et al. (1996) observed temperatures between the ground and one meter high reaching between 621-953°C; albeit measured in a simulation. However, the fire sweeps across the terrain in slash and burn rather than lingering (pers com: Leffelaar) and the high temperatures at the surface quickly diminish into the soil (Wan et al., 2001). Therefore, the aforementioned effects are accentuated in the top 2-3 cm of the soil, which even when averaged at a sample for even 0-10 cm depths, significant changes cannot be observed (Wan et al., 2001; Ellis et al., 1983; Kauffman et al., 1995; Kauffman et al., 1993). The FIELD model runs used a soil depth of 20 cm.

BurnSIM does not account for farmers' practice of collecting unburned woody residue into a pile and reburning them to diminish residue quantity, as observed by Kauffman et al. (1995). Unlike the sweeping fires of the first burn, second burns persist for an extended period of time and causes larger physical and chemical changes to the soil at deeper depths. Although the area of such a fire averaged across a hectare should not be important enough to include in a simple model like FIELD. Reburning would combust more woody material and consequently channel more nutrients into ash or volatize them as a loss; this can be accounted for by including the second fire combustion quantity into the TAGB combustion coefficient when inputting it into the model.

Leaching losses are not considered as no data were collected or found in literature. Jaramillo et al. (2003) found 88% of root biomass in the top 40 cm of the soil profile, and 51-61% in the top 20. As such, most roots are within the rooting depth of the successive first crop, maize.

The largely unexplored question of what happens belowground is interesting and significant considering its share in organism biomass, 25%, and nutrient storage. For the parameters used at all lengths of fallow, 23% of all fallow N held in biomass is in roots and 36% of all P. *Equation 8* was used for this calculation:

Equation 8.

$$\frac{\prod_{Cmpnt=CmpntPathwayRatios}(AllometricRatio^{Cmpnt} * Content^{Cmpnt}_{Nutrient})}{\sum_{Cmpnt=AllCmpnts}(\prod_{Cmpnt=CmpntPathwayRatios}(AllometricRatio^{Cmpnt} * Content^{Cmpnt}_{Nutrient}))}$$

Where:
$AllometricRatios^{cmpnt}$ = *Constant allometric ratios from* Table 2 *for component* cmpnt
$Content^{cmpnt}_{nutrient}$ = *Nutrient content of component* cmpnt *from* Table 2 *as a portion*

All component pathways refers to ratios from *Table 2* that define a component as a function of TAGB, for example, for coarse roots: $R_{root:shoot}$ and (1 - $R_{FineRoots:TotalRoots}$). This demonstrates FallowSIM's use as a thinking model; the simplification allows for identification of areas of interest to be explored into greater detail.

The allotment of ash **(1)**, residual woody elements after the burn **(2)**, fine roots **(3)** and coarse roots **(4)** into FIELD as fertilizers **(1)** except for C, crop residues **(2)**, organic amendments **(3)** and a separate crop residue roots pool **(4)** respectively reflects the chemical form of nutrients as it pertains to plant availability of these fallow components. Fine roots decay faster and as such are more appropriate as an organic amendment. The module makes the assumption that ash nutrient additions are in available inorganic form and are hence similar to fertilizers. C from woody residues is allotted to the resistant pool.

Indeed, short-term bursts of soluble inorganic P not spanning beyond a season are noticed post-fire (McGrath et al., 2006; Kutiel et al., 1989; Sáa et al., 1994). As such, a sizeable portion of P in ashes must be in soluble forms; as suggested by the higher amount of soluble P found by Sáa (1994) when soil was burned with plant material compared to without. However, combustion can also render P into insoluble forms that are not available for immediate plant-uptake (pers. comm.: Leffelaar); for example, it can bind with heavy metals at high temperatures (Sáa et al., 2006). Kutiel et al. (1989) found less available P from soil combusted at 600°C than from 250°C. Gray et al. (2006) found a peak of inorganic P from combusted leaves at 200°C, with trace amounts for higher temperatures where P was found predominantly bound in organic forms or insoluble inorganic forms. Ohno et al. (1990) found between 43%-56% of total P was in plant-available form for different wood ashes, an industrial byproduct of paper pulping. Moreover, some of P volatized into P_5O_{10} will bind onto smoke particles, react with basic oxides, or dissolve in water vapour to form phosphoric acid; all of which return to the earth in forms of different solubility (Gray et al., 2006). In general, the mechanistic details governing the fate of residual P in slash and burn is largely unexplored and this is reflected in FallowSIM.

For N, Wan et al. (2001) found a peak of NH_4 followed by a peak of $N0_3^-$ lasting up to two years after the fire concentrated in the uppermost soil layer, implying that a portion of it is directly from ashes. Even if ash N is partly insoluble post-fire, the peaks observed could be from rapid nitrifiers, as Kutiel et al. (1989) found for combusted soils. Gray et al. (2006) found a peak of NH_4 at 300°C and of $N0_3^-$ at 400°C for leaves of three different temperate trees, with an additional peak of ammonium at 100°C for huckleberry; with volatilization occurring as temperature increased.

The high variation found in data for ash contents and quantity is not surprising. Fire is spatially heterogeneous; van Reueler (1996) recorded barriers in the slashed field holding back fire and Mackensen et al. (1996) observed shaded areas of the field with higher moisture in the remaining residues retarding the spreading flames as they entered the patch. Kauffman et al. (2003) also mention the effect of topography and purposeful foresetting tactics as having an effect on the burn. Species have different contents in their components and burn differently due to physical and chemical properties (Gray et al., 2006); e.g. waxy cover around pine needles lower combustion efficacy. Wilbur et al. (1983) also found greater variability of nutrient concentrations on burned than unburned plots. As such, differing factors will affect fire spread, temperature and duration and hence results, which raises questions of to what degree in different ecosystems/forests, and at what classification scale (e.g. Miombo woodland, dry tropical forest, tropical forests) generalizations can be made. Such an exploration would be necessary to establish stronger relations between TAGB combustion coefficient, for example, and ash quantity, a relationship claimed by Mackensen et al. (1996). Similarly, ash nutrient contents could be included as dependent variables rather than being predetermined.

It is clear from literature that combustion does have effects on quantity and quality of nutrients, quality referring to their chemical form and solubility. Effects of combustion change with fire properties (e.g. duration, intensity) and vegetation properties (e.g. moisture, physical properties, chemical properties). Possibly, these properties could explain variability of ash nutrient contents and quantity at different magnitudes. The next step for FallowSIM would be to have input be related to these properties and the algorithm adjusted to calculate content parameters and ash quantity; this would allow for exploratory comparison between improved fallow types, for example.

Consequently, the possibility of fire management technique arises; can slash and burn can be designed to minimize losses and produce more plant-available chemical forms? Or is Hölscher (1997) correct in his assessment of slash and burn that it results in unsustainable losses and should be abandoned? As can be seen with FallowSIM/BurnSIM, a large amount of nutrients are contained in ashes and remaining wood residue. With this in mind, there is a tradeoff between avoiding nutrient loses and clearing the land. Less destructive options will clearly require more labour, which requires that the returns on that labour in consequent cropping have to be acceptable to the farmer for him to adopt such a practice.

K held in crop residues, crop root residues and organic amendments is not calculated in FIELD and the K stores of fallow except for that added as ash is lost from the calculations. K is in general not limiting in tropical soils, and Manica is no different (Maria et al., 2006); as such, it is not necessary to customize FallowSIM to include K feedback.

4.3 – Farm Level

In a relay, the first crop takes up the first part of the season when higher precipitation grants it high access to water. The growth of the second crop is limited by water availability for the rainfall pattern and amount used. This problem was addressed with separate monocultures. On the other hand, the first crop in a relay benefits from additional residue production of the relay crop.

Parameters regarding share of rainfall between crops and mineralized nutrients were estimated. Field experiments to provide better estimates for these values would offer more accurate model estimates. However, it is unlikely that observed values would deviate far enough from the estimates used to render the asymmetry invalid.

The consequence of this competition is underperformance of the relay crop in comparison to the first crop. Therefore, intensification options that do not grant additional water supply are bound to concentrate most yield increases on the first crop. Secondary application of fertilizer at the onset of the relay crop would also address nutrient competition, and make highly leachable nutrients more available to the relay crop (e.g. K). If simpler options are considered as was the case in this study (i.e. target labour productivity, do not address water supply, apply nutrients at the onset of the season), a greater degree of monocropping will have to be adopted to reap greater marginal benefits from inputs, through higher cash crop yields and hence revenue.

On the other hand, relay cropping was shown to grant higher value of output with stringent labour limitations and no inputs. Two crops make better use of labour throughout the year, as will be discussed shortly. Moreover, a positive effect of relay soybean on maize yields was noticed; probably due to soil amelioration with additions of N, through symbiotic fixation, and C. As such, use of relay cropping in current production systems in Manica seems justified.

The results obtained from the FARMSIM model imply that Farm type 1 on Dombe 1 soil is well situated to intensify and commercialize agricultural production in interaction with the market. This is based on the assumption that Farm type 1 farmers are able to utilize more labour per period than they currently do, that opportunity costs of labour hours for Farm type 1 are low. This is based on labour availability calculations involving how much hours are available per week in a Farm type household, and how many weeks are available for an activity. Considering their focus on agricultural production, this assumption is not unreasonable, but a comparison with alternative labour uses, e.g. plantation employment, would be useful to confirm the validity and rationality of such an assumption.

Two crops make better use of labour throughout the year, as different labour inputs for the two crops, particularly the peak input first weeding, occur at different times. By spreading out production, a greater amount of this limited resource is available as an input for production.

A complete overlap of activities between maize and soybean, as opposed to a more flexible partial one, only occurs at the second weeding of maize and the sowing of soybean. The labour saved in a relay system compared to separated monocrops is manifested in no separate land preparation for soybean and less sowing time. Given Farm type 1's higher productivity and greater amount of labour and land, the additional inputs for monocropping over relay cropping are compensated by higher production and profit. Indeed, type 1 farmers in Dombe already practice separate monocrops of maize and sesame with these very results (Leonardo, in prep.).

Type 1 farmers are the best endowed in terms of land, labour quantity and labour productivity; FARMSIM can be used to see whether farm level benefits can be accrued from monocropping over relay cropping for other Farm types. In these Farm types, labour use is diversified and hence has higher opportunity cost than for type 1 farmers; as such, the same amount of labour currently used should be maintained in modelling explorations unless higher returns on labour, taking into account other activities, can be established. With greater limitations of land and labour, these Farm types might also benefit from the efficient use of labour and higher land productivity offered by relay cropping (Mkamilo, 2004). Indeed, differential goals of farming for the different Farm types should be considered; Mkamilo (2004) states farmers see maize as the major crops with *any additional yield* of the relay sesame considered beneficial. Taking yield quantities into regard, Farm type 1 does not follow this mentality but a good argument can be made that other Farm types do to some degree. Other Farm types in Dombe and Zembe currently grow sesame and sunflower in a relay system respectively.

Location and soil types are also noteworthy as they change labour and land productivities and hence opportunity costs for labour. Although the effects of these variables were not explored, FARMSIM's current set-up allows for it.

On the farm level, fertilizer inputs were shown to result in higher overall profits if monocultures were practiced. FARMSIM results indicate that larger financial gain comes from fertilizer application on maize than soybean for Farm type 1 on Dombe 1 soil. This may not hold for other Farm types that do not sell their maize at the opportune times with higher market prices.

The magnitude of profits from the scenario runs should be interpreted carefully, they are dependent on the price parameters. A price sensitivity analysis was conducted for simulation 6. Input prices of labour and fertilizer showed a low sensitivity of -.02 and -.10 respectively. In comparison, output prices of soybean, maize high and maize medium were .25, .32, and .55 respectively. Therefore, the attractiveness of soybean and maize is highly dependent on market price; the greater profit obtained from fertilizing maize can easily be altered with relatively small market fluctuations. As such, diversification of crops is a sound strategy as a hedge against price volatility.

Although input prices show less sensitivity, they might be prone to greater variation. Fertilizer prices used as input are those from Chimoio, a market in Dombe and Zembe will likely sell them at higher prices. If fertilizer is to be encouraged for its positive effects on household income, it would be worthwhile to aid market connections into rural places, perhaps in the form of government supported distribution, to keep prices closer to city prices.

The choice of crop derives from historical human agency as well as bio-physical endowment inherent to the land. In Dombe, production of sesame was destined for local consumption before a trader connected it with the export market, spurring higher production (pers. comm.: Leonardo). In Zembe, a man called Abraham arrived after 1992 on government assignment to help resettle the land; settling down, he began offering seeds and teaching local farmers how to crop sunflower, to feed the pressing operation he began (personal comm.: Leonard, van de Ven). In Matsinho, relay cash crops were not observed; its location nearest Chimoio offers more options for labour. Any effort to promote a crop in an exploration study must be supported by structural development, as stressed by Hanlon et al. (2012).

Within sight of Matsinho is a large industrial poultry farm which offers free manure to those who come to take it. In Matsinho, some farmers use this fertilizer but only for horticultural production, not for cropping. They claim it is not worth it for cropping because the land is large; the returns are too low for the effort investment. As seen during field visits; manure is transported by bicycle as only the best-off farmers have access to animal draft carts. Developing market connections for provision of fertilizer will keep costs and opportunity costs low and encourage their wider use.

- 5 - Conclusion -

On the field level:

- on tropical soils, fallow accumulates macronutrients predominantly in biomass and transfers them into the cropping cycle through ash (P, K) and through unburned residue (N,P,K); this amount can be large and increases with fallow time until reaching climax vegetation
- nutrient provision from fallow to cropping cycles can be significant, resulting in sustained higher successive cropping yields compared to not having conducted fallow
- fallow of short duration (i.e. one year) has limited effects on yield and, considering nutrient losses occurring with burning, is not a good long-term strategy for nutrient management
- belowground fallow biomass pools were shown to be large, their fate (e.g. leaching of mineralized nutrients, decomposition rates) must be better understood to improve understanding of nutrient transfer from fallow to cropping
- relay regimes of maize and soybean showed greater yields for maize and lower yields for soybean than respective monocultures, increases in nutrient availability are predominantly utilized by maize resulting in low yield response of relay soybean to nutrient inputs; soybean yields can be improved by cultivating them in monoculture or addressing water and nutrient limitations in a relay system
- FIELD without including K variables and calculations could be more appropriate for modelling relay cropping with fallow as K becomes limiting while this is not the case in Wilson's field trials; alternatively, its formulation in the algorithm has to be improved

At the farm level:

- relay cropping systems has a higher total value per ha than monocropping in the case of no input of mineral fertilizer; the use of fallow in the context of land abundance allows for higher yields
- fertilizer use results in larger incomes for Farm type 1 on Dombe 1 soil, for both maize and soybean (with market prices from data)
- FARMSIM should be used to explore labour saving technologies as they increase labour productivity for smallholders in Manica Province
- market structure is key to implementation of intensification options

The aim of this work was to adapt and use FARMSIM to compare and judge different options for intensification. FIELD has been adapted to allow for relay cropping and for use of fallow; this will allow for current practices in Manica to be compared to alternatives (e.g. use of mineral fertilizer, monocultures) on a field scale. At a farm level, effect of labour on farm performance was integrated indirectly through the inputs that are input into the farm level parts; for example, Farm type 1's yield and labour requirements are accounted for without accounting for the interaction between. A relation in the model could not be established. Income from agricultural income is calculated in the set-up without accounting for losses.

The framework was used to explore fertilizer use in different cropping arrangements and its effect at the farm level. The process has been shown to work at a static level. Adding a time dimension by using weather data should be straight forward. Other farm types and soil types can be explored by changing parameters. Moreover, sweet sorghum can be included. The modeling framework will not support long-term explorations (e.g. 20 years) as the fallow simulation will become inaccurate and constants at the farm level (e.g. productivity, household size, input costs, output costs) will in reality change.

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- 7 - Appendices -

Appendix 1 – History of Mozambique and Manica Province

The people populating the lands delineated by modern Mozambique through history have continuously been influenced by the wider world through trade and coercion. Invasions, settlements and trade connections came from the interior (e.g. Karanga, Maravi, British South Africa Company) as well as from the coast (e.g. Madagascar, Turks). Several centuries before Portuguese arrival, Swahili and Arab traders established themselves mainly on coastal entrepôts, with some backtracking of trade flows into the interior, to trade for gold and feed it into the Indian Ocean trade network. At the end of the 15th century, Vasco de Gama passed through Mozambique en route to India. For the Portuguese, the primary focus was India, but encountering financing difficulties they sought to profit from the Mozambique gold trade and seize it from the Arabs. The Portuguese crown established trading and military forts, primarily on Mozambique Island and Sofala; and slowly spread them throughout the coast, and, much more slowly, into the interior.

The Portuguese did not exercise an absolute control of Mozambique for most of their history in the area. The system of strong local chieftaincies was well maintained and the Portuguese, often devoid of force, relied heavily on diplomacy. New strong centralized "states" rose from both native and Afro-European origin and were strategically befriended or challenged to maintain Portuguese profit from trade.

In the wider scramble for Africa of the late 19th century, Portugal sought to establish their sovereignty over the lands of Mozambique and adopted a stronger colonial model, later further restricted when the territory became an overseas province of Portugal under the fascist Estado Novo (1933-1974). As in the rest of Africa, this direct form of colonialism resulted in gross manifestations of inhumanity and led to independence movements. In Mozambique, FRELIMO (Frente de Libertação de Moçambique) was formed in 1962 by Mozambican intellectuals in Dar es-Salam and began guerilla operations two years later which culminated into a front of the Portuguese Colonial War. Following the Carnation Revolution in Portugal of 1974, Portugal offered independence to its oversea colonies.

FRELIMO sought to establish a socialist state which, amongst other things, included agricultural collectives. Three years after independence, RENAMO (Resistência Nacional Moçambicana) took up arms to start the Mozambican Civil War. The group was supported significantly by the South African government. It adopted a strategy of rural terrorism which brought much devastation to the infrastructure and humanity of the countryside and caused a great disruption in agricultural activity.

In 1992, hostilities officially ceased and Mozambique was given the fresh gasp of peace. FRELIMO abandoned Marxism for a free market democracy model, including RENAMO as a political party. The government sought to resettle areas which had been vacated due to decades of violence with private holdings.

It is known that Manica Province was connected to the local trade network from coast to the interior long before Portuguese arrival. By the 16th century, the Karanga dominated this area, consisting mostly of small strong chieftancies, sometimes organized, often weakly, into a large political entity. Believing in the fact that large gold deposits existed in Manica, the Portuguese crown sought profit and sent a military expedition headed by Francisco Barreto in 1573. Dying, his next in command, Vasco Homem, succeeded in entering Manica and, achieving a hollow victory against the Kiteve and being gravely disappointed upon seeing the rumored mines, fully retreated. Several larger kingdom were founded on this territory such as the Manica Kingdom. The Portuguese established some *feiras* (fairs) for trade and later a few outposts, at times destroyed, at times rebuilt. Portuguese sources describe low productivity and lack of surpluses (Newitt, 1995) although the accounts come from the momentary impression of moving travelers.

Overall, Manica remained largely outside direct Portuguese influence until the beginning of the 20th century. In 1884, it was declared an official administrative district of the Portuguese colony of Mozambique together with Sofala, although few Portuguese lived there and political control was weak at best. Its current border with Zimbabwe was a product of a British-Portuguese treaty in 1890, which expelled Cecil Rhodes' private army of the British South Africa Company trying to seize the province for its mineral wealth and ambitiously seeking access to the sea.

Since 1884, Sofala-Manica was given as a concession to the Companhia de Moçambique until 1942. The company attracted European settlers who were given large lands for commercial production of cash crops.

FRELIMO guerilla activities spread from the north of the country and took hold in Manica. Although most activities occurred in the countryside, Chimoio became the only urban center to witness a direct attack by FRELIMO. Smallholder agriculture suffered some retribution from Portuguese, as FRELIMO would dissipate into rural fabrics after forming for an attack. Some settler farms also suffered from FRELIMO attacks.

The Mozambican Civil War brought significantly heavier devastation for Manica. Large tracts of land fell to the rural terror of RENAMO resulting in large displacement and death. The new collective farms producing cash crops were important targets for RENAMO. As in Mozambique in general, agricultural production collapsed, resulting in moments of famine.

With peace returning, agriculture returned to Manica. Most farmers met in the province say they started farming their land a few years before or after peace. Many non-natives were also granted land in Manica.

Appendix 2 – FIELD parameters used for Simulations

Tab. A2-1. Soil related parameters as used for simulations.

Parameter	Value
max Relative Decomposition Rate (RDR) C Labile	0.9
max RDR C Resistant	0.2
max RDR organic ammendments labile	0.6
max RDR organic ammendments resistant	0.2
humification coefficient	0.4
bulk density	1400
soil depth (being considered)	0.2
max RDR root	0.8
frstrt	0.5
fraction stabalized manure	0.5
max RDR active organic C	0.5
max RDR soil C	0.02
inertCrtr	0
humification factor	0.2
fraction stabalized somC	0.2
growth effect microogranisms	0.45
active organic matter (aom) C	6000
aom CN ratio	12
aom CP ratio	80
soil organic matter (som) C	24000
max som C	40000
Inert C	0
fraction aom C	0.5
fraction lost soil N	0.1
fraction lost fertilzer N	0.3
fraction lost N organic	0.1
fraction captured soil P	1
fraction captured fertilizer P	0.2
fraction captured P organic	0.2
fraction lost fertilizer K	0.5
fraction lost soil K	0
K saturation	0.039
Portion of soil mineralization during 1st Crop*	0.75

*parameter added.

Tab. A2-2. Management parameters to reflect mostly initial crop residues. Second crop residue column was added. Values are proportions or in kg/ha. N/U=not used.

Parameter	Crop 1	Crop 2
Initial amount of crop residues in the field	1000	800
Initial crop residues crop	1	2
Labile fraction of the crop residues	0.7	0.7
Labile fraction of the organic amendments	0.7	N/U
Initial amount of crop residue root matter	800	500

Tab. A2-3. Weather related parameters as used for simulations. Rain pattern refers to the portion of total rain available for the first crop. Rainfall is in mm/yr.

Season	Rainfall	Rain Pattern
1	1000	.7
2	1000	.7
3	1000	.7
4	1000	.7
5	1000	.7
6	1000	.7
7	1000	.7
8	1000	.7

9	1000	.7
10	1000	.7
11	1000	.7
12	1000	.7
13	1000	.7
14	1000	.7
15	1000	.7
16	1000	.7
17	1000	.7
18	1000	.7
19	1000	.7
20	1000	.7

Tab. A2-4. Fertilizer related parameters as used for simulations. Applications and N,P,K values are altered to reflect addition amounts. The parameters are defined for each season in kg/ha. DM = Dry Matter.

Fertiliser application	Parameter	Value
mineral	N	0
	P	0
	K	0
manure	application	0
	DM Content	1
	C Content	0.3
	N Content	0.011
	P Content	0.0018
organic amendments	application	0
	DM Content	1
	C Content	0.42
	N Content	0.05
	P Content	0.015

Tab. A2-5. Crop parameters used for simulations.

crop		Maize	Soybean	Sweet Sorghum
crop identifier		1	2	3
legume: yes or no		0	0	0
legume: response type		0	0	0
harvest index		0.48	0.33	0.8
shoot:root-ratio		6	6	6
light determined yield (LDY)	LDY	19200	19200	85000
water capture efficiency		0.34	0.2	0.85
water conversion efficiency		72	72	72
Parameter for reduction factor relationship for water capture efficiency	prmta	0.9889	0.9889	0.9889
	prmtb	-0.4706	-0.4706	-0.4706
	prmtr	0.9028	0.9028	0.9028
Parameters affecting target uptake for N, P and K as defined by LDY	alfaN	0.7	0.7	0.7
	alfaP	0.7	0.7	0.7
	alfaK	0.7	0.7	0.7
Parameters affecting reduction factor for N, P and K	betaN	1	1	1
	betaP	1	1	1
	betaK	1	1	1
Water effect on yield		0.59	0.59	0.59
Minimum and maximum values for N, P and K in grains (gr) and stover (st)	Nmaxgr	0.032	0.056	0.002
	Nmingr	0.009	0.032	0.000583
	Nmaxst	0.01	0.022	0.0002
	Nminst	0.0035	0.005	5.83E-05
	Pmaxgr	0.009	0.008	0.0005
	Pmingr	0.001	0.0022	8.33E-05
	Pmaxst	0.0035	0.0052	0.00005
	Pminst	0.0005	0.0008	8.33E-06
	Kmaxgr	0.008	0.026	0.004667
	Kmingr	0.003	0.012	0.001333

	Kmaxst	0.024	0.024	0.000467
	Kminst	0.01	0.007	0.000133
Dry matter content		1	1	0.25
Carbon content		0.42	0.45	0.42
Nitrogen content		0.005	0.0125	0.0025
Phosphorus content		0.0015	0.003	0.00075
C:N-ratio		84	36	168
C:P-ratio		280	150	560
root C content		0.32	0.32	0.32
root N content		0.005	0.005	0.005
root P content		0.001	0.001	0.001
N fixing (% of total N used)		0	0.7	0
Rotation Effect		0	0	0
Leaf N content at full maturity		0.00426	0.01	0.00426
Leaf P content at full maturity		0.0034	0.0055	0.0034
Competition Effect of crop on Yield of the other crop (portion lowered)*		0	0	0

*parameter added, value kept at 0 as no competitive effect assumed for relay cropping.

Tab. A2-6. Rototation parameters used for simulations. N/S = not significant as a 0 in First Crop triggers fallow. The parameters are defined for each season.

Activity	Fallow	Cropping
First Crop	0	1
Relay Crop	*N/S*	2
Residue left in the field	0.9	0.9

Soil Property parameters are included as *Table 1* and fallow parameters are included as *Table 2*.

Appendix 3 – Original LABOURSIM (not used)

LABOURSIM module was developed as one of the main aims of this thesis. The module would account for labour flows on the farm level.

All FARMSIM modules as well as a farm level integrate algorithm were to be constructed to have all calculations occur in R to take advantage of the program's power and flexibility for statistical analysis. A LABOURSIM construction was already used by van Wijk et al. (2009) within the FARMSIM framework. A certain quantity of labour is required for each farming activity (land preparation, sowing, weeding, harvesting) in a season. If a farm is unable to meet this requirement, the biophysically determined yield is reduced as a result. A linear regression was used for this relationship, interpolated from labour needed for *optimal production* and labour needed to achieve any yield (pers comm.: van Wijk).

This approach was deemed appropriate for this case study. It would be simple and fit into the FARMSIM framework in interaction with FIELD. The assumption of constant labour returns implied by adopting a linear relationship is appropriate in the context of a simple summary model.

Labour supply available for work on the farm is a function of household size, labour hired in, labour hired out, labour used for vegeTable production, off-farm labour. The last four are constants. Labour supply is arranged as a matrix with seasons in one dimension and periods throughout a season in the other dimension.

Equation A3-1.

$$Lb^{a}_{supply} = HH.size * hrs + Lb_{hiredin} – (Lb_{hiredout} + Lb_{vegi} + Lb_{off\text{-}farm})$$

Where:

a	*= FIELD related activity (land preparation, sowing, weedings 1&2, and harvesting)*
Lb_{supply}	*= Labour supply for activity a (hrs)*
HH.size	*= Household size*
hrs	*= hours during a when work is possible (i.e. no rain, daytime, etc.)*
$Lb_{hiredin}$	*= Labour hired in (hrs) during activity a*
$Lb_{hiredout}$	*= Labour hired out (hrs) during activity a*
Lb_{vegi}	*= Labour used on vegeTable production during activity a*
$Lb_{off\text{-}farm}$	*= Labour employed in off-farm activity (hrs) during activity a*

Labour demand for activity *a* is a function of hours required per crop *c* for both crops in the relay and the total area on which they are cultivated. Labour demand is arranged as an array with seasons in one dimension, periods throughout a season in another dimension, and all the crops, first and relay from each FIELD on the farm, in the third dimension. Summing the third dimension into a matrix yields total labour demand for each period in each season.

Equ.

Equation A3-2.

$$Lb^{a}_{demand} = \Sigma_c\, Area_c * Lb.req^{a}_{c} * Lb.mt^{a.first*a.relay}$$

Where:

c	*=crop used in FIELD (first and relay crop)*
a	*=FIELD related activity*
Lb^{a}_{demand}	*= Labour demand for activity a (hrs)*
$Area_c$	*= Area within which crop c is cultivated*
$Lb.req^{a}_{c}$	*= Labour required for activity a for crop c*
$Lb.mt^{a}_{c}$	*= Coefficient for labour saved because of multitasking between crop activities*

Labour supply and demand are used to determine the labour differential. A positive value signifies surplus, a negative signifies deficiency.

A reduction coefficient as determined from the linear interpolations would be applied on crop *c* yield when labour deficiency is present during period *p*. To parameterize this construction, yields as they relate to labour hours spend on each activity should be examined. Assuming that labour restrictions have an effect on yields, a pattern should be observed where higher amounts of labour per area generate higher yields, the slope of which will describe the effect of labour availability for an activity on yield. Rich farms, which are able to access required labour, should demonstrate non-labour restricted production and smaller farms, with lower labour per ha, should demonstrate lower yields.

The calculation is performed after farm level integration of different FIELDs, having been run with the FIELD model. As such, it stacks yield results of biomass and grain of the first crop and relay crop from these runs into arrays, representing different FIELDs on the farm. The amount of periods is definable in a construct of the relay wherein the activity per crop is separated between the periods.

The construct of LABOURSIM as it relates to FIELD is a sequential calculation rather than included as feedback during the loop calculations for each season. In the presence of labour limitations and their restrictions on yield, calculations will progressively be biased as FIELD uses higher yields for soil nutrient use and crop residue quantities than yields obtained by LABOURSIM.

Appendix 4–Relation between Maize Use and Household Size

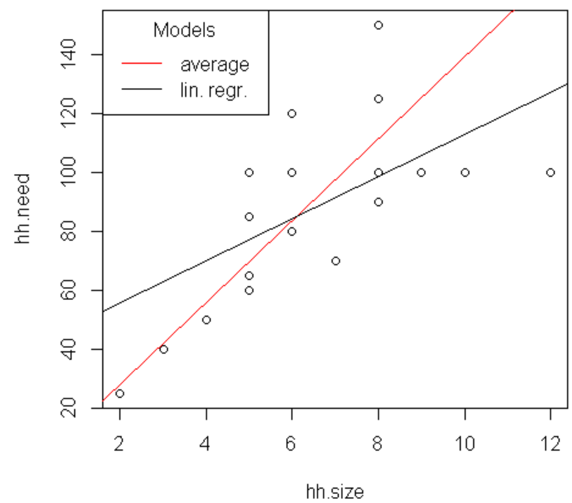

Fig. A4. Household need (*hh.need*) in maize kg per month as a function of household size (*hh.size*) and two different models, a no intercept model with slope as the average (*average*) and one determined by ordinary least squares (*lin. regr.*).

Maize need is correlated to household size. A linear model of this relationship was found to have an adjusted R^2 of .3741; an intercept of 41.377 and a coefficient 7.155, both significant with a p-value of .00497 and .00089 respectively. This regression overestimates consumption of small households to a large degree. As a point of comparison, the average maize consumption of a household member for all Farm types was calculated and applied as the slope of an alternative linear model, with a y-intercept of 0. Indeed, the *average* model demonstrates a better fit for small household numbers. The two models and the data points are shown in *Figure A4*. The *average* model implies that almost 14 kg per maize are consumed by each family member each month, which would amount to around 51,000 kcal (USDA, 2011), or most of a 2000 kcal diet per day (60,000 kcal per month). It seems this is too little for an active lifestyle (FAO, 2001). The average could be a product of a lay season with little activity averaged over a year or a larger portion of calories coming from non-maize sources than expected.

Richer households could consume more non-maize food or could have more child members than smaller households. As such, a non-linear model could be more appropriate, although this option was not explored. The aforementioned alternative (see 2.5) would seem to be a more time-worthy effort and would be applicable to data sets outside of Manica Province. Using available data, as was done in this case, seems to be an even better alternative as it represents actual field observations.

Appendix 5– Additional Figures for labour data analysis

A quantitative relationship was sought between labour input for an activity and final yield:

For maize, labour per ha for land preparation (adjusted R^2 = .015), sowing (adjusted R^2 = .246), first weeding (adjusted R^2 = .019), second weeding (adjusted R^2 = .022), and harvesting (adjusted R^2 = .001), were not found to have a significant relationship with yield (*Appendix 5A*), even when location was accounted for (*Appendix 5B*). This can also be seen visually in the cloud scatterplots (*Appendix 5C*). For sowing, a weak significant relationship was found between labour available and yield, also seen in a higher than average adjusted R^2. The negative nature of the relationship nonsensically implies that increased amount of labour per ha lead to lower final yields and can be discarded as a product of chance. As with maize, linear models for sesame and sunflower relating yields to labour per ha spent on an activity are poor. All assumptions for use of simple linear regressions were checked and sufficiently satisfied (not shown).

Farm types, location and the proxy variable, area, are found to correlate with total labour productivities (final maize yield per hour spent on activity) (see *Appendix 5F*), with lower farm type values having higher productivities and Dombe having a higher productivity than Zembe.

5.A - Linear models for yields for maize, sesame and sunflower as a function of farm activity labour per ha.

Maize

R output presented for linear regressions of maize yields per ha (`maize.yield`) as a function of hours spent on an activity per ha. Activities are in the following order: land preparation (`maize.landprep.ha`), sowing (`maize.sowing.ha`), first weeding (`maize.weeding1.ha`), second weeding (`maize.weeding2.ha`), and harvest (`maize.harvest.ha`).

```
> summary(lm(maize.yield~maize.landprep.ha))

Call:
lm(formula = maize.yield ~ maize.landprep.ha)

Residuals:
    Min      1Q  Median      3Q     Max 
-700.92 -448.75    4.02  355.41  769.52 

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)    
(Intercept)       1959.0881   259.7988   7.541 1.55e-07 ***
maize.landprep.ha   -1.1341     0.9736  -1.165    0.257    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 482.9 on 22 degrees of freedom
Multiple R-squared: 0.0581,           Adjusted R-squared: 
0.01528 
F-statistic: 1.357 on 1 and 22 DF,  p-value: 0.2565

> summary(lm(maize.yield~maize.sowing.ha))

Call:
lm(formula = maize.yield ~ maize.sowing.ha)

Residuals:
   Min     1Q Median     3Q    Max 
-763.1 -234.4 -112.2  203.2  799.5 

Coefficients:
                Estimate Std. Error t value Pr(>|t|)    
(Intercept)     2310.159    233.021   9.914 1.41e-09 ***
maize.sowing.ha   -9.876      3.388  -2.915  0.00802 ** 
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 422.6 on 22 degrees of freedom
Multiple R-squared: 0.2787,           Adjusted R-squared: 
0.2459 
F-statistic: 8.499 on 1 and 22 DF,  p-value: 0.008018

> summary(lm(maize.yield~maize.weeding1.ha))

Call:
lm(formula = maize.yield ~ maize.weeding1.ha)

Residuals:
    Min      1Q  Median      3Q     Max 
-711.02 -334.22  -83.59  324.62  947.09 

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)    
(Intercept)       2043.8640   318.5592   6.416 1.87e-06 ***
maize.weeding1.ha   -1.1587     0.9624  -1.204    0.241    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 482 on 22 degrees of freedom
Multiple R-squared: 0.06181,          Adjusted R-squared: 
0.01917 
F-statistic: 1.449 on 1 and 22 DF,  p-value: 0.2414

> summary(lm(maize.yield~maize.weeding2.ha))

Call:
lm(formula = maize.yield ~ maize.weeding2.ha)

Residuals:
    Min      1Q  Median      3Q     Max 
-794.99 -440.23   11.25  310.78  934.06 

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)    
(Intercept)       1478.725    296.795   4.982  5.5e-05 ***
maize.weeding2.ha    1.153      1.607   0.717    0.481    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 491.9 on 22 degrees of freedom
Multiple R-squared: 0.02286,          Adjusted R-squared: -
0.02156 
F-statistic: 0.5146 on 1 and 22 DF,  p-value: 0.4807

> summary(lm(maize.yield~maize.harvest.ha))
```

```
Call:
lm(formula = maize.yield ~ maize.harvest.ha)

Residuals:
    Min      1Q  Median      3Q     Max
-810.01 -417.16  -27.32  362.36  809.92

Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
(Intercept)      1401.399    297.195   4.715 0.000105 ***
maize.harvest.ha    1.703      1.717   0.991 0.332262
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 486.8 on 22 degrees of freedom
Multiple R-squared: 0.04277,          Adjusted R-squared: -
0.0007438
F-statistic: 0.9829 on 1 and 22 DF,  p-value: 0.3323
```

Sesame

R output presented for linear regressions of sesame yields per ha (`sesame.yield`) as a function of hours spent on an activity per ha. Activities are in the following order: land preparation (`sesame.landprep.ha`), sowing (`sesame.sowing.ha`), first weeding (`sesame.weeding1.ha`), second weeding (`sesame.weeding2.ha`), and harvest (`sesame.harvest.ha`).

```
> summary(lm(sesame.yield~sesame.landprep.ha))

Call:
lm(formula = sesame.yield ~ sesame.landprep.ha)

Residuals:
    Min      1Q  Median      3Q     Max
-316.46 -136.01  -19.46   74.20  492.54

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)        1126.458     82.632  13.632 8.73e-08 ***
sesame.landprep.ha    1.261      0.602   2.095   0.0626 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 252.5 on 10 degrees of freedom
Multiple R-squared: 0.305,          Adjusted R-squared:
0.2355
F-statistic: 4.388 on 1 and 10 DF,  p-value: 0.06263

> summary(lm(sesame.yield~sesame.sowing.ha))

Call:
lm(formula = sesame.yield ~ sesame.sowing.ha)

Residuals:
    Min      1Q  Median      3Q     Max
-306.64 -208.56  -42.76  165.23  412.51

Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
(Intercept)      1558.963    259.438   6.009 0.000131 ***
sesame.sowing.ha   -7.039      4.951  -1.422 0.185571
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 276.2 on 10 degrees of freedom
Multiple R-squared: 0.1681,          Adjusted R-squared:
0.08493
F-statistic: 2.021 on 1 and 10 DF,  p-value: 0.1856

> summary(lm(sesame.yield~sesame.weeding1.ha))

Call:
lm(formula = sesame.yield ~ sesame.weeding1.ha)

Residuals:
    Min      1Q  Median      3Q     Max
-362.23 -188.73  -32.62  186.62  499.28

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)        1539.779    631.021   2.440   0.0348 *
sesame.weeding1.ha   -1.500      2.827  -0.531   0.6072
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 298.7 on 10 degrees of freedom
Multiple R-squared: 0.0274,          Adjusted R-squared: -
0.06986
F-statistic: 0.2817 on 1 and 10 DF,  p-value: 0.6072

> summary(lm(sesame.yield~sesame.weeding2.ha))

Call:
lm(formula = sesame.yield ~ sesame.weeding2.ha)

Residuals:
   Min     1Q Median     3Q    Max
-336.6 -223.3  -43.8  240.9  472.4

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)         2266.25    1571.25   1.442    0.180
sesame.weeding2.ha   -22.39      33.20  -0.675    0.515

Residual standard error: 296.2 on 10 degrees of freedom
Multiple R-squared: 0.04352,          Adjusted R-squared: -
0.05213
F-statistic: 0.455 on 1 and 10 DF,  p-value: 0.5153

> summary(lm(sesame.yield~sesame.harvest.ha))

Call:
lm(formula = sesame.yield ~ sesame.harvest.ha)

Residuals:
    Min      1Q  Median      3Q     Max
-418.74 -184.92  -42.93  252.05  447.88

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)       1127.876    352.172   3.203  0.00945 **
sesame.harvest.ha    1.441      6.136   0.235  0.81908
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 302 on 10 degrees of freedom
Multiple R-squared: 0.005484,          Adjusted R-squared: -
0.09397
F-statistic: 0.05514 on 1 and 10 DF,  p-value: 0.8191
```

Sunflower

R output presented for linear regressions of sunflower yields per ha (`sflower.yield`) as a function of hours spent on an activity per ha. Activities are in the following order: land preparation (`sflower.landprep.ha`), sowing (`sflower.sowing.ha`), first weeding (`sflower.weeding1.ha`), second weeding (`sflower.weeding2.ha`), and harvest (`sflower.harvest.ha`). For land preparation and first weeding, all labour values were 0, coefficient could not be calculated.

```
> summary(lm(sflower.yield~sflower.landprep.ha))

Call:
lm(formula = sflower.yield ~ sflower.landprep.ha)

Residuals:
    Min      1Q  Median      3Q     Max
-104.17  -50.42   15.83   50.83   70.83

Coefficients: (1 not defined because of singularities)
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)           239.17      16.93   14.12 2.14e-08
***
sflower.landprep.ha       NA         NA      NA       NA
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 58.65 on 11 degrees of freedom

> summary(lm(sflower.yield~sflower.sowing.ha))

Call:
```

```
lm(formula = sflower.yield ~ sflower.sowing.ha)

Residuals:
    Min      1Q  Median      3Q     Max 
-110.26  -44.27   12.82   42.88   76.57 

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)    
(Intercept)       227.8651    39.4338   5.778 0.000178 ***
sflower.sowing.ha   0.1988     0.6201   0.321 0.755134    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '
' 1

Residual standard error: 61.2 on 10 degrees of freedom
Multiple R-squared: 0.01017,          Adjusted R-squared: -
0.08881 
F-statistic: 0.1028 on 1 and 10 DF,  p-value: 0.7551

> summary(lm(sflower.yield~sflower.weeding1.ha))

Call:
lm(formula = sflower.yield ~ sflower.weeding1.ha)

Residuals:
    Min      1Q  Median      3Q     Max 
-104.17  -50.42   15.83   50.83   70.83 

Coefficients: (1 not defined because of singularities)
                    Estimate Std. Error t value Pr(>|t|)    
(Intercept)           239.17      16.93   14.12 2.14e-08 
***
sflower.weeding1.ha       NA         NA      NA       NA    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '
' 1

Residual standard error: 58.65 on 11 degrees of freedom

> summary(lm(sflower.yield~sflower.weeding2.ha))

Call:
lm(formula = sflower.yield ~ sflower.weeding2.ha)

Residuals:
    Min      1Q  Median      3Q     Max 
-86.787 -45.111   8.196  42.712  69.691 

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)    
(Intercept)         277.9056    34.1947   8.127 1.03e-05 
***
sflower.weeding2.ha  -0.3291     0.2547  -1.292    0.225    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '
' 1

Residual standard error: 56.95 on 10 degrees of freedom
Multiple R-squared: 0.143,            Adjusted R-squared: 
0.05735 
F-statistic: 1.669 on 1 and 10 DF,  p-value: 0.2254

> summary(lm(sflower.yield~sflower.harvest.ha))

Call:
lm(formula = sflower.yield ~ sflower.harvest.ha)

Residuals:
    Min      1Q  Median      3Q     Max 
-107.51  -46.90   16.88   45.98   74.39 

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)    
(Intercept)        233.09588   40.08820   5.815  0.00017 
***
sflower.harvest.ha   0.08964    0.53089   0.169  0.86928    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '
' 1

Residual standard error: 61.43 on 10 degrees of freedom
Multiple R-squared: 0.002843,         Adjusted R-squared: -
0.09687 
F-statistic: 0.02851 on 1 and 10 DF,  p-value: 0.8693
```

5.B - Linear models related to location

R output presented for linear regressions of maize yields per ha (`maize.yield`) as a function of hours spent on an activity per ha and location as a dummy variable. Activities are in the following order: land preparation (`maize.landprep.ha`), sowing (`maize.sowing.ha`), first weeding (`maize.weeding1.ha`), second weeding (`maize.weeding2.ha`), and harvest (`maize.harvest.ha`).

```
> summary(lm(maize.yield~maize.landprep.ha+maize.loc))

Call:
lm(formula = maize.yield ~ maize.landprep.ha + maize.loc)

Residuals:
   Min     1Q Median     3Q    Max 
-722.3 -335.6  -19.1  373.4  580.6 

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)    
(Intercept)       2140.3921   232.9912   9.187 8.38e-09 ***
maize.landprep.ha   -0.8585     0.8466  -1.014  0.32212    
maize.locZembe    -498.7108   171.4393  -2.909  0.00839 ** 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '
' 1

Residual standard error: 417.3 on 21 degrees of freedom
Multiple R-squared: 0.3286,           Adjusted R-squared: 
0.2647 
F-statistic:  5.14 on 2 and 21 DF,  p-value: 0.01524

> summary(lm(maize.yield~maize.sowing.ha+maize.loc))

Call:
lm(formula = maize.yield ~ maize.sowing.ha + maize.loc)

Residuals:
   Min     1Q Median     3Q    Max 
-683.3 -284.4    5.9  282.9  592.9 

Coefficients:
                Estimate Std. Error t value Pr(>|t|)    
(Intercept)     2369.924    209.936  11.289 2.23e-10 ***
maize.sowing.ha   -7.612      3.161  -2.408   0.0253 *  
maize.locZembe  -408.840    160.989  -2.540   0.0191 *  
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '
' 1
Residual standard error: 378.3 on 21 degrees of freedom
Multiple R-squared: 0.4482,           Adjusted R-squared: 
0.3956 
F-statistic: 8.527 on 2 and 21 DF,  p-value: 0.001946

> summary(lm(maize.yield~maize.weeding1.ha+maize.loc))

Call:
lm(formula = maize.yield ~ maize.weeding1.ha + maize.loc)

Residuals:
    Min      1Q  Median      3Q     Max 
-692.50 -318.92  -77.66  377.52  717.31 

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)    
(Intercept)      2081.3214   280.6951   7.415 2.72e-07 ***
maize.weeding1.ha  -0.4993     0.8810  -0.567   0.5769    
maize.locZembe   -490.0876   180.1113  -2.721   0.0128 *  
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '
' 1

Residual standard error: 424.2 on 21 degrees of freedom
Multiple R-squared: 0.3064,           Adjusted R-squared: 
0.2403 
F-statistic: 4.638 on 2 and 21 DF,  p-value: 0.02147

> summary(lm(maize.yield~maize.weeding2.ha+maize.loc))

Call:
lm(formula = maize.yield ~ maize.weeding2.ha + maize.loc)

Residuals:
    Min      1Q  Median      3Q     Max 
-701.82 -398.94  -68.87  412.44  714.06 

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)    
(Intercept)       1929.87213  302.51241   6.379 2.52e-06 
***
maize.weeding2.ha    0.04354    1.44976   0.030  0.97633    
maize.locZembe    -516.70764  181.11768  -2.853  0.00953 ** 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '
' 1

Residual standard error: 427.4 on 21 degrees of freedom
Multiple R-squared: 0.2958,           Adjusted R-squared: 
0.2287 
F-statistic:  4.41 on 2 and 21 DF,  p-value: 0.02517
```

```
> summary(lm(maize.yield~maize.harvest.ha+maize.loc))

Call:
lm(formula = maize.yield ~ maize.harvest.ha + maize.loc)

Residuals:
    Min      1Q  Median      3Q     Max 
-704.45 -368.01  -75.83  379.72  782.38 

Coefficients:
                 Estimate Std. Error t value Pr(>|t|)    
(Intercept)      2056.925    351.155   5.858 8.17e-06 ***
maize.harvest.ha   -0.621      1.720  -0.361   0.7217    
maize.locZembe   -553.109    199.053  -2.779   0.0113 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 426.1 on 21 degrees of freedom
Multiple R-squared: 0.3001,	Adjusted R-squared: 
0.2334 
F-statistic: 4.502 on 2 and 21 DF,  p-value: 0.0236
```

R output presented for linear regressions labour per ha for activities as a function of location (`maize.loc`).

```
> summary(lm(maize.weeding1.ha~maize.loc))

Call:
lm(formula = maize.weeding1.ha ~ maize.loc)

Residuals:
     Min       1Q   Median       3Q      Max 
-139.604  -64.511    2.013   20.094  274.205 

Coefficients:
               Estimate Std. Error t value Pr(>|t|)    
(Intercept)      286.70      29.63   9.675 2.19e-09 ***
maize.locZembe    56.24      41.91   1.342    0.193    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 102.6 on 22 degrees of freedom
Multiple R-squared: 0.07566,	Adjusted R-squared: 
0.03365 
F-statistic: 1.801 on 1 and 22 DF,  p-value: 0.1933
> summary(lm(maize.landprep.ha~maize.loc))

Call:
lm(formula = maize.landprep.ha ~ maize.loc)

Residuals:
    Min      1Q  Median      3Q     Max 
-195.22  -54.14  -25.92   84.51  239.44 

Coefficients:
               Estimate Std. Error t value Pr(>|t|)    
(Intercept)      235.56      30.34   7.765 9.65e-08 ***
maize.locZembe    22.66      42.90   0.528    0.603    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 105.1 on 22 degrees of freedom
Multiple R-squared: 0.01253,	Adjusted R-squared: -
0.03236 
F-statistic: 0.2791 on 1 and 22 DF,  p-value: 0.6026
> summary(lm(maize.sowing.ha~maize.loc))

Call:
lm(formula = maize.sowing.ha ~ maize.loc)

Residuals:
    Min      1Q  Median      3Q     Max 
-41.913 -18.869   2.813  15.699  43.206 

Coefficients:
               Estimate Std. Error t value Pr(>|t|)    
(Intercept)      56.718      7.366   7.700 1.11e-07 ***
maize.locZembe   14.362     10.417   1.379    0.182    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 25.52 on 22 degrees of freedom
Multiple R-squared: 0.07952,	Adjusted R-squared: 
0.03768 
F-statistic: 1.901 on 1 and 22 DF,  p-value: 0.1819
```


```
> summary(lm(maize.weeding1.ha~maize.loc))

Call:
lm(formula = maize.weeding1.ha ~ maize.loc)

Residuals:
     Min       1Q   Median       3Q      Max 
-139.604  -64.511    2.013   20.094  274.205 

Coefficients:
               Estimate Std. Error t value Pr(>|t|)    
(Intercept)      286.70      29.63   9.675 2.19e-09 ***
maize.locZembe    56.24      41.91   1.342    0.193    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 102.6 on 22 degrees of freedom
Multiple R-squared: 0.07566,	Adjusted R-squared: 
0.03365 
F-statistic: 1.801 on 1 and 22 DF,  p-value: 0.1933
```


```
> summary(lm(maize.weeding2.ha~maize.loc))

Call:
lm(formula = maize.weeding2.ha ~ maize.loc)

Residuals:
     Min       1Q   Median       3Q      Max 
-157.008  -35.550    1.742   39.229  117.278 

Coefficients:
               Estimate Std. Error t value Pr(>|t|)    
(Intercept)      190.52      18.14  10.501 4.93e-10 ***
maize.locZembe   -33.51      25.66  -1.306    0.205    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 62.85 on 22 degrees of freedom
Multiple R-squared: 0.07196,	Adjusted R-squared: 
0.02978 
F-statistic: 1.706 on 1 and 22 DF,  p-value: 0.205
> summary(lm(maize.harvest.ha~maize.loc))

Call:
lm(formula = maize.harvest.ha ~ maize.loc)

Residuals:
    Min      1Q  Median      3Q     Max 
-83.924 -29.528  -7.394  15.468 108.767 

Coefficients:
               Estimate Std. Error t value Pr(>|t|)    
(Intercept)      191.23      15.25   12.54 1.69e-11 ***
maize.locZembe   -56.27      21.56   -2.61    0.016 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 52.82 on 22 degrees of freedom
Multiple R-squared: 0.2364,	Adjusted R-squared: 
0.2017 
F-statistic:  6.81 on 1 and 22 DF,  p-value: 0.016
```

5.C – Scatter Plots of maize yields vs. labour per ha and total labour for each FIELD activity.

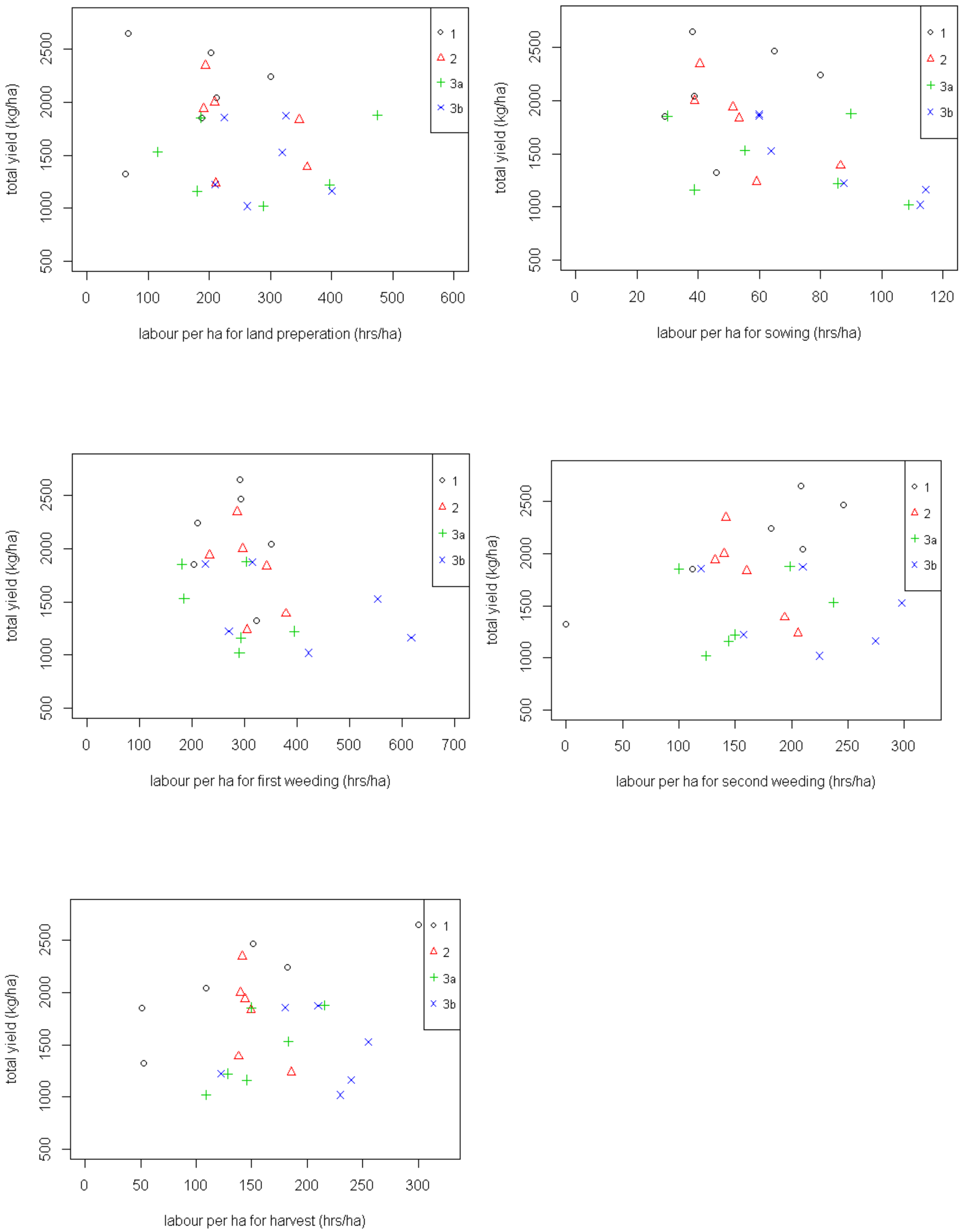

Fig. A5C. Scatter plots for labour per ha and total labour for different crop production activities for Zembe and Dombe, points are segregated by farm type (see legend). Grain yield is 44% (harvest index parameter) of total yield (biomass yield).

5.D – Maize Yield vs. Productivities

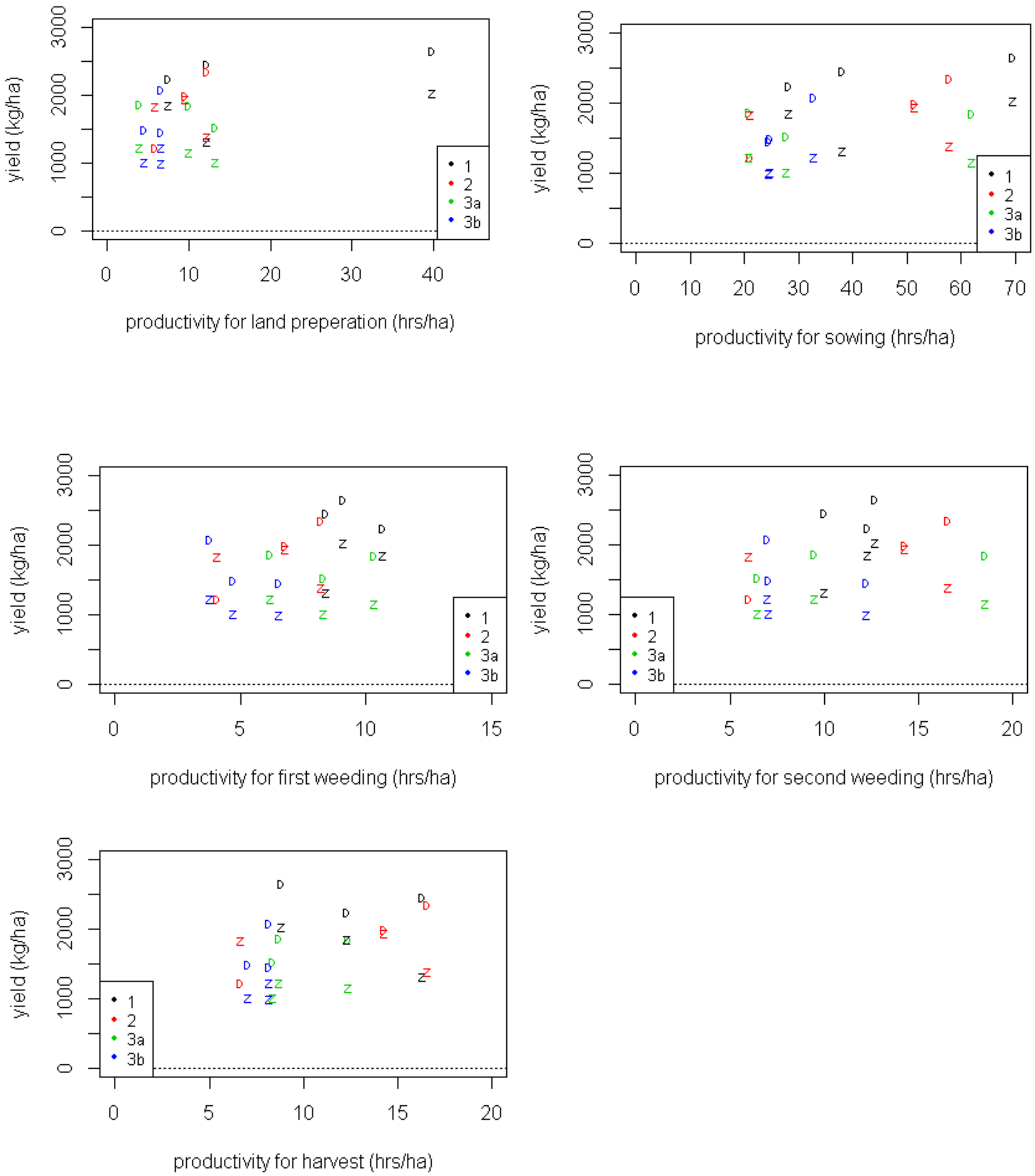

Fig. A5D. Productivities of land preparation (topleft), sowing (topright), first weeding (center left), second weeding (center right) and harvest (bottom) vs. cultivated area for different Farm types (see legends). Linear models are also plotted.

5.E – Maize Yield vs. Area Linear Model

```
> summary(lm(maize.yield~maize.area))

Call:
lm(formula = maize.yield ~ maize.area)

Residuals:
```

```
    Min      1Q  Median      3Q     Max 
-500.28 -158.09  -80.65  249.23  521.47 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)   938.11     124.43   7.539 1.56e-07 ***
maize.area    444.59      66.03   6.733 9.11e-07 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 284.4 on 22 degrees of freedom
Multiple R-squared: 0.6733,	Adjusted R-squared: 0.6584 
F-statistic: 45.33 on 1 and 22 DF,  p-value: 9.111e-07
```

5.F – Maize Productivity vs. Area Linear Model

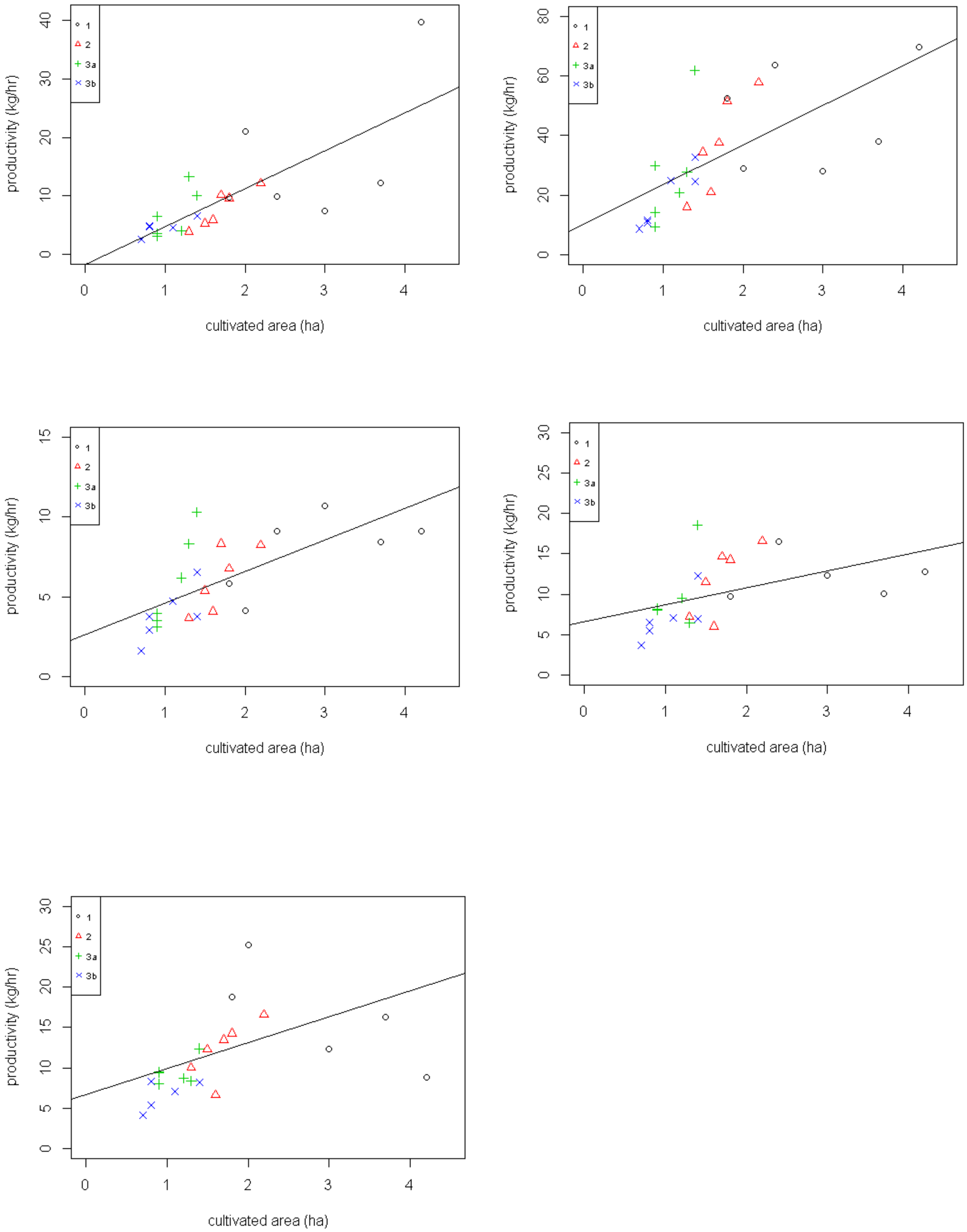

Fig. A5F. Productivities of land preparation (topleft), sowing (topright), first weeding (center left), second weeding (center right) and harvest (bottom) vs. cultivated area for different Farm types (see legends). Linear models are also plotted.

Linear models of activity labour productivities (yield per ha/labour per ha) as a function of area.

```
> summary(lm(prod.landprep~maize.area))

Call:
lm(formula = prod.landprep ~ maize.area)

Residuals:
     Min       1Q   Median       3Q      Max 
-10.2092  -2.2075  -0.4422   1.2966  14.3146 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)   -1.777      2.311  -0.769     0.45    
maize.area     6.490      1.226   5.293  2.6e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 5.282 on 22 degrees of freedom
Multiple R-squared: 0.5601,          Adjusted R-squared: 
0.5401 
F-statistic: 28.01 on 1 and 22 DF,  p-value: 2.602e-05

> summary(lm(prod.sowing~maize.area))

Call:
lm(formula = prod.sowing ~ maize.area)

Residuals:
    Min      1Q  Median      3Q     Max 
-21.950 -10.125  -2.174   5.586  33.080 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)   10.276      6.243   1.646 0.113955    
maize.area    13.245      3.313   3.998 0.000606 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 14.27 on 22 degrees of freedom
Multiple R-squared: 0.4208,          Adjusted R-squared: 
0.3945 
F-statistic: 15.99 on 1 and 22 DF,  p-value: 0.0006058

> summary(lm(prod.weeding1~maize.area))

Call:
lm(formula = prod.weeding1 ~ maize.area)

Residuals:
    Min      1Q  Median      3Q     Max 
-2.4735 -1.5411 -0.4039  1.1933  4.9100 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)   2.6346     0.8429   3.126 0.004920 ** 
maize.area    1.9800     0.4473   4.427 0.000213 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 1.927 on 22 degrees of freedom
Multiple R-squared: 0.4711,          Adjusted R-squared: 
0.4471 
F-statistic:  19.6 on 1 and 22 DF,  p-value: 0.0002127

> summary(lm(prod.weeding2[-15]~maize.area[-15]))

Call:
lm(formula = prod.weeding2[-15] ~ maize.area[-15])

Residuals:
   Min     1Q Median     3Q    Max 
-4.456 -2.645 -0.596  2.185  8.998 

Coefficients:
                Estimate Std. Error t value Pr(>|t|)    
(Intercept)       6.6320     1.5862   4.181 0.000422 ***
maize.area[-15]   2.0997     0.8441   2.488 0.021346 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 3.624 on 21 degrees of freedom
Multiple R-squared: 0.2276,          Adjusted R-squared: 
0.1908 
F-statistic: 6.188 on 1 and 21 DF,  p-value: 0.02135

> summary(lm(prod.harvest~maize.area))

Call:
lm(formula = prod.harvest ~ maize.area)

Residuals:
    Min      1Q  Median      3Q     Max 
-11.296  -3.043  -1.267   1.230  22.004 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)  
(Intercept)    6.698      2.863   2.340   0.0288 *
maize.area     3.200      1.519   2.107   0.0468 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 6.544 on 22 degrees of freedom
Multiple R-squared: 0.1679,          Adjusted R-squared: 
0.13 
F-statistic: 4.438 on 1 and 22 DF,  p-value: 0.04679
```