Agricultural intensification -

Saving space for wildlife?

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Agricultural intensification – saving space for wildlife?

Frédéric Baudron

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Pour Louis

ABSTRACT

Increasing agricultural production and preventing further losses in biodiversity are both legitimate objectives, but they compete strongly in the developing world. In this study, current tensions between agricultural production and environmental conservation were described and analysed in Mbire District, an agricultural frontier shared with wildlife that lies in the Mid-Zambezi Valley, in the northern fringe of Zimbabwe. The potential of conservation agriculture (CA) to intensify agricultural production with minimum negative environmental effects was then explored. The population of Mbire District almost doubled between 1992 and 2002, while the livestock densities increased at rates above 15% in the early 1990s and the late 2000s. From 1980 to 2007, the expansion of farmland over the years was described by an exponential relationship. It was suggested that these changes affected elephant and buffalo numbers negatively. Increase in human population, increase in cattle population, and expansion of cotton farming were all drivers on the observed land use change. However, cotton farming was demonstrated to be paramount, enabling cattle accumulation and expansion of plough-based agriculture. The 'environmental footprint' per farm was increasing significantly with the area under cotton and with the number of draught animals owned. A kilogram of seed cotton required 50% more land, removed twice as much N, 50% more K and 20% more P than a kilogram of cereal. However, except for pesticide, one man-day invested in cotton production had a smaller environmental footprint than a man-day invested in cereal production. As farming in Mbire District is limited by labour more than by land, specialising in cereal production would increase the total area occupied by crops and fallows, whilst specializing in cotton production would reduce this area. Therefore, maintaining or increasing the relative profitability of cotton vs. cereal may 'spare land' for nature. Compared with current farmers' cropping practices (CP), CA had no effect on cotton productivity during years that received average or above average rainfall. During a drier year, however, CA was found to have a slightly negative effect (110 kg ha^{-1} less in on-farm trials and 220 kg ha^{-1} less in farmers' cotton fields). Most soils in the study area are coarse-textured soils, on which runoff were significantly greater with CA than with CP. For these reasons, farmers perceived ploughing as necessary during drier years to maximize water infiltration, but saw CA as beneficial during wetter years as a means to ‘shed water’ and avoid waterlogging. In Zimbabwe, the approach used in the extension of CA appears to differ little from an earlier attempt to intensify smallholder agricultural production almost a century earlier: the Alvord model. In particular, the rationale of African smallholder farming has been persistently ignored. The analysis of smallholder farming practices in Mbire District showed how the socio-economic constraints they faced predisposed them towards extensification. In particular, labour availability for weeding was found to be a major limiting factor in the area. The increased weed pressure in CA is therefore a major reason preventing smallholders from embracing it. As a conclusion, mitigating conflicts between agricultural production and biodiversity conservation will require major innovations, far beyond CA. CA should be seen as part of a larger basket of technologies aiming at ‘ecological intensification’. In parallel to the development of technical innovations, local institutions should be empowered and strong regulations put in place.

Key words: agricultural frontier; smallholder; intensification; semi-arid area; wildlife; conservation agriculture; cotton; Zimbabwe.

Contents

Chapter 1

General introduction

1.1. BACKGROUND

Competing claims for land are acute in developing countries (Giller at al., 2008). Reducing the number of undernourished people, estimated to be 1.02 billion (FAO, 2009a), not only requires a reduction in poverty and more equity in food access, but also an increase in food production. Meeting this goal comes at a cost for some of the last biodiversity-rich areas on Earth. The need to slow down deforestation and extinction rates appears more pressing as the links between biodiversity and ecosystem processes on which human existence depends become better understood (Vitousek et al., 1997; Chapin et al., 2000; Loreau et al., 2001). Increasing agricultural production and at the same time minimizing the negative consequences of agriculture on biodiversity constitute probably one of the greatest challenges ahead for developing countries. Meeting this challenge will not be short of a new revolution (Tilman, 1998; Gregory et al., 2002).

Conversion of rainforest to palm plantations in Southeast Asian and its acceleration due to demand for biofuel is prominent in the media (e.g. Fargione et al., 2008). For African savannas, the consequences of the increased demand for food, fiber and fuel on the habitat of the emblematic megafauna is of equal importance. In this study, I analyse competing claims on land between agriculture and conservation in an African savanna shared by people and wildlife: the Mid-Zambezi Valley, in northern Zimbabwe.

1.2. NEED FOR INNOVATION

Agriculture affects biodiversity directly through changes in land use. Wild species are actively removed, controlled by the release of synthetic biocides or affected by disturbances associated to farming (Figure 1). The loss of a given species, particularly in the case of ‘keystone species’, may lead to further extinctions in trophic chains (Mills et al., 1993; Pace et al., 1999). In addition to these local impacts, agriculture may affect biodiversity regionally or globally through indirect changes (Figure 1). First, agriculture will often affect the biodiversity of adjacent landscapes through habitat fragmentation and fragment isolation (Pimm et al., 1995; Fischer and Lindenmayer, 2007). Second, agriculture affects hydrological and biogeochemical cycles, which may have far-reaching consequences on distant biodiversity. Farmland runoffs may cause siltation of distant streams, lakes, estuaries and coral reefs (Farella et al., 2001). Similarly, mobile nutrients such as nitrate and pesticides may contaminate regions downstream or downwind (Pimentel, 1995; Almasri and Kaluarachchi, 2004). The conversion of natural ecosystems to agriculture also releases CO_2, which may contribute to global climate change and affect global biodiversity (Dixon et al., 1994; Vitousek et al., 1997).

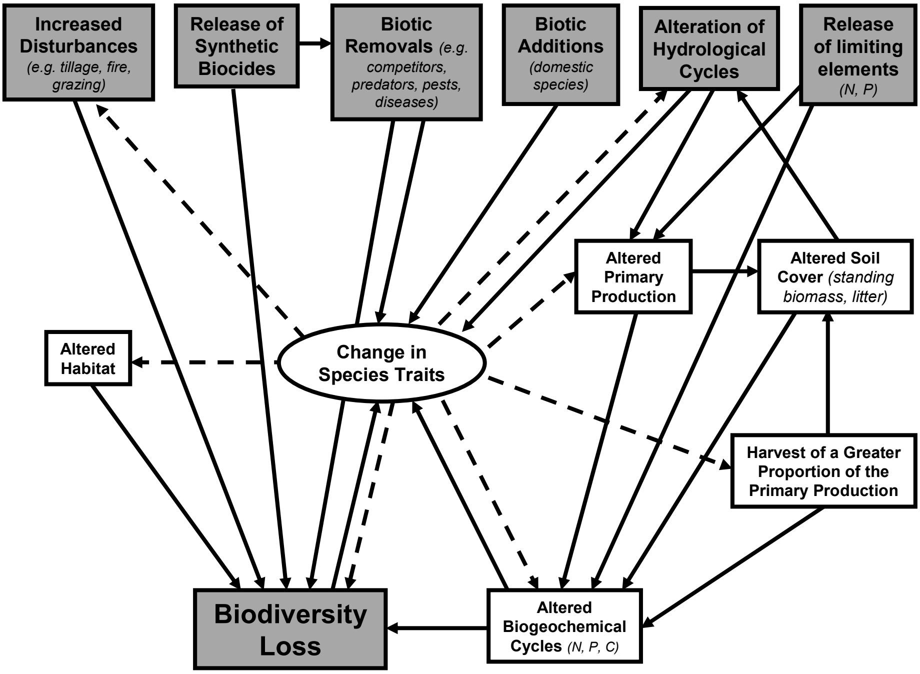


Figure 1. Direct and indirect effects of agriculture on biodiversity (after Vitousek et al., 1997; Chapin et al., 2000; Tilman et al., 2001)

How can agricultural production be increased with minimum negative consequences for biodiversity? Two main approaches can be distinguished. The first approach, ‘wildlife-friendly farming’, proposes to use little or no external input and to retain natural and semi-natural patches within farmlands (i.e. extensive agriculture; Krebs et al., 1999; Green et al., 2005). It is based on a land use model integrating production and conservation in the same land units. The alternative approach, ‘land-sparing’, proposes to maximize yield on existing farmland, hence reducing the need to expand into remaining wild nature (i.e. intensification, Ausubel, 2000; Green et al., 2005). It is based on a land use model separating production and conservation in distinct land units.

From an ecological perspective, Green et al. (2005) suggest that the choice between wildlife-friendly farming and land-sparing can be made by considering species-specific density-yield functions (Figure 2). Given species (such as many European birds) can be maintained at low farming intensity and harbour a convex (upward) density-yield function: these species can be effectively conserved through wildlife-friendly farming. The population density of other species drops quickly with increasing farming intensity. These species harbour a concave (upward) density-yield function and would benefit more from land sparing combined with maximum-yield agriculture than from wildlife-friendly farming. Most species in the developing world are likely to belong to the second category. Unlike European birds, these species have not co-evolved in heterogeneous farmland habitats created and maintained by low-input agriculture and extensive livestock rearing (Benton et al., 2003), but are rather ‘agriculturally naïve’. For example, half or more of all species occurring in unmodified habitats of the developing world are absent even from low-intensity farmland (Green et al., 2005).

For a given agricultural landscape, the choice between intensification (wildlife-friendly farming) or extensification (land sparing) is a product of individual farmers’ decisions. These decisions are influenced by complex interactions amongst factors such as population density (influencing land availability), resource endowment (capital and labour), technological options (land-saving and/or labour-saving), input and output markets, and policies (Boserup, 1965; Woodhouse, 2002; Bamire and Manyong, 2003; Mattison and Norris, 2005; White et al., 2005; Erenstein, 2006)

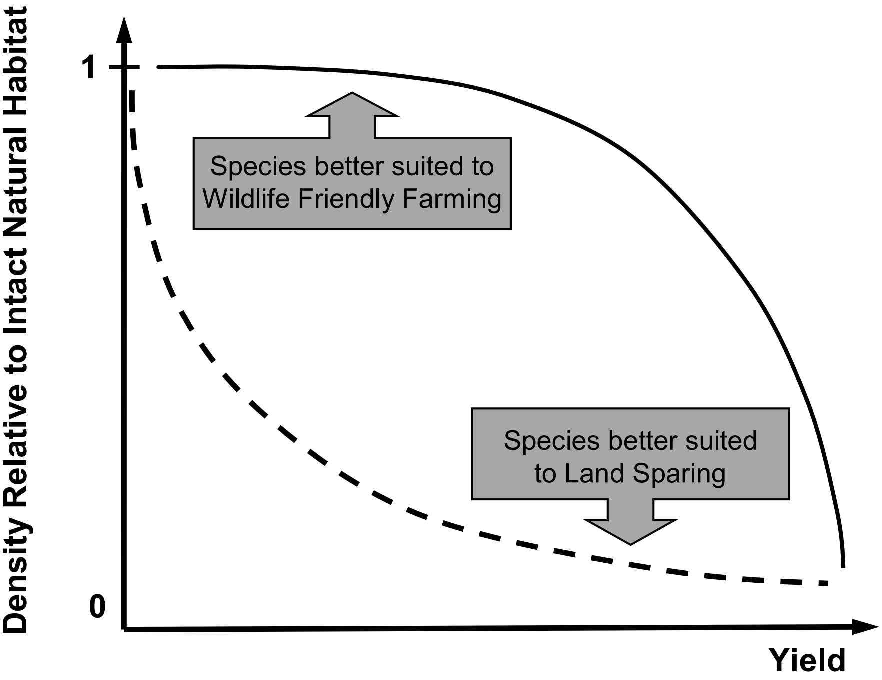


Figure 2. Yield-density relationship describing how the population density of a given species of interest varies along an agricultural yield gradient. Wildlife-friendly farming is the most appropriate strategy for species that remain at a density similar to the density in natural habitat under low-intensity agriculture. Land sparing is the most appropriate technology for species that can not maintain themselves in farmland, even under low intensity agriculture (from Green et al., 2005).

1.3. THE PROMISE OF CONSERVATION AGRICULTURE

Innovative farming technologies using the principles of ‘conservation agriculture’ (CA) have recently spread in various areas of the world, with the aim of intensifying agriculture with minimum negative consequences for the environment. It is defined by the Food and Agriculture Organization of the United Nations (FAO) as the simultaneous application of minimal soil disturbance, permanent soil cover through a mulch of crop residues or living plants, and crop rotation (www.fao.org/ag/ca). CA has mainly been adopted in the Americas and to a lesser extent in Australia and New Zealand (http://www.rolf-derpsch.com/globaloverview.pdf). Recently, it has also been vigorously promoted by international agencies and their donors in southern Africa. During the 2009-10 season, 180,000 and 110,000 smallholders were financially supported to adopt some form of CA in Zambia (www.conservationagriculture.org) and Zimbabwe (www.prpzim.info), respectively.

Can CA be a technical innovation helping developing countries to intensify their agriculture and minimize environmental degradation and biodiversity loss? CA seeks to improve water and nutrient use efficiency (Hobbs et al., 2008; Gowing and Palmer, 2008) by controlling horizontal losses (e.g. water runoff, nutrient losses through erosion) and vertical losses (e.g. deep percolation of water, nutrient leaching; Figure 3). Thus, CA is seen as a pathway to what is sometimes referred to as 'ecological intensification' or 'eco-efficient agriculture' – i.e. a form of agriculture that achieves high production levels, in terms of quantity and quality, and uses land, water, nutrients, energy, labour, and capital as efficiently as possible, thus causing minimum environmental damage (Cassman, 1999; Keating et al., 2010). This study focuses on the following question: can CA increase agricultural productivity and reduce wildlife decline in Mbire District?

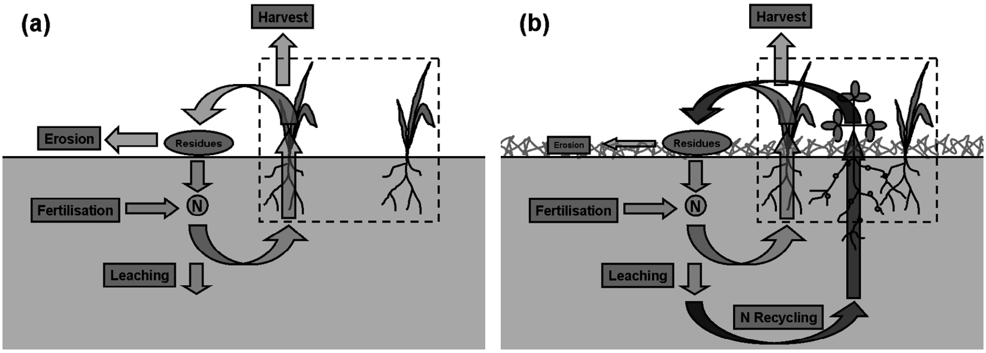


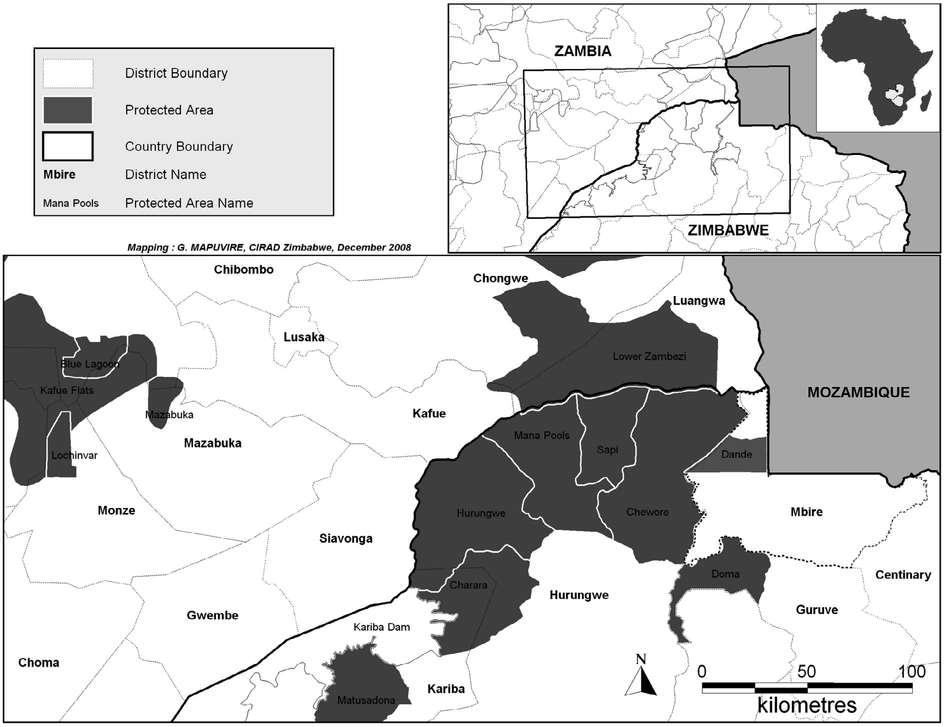
Figure 3. Hypothetical nitrogen (N) cycle (a) in a 'conventional' system, with extraction of a great fraction of the residues produced, high losses through erosion as a result of a quasi-bare soil, and high losses through leaching; and (b) in a system managed through conservation agriculture, where crop residues are retained as mulch, reducing loss through erosion, and where a deep-rooted secondary crop is associated to the main crop, recycling nitrogen.

1.4. THE MID-ZAMBEZI VALLEY: AN AGRICULTURAL FRONTIER SHARED WITH WILDLIFE

The Mid-Zambezi Valley is a low-land area along the Zambezi River, encompassing the Zimbabwe-Zambia border and part of northwestern Mozambique (Figure 3). The

Mid-Zambezi Valley hosts 1,500-2,000 plant species, which reflects its wide range of habitats, over 400 bird species, and a relatively intact and diverse mammal fauna including large carnivores (e.g. lion, leopard, spotted hyena), major populations of elephant, hippopotamus and buffalo, as well as a small concentration of black rhinoceros (Gumbo et al., 2003). It is a priority area for conservation, as demonstrated by its inclusion in various regional landscape conservation initiatives, such as the 'Zambezi Heartland' of the African Wildlife Foundation (Muruthi, 2005) and the 'Mid-Zambezi Valley Area of Biological Significance' of the World Wide Fund for conservation of nature (WWF Ecoregion Conservation Programme, 2003). At the heart of the Mid-Zambezi Valley, lies a network of protected area that straddles the Zimbabwe-Zambia border (Figure 4). This network includes a complex formed by Mana Pools National Park, Sapi Safari Area and Chewore Safari Area, which together form a world heritage site since 1984. Communal areas – i.e. state-owned land aimed at small-scale family farming - adjacent to these protected areas, such as Mbire District, also sustain significant wildlife populations (Gaidet et al., 2003). Mbire District was one of the first sites in which the world-renowned Communal Area Management Programme for Indigenous Resources (CAMPFIRE) was initiated in 1989 (Taylor, 2009). CAMPFIRE has been one of the earliest initiatives expressing the 'new conservation approach', which departs from the 'fortress conservation approach' by inviting local people to manage wildlife as an economic asset for rural development (Hulme and Murphree, 1999).

The area is characterised by wildlife abundance since until recently Mbire District was considered as marginal for agriculture. It receives low and erratic rainfall and was historically part of the so-called 'common fly-belt' where the abundance of tsetse fly prevented cattle keeping (Pollock, 1991). After Zimbabwe's independence in 1980, however, the new government was committed to stimulate smallholder agricultural development. Large-scale tsetse eradication campaigns and smallholder resettlement schemes were funded by the government and international donors. Cotton was identified as the most suitable cash crop for the area, due to its adaptation to hot temperatures and low rainfall (Parry, 1986). Cotton farming was aggressively promoted through extension, and access to credit was facilitated (Aubin, 1997). Starting in the late 1980s, a 'cotton boom' changed Mbire District from a wildlife area to an agricultural frontier. As a result, wildlife habitat has shrunk and wildlife numbers have been reported to decline (Biodiversity Project, 2001), representing the loss of both a global asset and a secondary source of income, through CAMPFIRE.



Mapping : G. MAPUVIRE, CIRAD Zimbabwe, December 2008

Figure 4. Location of the Mid-Zambezi Valley

1.5. STUDY OBJECTIVES AND METHODOLOGY

Although the understanding of the relations between agricultural production and environmental conservation has greatly progressed in the past decades, this knowledge has been compartmentalised by discipline (e.g. ecology, geography, social science, agronomy) and by scale (e.g. landscape, farm, plot). This renders the mobilisation of current knowledge difficult to answer pragmatic societal needs related to competing claims between agriculture and biodiversity conservation. With the development of remote sensing, spatial ecologists have immensely contributed to our understanding of the dynamics of land use and land cover change at regional and global levels. These studies, however, often fail to connect observed patterns with the diversity and the dynamics of individual land users. Social scientists have improved our understanding of the social, economic, and cultural circumstances that influence current land uses. These studies offer insight to their rationale, but lack the biophysical understanding necessary to propose and explore alternatives. Agronomists have improved our knowledge of the mechanisms governing the productivity and the efficiency of crop and livestock systems and have designed innovative technical packages (including CA). These studies are often carried at the level of the plot or herd, and little is known about the likely impact of their adoption at farm or landscape level or socio-economic environment in which they are likely to be adopted.

In this study, I attempt to integrate insights from various disciplines and spatial dimensions to (1) describe and analyse current tensions between agricultural production and environmental conservation; and (2) explore the potential of CA to intensify agricultural production with minimum negative environmental effects.

Specific objectives of the study were to:

1. Quantify land use changes that have occurred in the Mid-Zambezi Valley and analyse the contribution of different possible drivers
2. Describe the heterogeneity of farms in the Mid-Zambezi Valley and assess their impact on the environment
3. Compare the performance of conservation agriculture to the performance of current cropping practices in smallholder rainfed agriculture in the Mid-Zambezi Valley
4. Gain an understanding of smallholders' farm development pathways in terms of intensification or extensification, and how these are shaped by the socio-economic environment, on-farm constraints and opportunities and farmers' production orientations.

Objective 1 and Objective 2 aim at describing and analysing the current situation at landscape-level and farm-level, respectively (Figure 5). Objective 3 and Objective 4 aim at exploring the consequences of adopting CA, at the plot-level and at farm level.

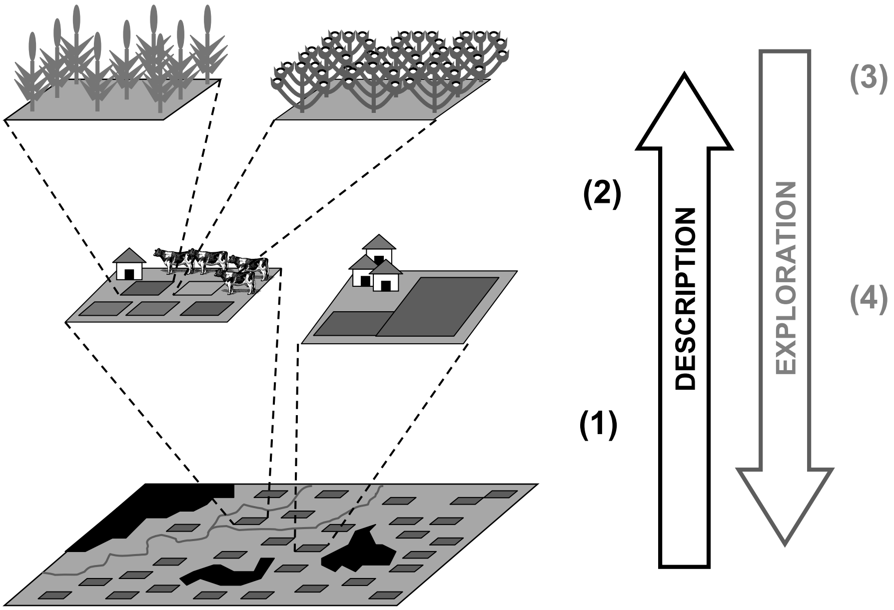


Figure 5. Methodology used in our research, with a 'zoom in' describing and analysing the current situation (from landscape level to farm-level and plot-level) and a 'zoom out' exploring the potential consequences of adopting conservation agriculture. Numbers correspond to the four specific objectives of this study, and their positions correspond to the level at which these objectives were fulfilled.

1.6. THESIS OUTLINE

Chapter 2 quantifies the land use changes that have occurred in Mbire District, in the Mid-Zambezi Valley, since 1980 and analyses the contribution of three major potential drivers: increase in human population; increase in cattle population (and the expansion of associated plough-based agriculture), and expansion of cotton farming (Objective 1). In Chapter 3 the 'environmental footprint' of the diversity of smallholder farmers in Mbire District is quantified, and the 'environmental footprint' of cotton production is compared with that of cereal production (Objective 2). Chapter 4 explores the possibility of CA to improve the productivity and efficiency of the cotton-cereal systems of Mbire District, under typical smallholder farm conditions (Objective 3). Chapter 5 evaluates how CA fits in the farming systems of Mbire District, from an understanding of the rationale of farmers (Objective 4). Conclusions from a discussion of the findings in the previous chapters are drawn in the final chapter, which also presents a decision-making tree on the suitability of the components of CA in African smallholder cotton systems, develops a simple conceptual model simulating the dynamics of farming systems in agricultural frontiers and proposes an approach integrating agricultural intensification and payment for environmental services at landscape level.

Chapter 2

Delineating the drivers of waning wildlife habitat: The predominance of cotton farming on the fringe of protected areas in the Mid-Zambezi Valley, Zimbabwe

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ABSTRACT

Zimbabwe's Mid-Zambezi Valley is of global importance for the emblematic mega-fauna of Africa. Over the past 30 years rapid land use change in this area has substantially reduced wildlife habitat. Tsetse control operations are often blamed for this. In this study, we quantify this change for the Dande Communal Area, Mbire District, of the Mid-Zambezi Valley and analyse the contribution of three major potential drivers: (1) increase in human population; (2) increase in cattle population (and the expansion of associated plough-based agriculture), and; (3) expansion of cotton farming. Although direct effects of land use change on wildlife densities could not be proven, our study suggests that the consequences for elephant and buffalo numbers are negative. All three of the above drivers have contributed to the observed land use change. However, we found farmland to have expanded faster than the human population, and to have followed a similar rate of expansion in cattle sparse, tsetse infested areas as in tsetse free areas where cattle-drawn plough agriculture dominates. This implies the existence of a paramount driver, which we demonstrate to be cotton farming. Contrary to common belief, we argue that tsetse control was not the major trigger behind the dramatic land use change observed, but merely alleviated a constraint to cattle accumulation. We argue that without the presence of a cash crop (cotton), land use change would have been neither as extensive nor as rapid as has been observed. Therefore, conservation agencies should be as concerned by the way people farm as they are by population increase. Conserving biodiversity without jeopardizing agricultural production will require the development of innovative technological and institutional options in association with policy and market interventions.

Keywords: Zimbabwe; agricultural frontier; wildlife; livelihood; tsetse fly; cotton.

2.1. INTRODUCTION

Globally, agricultural expansion represents the most significant threat to biodiversity (Vitousek et al., 1997), which is affected directly through biotic additions and removals, and indirectly through modifications of the biogeochemical cycles. Conversion to agriculture disturbs flows of energy, material and organisms within a wider ecological unit and may reduce, through isolation, the capacity of a protected area to support biodiversity (DeFries et al., 2007). The consequences of fragmentation on wildlife populations can take several generations to be fully manifested, and land use change may represent an “extinction debt” for the future (Tilman et al., 1994; Cowlishaw, 1999).

Today, agricultural expansion occurs mostly in the developing world (Gibbs et al., 2010): whereas cropland area shrank in the developed world, the total area of cropland in the developing world increased by more than 20% between 1961 and 1999 (Green et al., 2005). Population growth is an important driver of this expansion, but often neither the only nor the main one (Lambin et al., 2001). Policy and markets increasingly shape farming practices, (Mattison and Norris, 2005), rendering a Malthusian framework – stressing population growth and assuming subsistence-oriented agricultural production – too limited for the understanding of the drivers of land use change (Angelsen, 1999; Madhusan, 2003).

Agricultural policies are often at odds with conservation objectives. For instance, policies which improved market access, subsidized farm gate prices, and provided extension services in Zimbabwe in the early 1980s, contributed to an expansion of land cultivated to maize and, to a lesser extent, cotton (Chipika and Kowero, 2000). Interventions in urban centres may also have important consequences for land use change, due to rural-urban ties (Jones and O’Neill, 1994). Finally, macro-economic policy may indirectly increase the pressure on wildlife habitats, as has been noticed in the case of several developing countries after policy reforms included in economic liberalization and adjustment programmes (Angelsen and Kaimowitz, 1999). Land use change is thus driven by a wide range of factors which have locally specific impacts (Scriesciu, 2007). Conservation practices and strategies, therefore, should be based on an intimate understanding of the dynamics, and the drivers of these dynamics, within the area they target.

In this study, we illustrate this complexity with the particular case of the Dande Communal Land in the Mid-Zambezi Valley. As in many areas of sub-Saharan Africa, operations of tsetse control enabled the expansion of human settlements, reinforcing the common perception that tsetse fly is an ally of conservation (Happold, 1995). The Mid-Zambezi Valley is shared between Mozambique, Zambia and Zimbabwe. It is home to all the emblematic African mega-fauna, with the notable exception of the Black Rhinoceros (*Diceros bicornis* Linnaeus) which became locally extinct due to extensive poaching between 1989 and 1991 (Cumming and Lynam, 1997). It is a priority area for conservation, as demonstrated by its inclusion in various regional landscape conservation initiatives, such as the “Zambezi Heartland” of the African Wildlife Foundation (Muruthi, 2005) and the “Mid-Zambezi Valley Area of Biological Significance” of the World Wide Fund for conservation of nature (WWF Ecoregion Conservation Programme, 2003). At the heart of the Mid-Zambezi Valley, wildlife is well-preserved in a complex of protected areas formed by Mana Pools National Park, Sapi Safari Area and Chewore Safari Area – a world heritage site since 1984. However, smallholder farming areas adjacent to these protected areas, such as the Dande Communal Area in Mbire District, also sustain significant wildlife populations (Gaidet et al., 2003). This landscape shared between people and wildlife, was one of the first sites in which the world-renowned Communal Area Management Programme for Indigenous Resources (CAMPFIRE) was initiated in 1989. CAMPFIRE aims to finance rural development through the sustainable use of wildlife and other natural resources (Taylor, 2009). Around 90% of CAMPFIRE revenues in the study area are derived from elephant and buffalo (Gaidet et al., 2006).

Wildlife abundance in the Mbire District is at least partially the result of the area being part of the so-called “common fly-belt” extending from Zimbabwe into Mozambique, Zambia and Malawi. Until the late 1980s, it remained infested by tsetse flies (*Glossina morsitans morsitans* Westwood and *G. pallipides* Austen), vectors of trypanosomiasis. Of low risk to humans, this disease is lethal for cattle (Pollock, 1991). After Zimbabwe’s independence in 1980, the new government sought to stimulate smallholder agricultural development. As tsetse fly was perceived as the major limiting factor to such development in the then sparsely populated Mid-Zambezi Valley, large-scale operations of aerial and ground spraying of insecticides were conducted in the mid-1980s, and gradually replaced by the more environmental-friendly method of deploying target traps (RTTCP, 1995). Tsetse eradication has often been presented as the single most important factor causing the dramatic decrease of prime wildlife area in Dande Communal Area since the 1980s, threatening a remarkable biodiversity and eroding the revenues generated by CAMPFIRE (Aubin, 1997; Cumming and Lynam, 1997; Biodiversity Project, 2002).

The objectives of this study were to quantify land use changes that occurred since independence in a pilot zone of the Dande Communal Area neighbouring the Mana Pools-Sapi-Chewore complex and to review three possible drivers: population growth (including state-planned resettlement), the expansion of plough-based agriculture (made possible by tsetse eradication), and the expansion of cotton farming.

2.2. MATERIALS AND METHODS

2.2.1. Site description

The study focused on the Mid-Zambezi Valley, Northern Zimbabwe, between 30°00 and 31°45 longitude east and 16°00 and 16°30 latitude south. It is designated Communal Area (Dande Communal Area), which is state-owned land that may be used for small-scale farming and residential purposes by individual households whose access is regulated by customary arrangements. The area studied is comprised of three wards (Wards 2, 3 and 9), which are administrative sub-divisions of districts that, in the case of Mbire district, comprise some 10 to 15 villages (Figure 1). In this paper, we define “West Ward 2” as the part of Ward 2 West of the Angwa river, “East Ward 2” as the area of Ward 2 East of the Angwa river, and “Wards 3 and 9” as the area formed by Ward 3 and Ward 9. Angwa growth point lies at the centre of Ward 2 and Mushumbi Pools at the heart of Wards 3 and 9. The area lies in the former floodplains of the Zambezi River, at an average altitude of 400 m above sea level, and is drained by two main rivers: the Angwa and the Manyame. It has a dry tropical climate, with low and very variable annual rainfall (on average between 450 and 650 mm year^{-1}) and a mean annual temperature of 25°C. Two seasons are clearly defined: a rainy season from December to March and a long dry season from April to November.

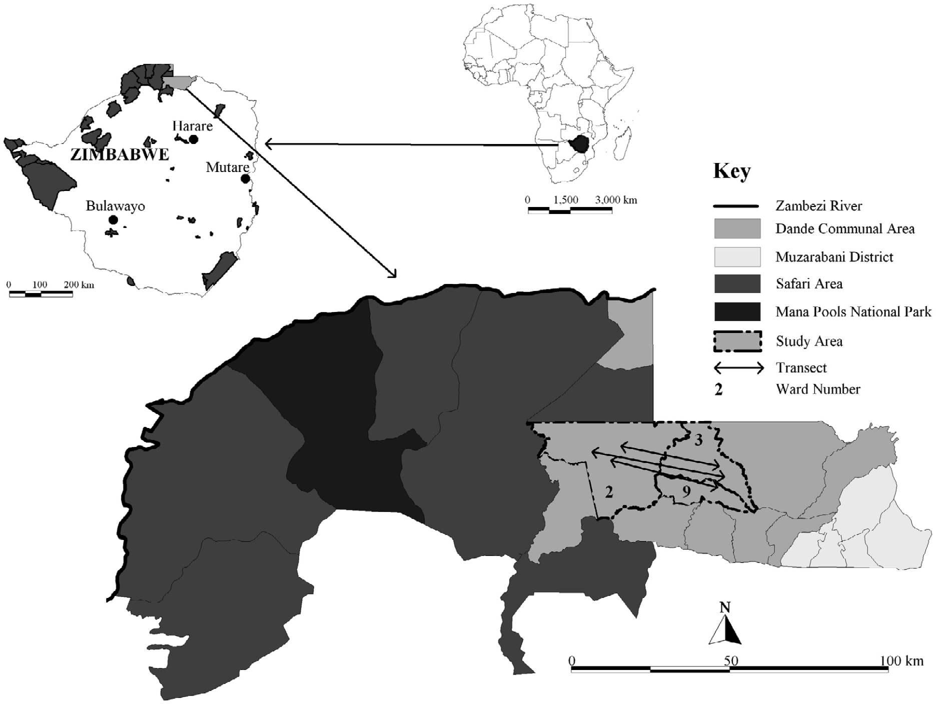

Figure 1. Location of the study area in northern Zimbabwe (NP: National Park)

The natural land cover is deciduous dry savanna, dominated by Mopane trees (*Colophospermum mopane* (J.Kirk ex J.Léonard)). The local biodiversity is relatively intact, with more than 40 large mammal, 200 bird and 700 plant species (Biodiversity Project, 2002). In 2002, a total of 71,000 people lived in this area of 4,100 km^2, but population densities vary considerably: 5.7, 29.2 and 42.9 inhab km^{-2} in Wards 2, 3 and 9 respectively (Central Statistical Office, 2002). Settlements occur predominantly along the main rivers and the major activity is dryland farming of cotton, maize and sorghum.

2.2.2. Development of a land use data base

Land use change was assessed in terms of conversion of natural vegetation to agriculture for the period 1980 to 2007. For this, expansion of farmland, which was defined as any surface that has been cleared for cultivation or residential purpose (i.e. homesteads, cultivated fields and fallows) was analysed through remote sensing.

We used Landsat Thematic Mapper (Landsat) of 2007, “Système Pour l’Observation de la Terre” (SPOT) Multispectral (XS) satellite images of 1990, 1997 and 2001, as well as aerial photographs of 1980, all taken during the dry season between July and September, to estimate farmland areas. Landsat has a spatial resolution of 30 m, while SPOT XS has a 20 m spatial resolution. Aerial photographs that we used have a spatial resolution of 5 m. Aerial photographs and SPOT (XS) satellite images were re-sampled to 30 m to be compatible with the Landsat images and all images were geo-referenced.

Farmland was determined through on-screen visual interpretation and digitization in a Geographical Information System: fields, fallows and homesteads can clearly be delineated when images are displayed in pseudo-natural colours, as they appear near regular, light toned and relatively smooth. We assessed the accuracy of the visual interpretations of the 1990 and 1997 SPOT (XS) images using farmland classifications from aerial photographs of 1990 and 1997. We use SPOT images in Google earth of 2007 to assess the accuracy of the 2007 Landsat image visual interpretation (as in Knorn et al., 2009). The Kappa statistics obtained were 0.93 for 1990 with 88 samples, 0.87 for 1997 with 108 samples, 0.77 in 2001 with 100 samples, and 0.94 for 2007 with 130 samples. For a given ward and a given year, we then calculated the proportions of farmland. Differences were tested using comparison of proportion tests. We calculated 95 % confidence intervals using standard error and the Z value i.e. 1.96.

2.2.3. Secondary data on population dynamics: people, livestock and wildlife.

In order to relate land use changes in Mbire District to demographic changes, cattle numbers and farming practices, secondary data were extracted from reports issued by the Rural District Councils of the Mbire and Guruve governmental departments - Department of Veterinary Service (DVS), Agricultural Technical Extension services (AGRITEX) - the Regional Tsetse and Trypanosomiasis Control Programme

(RTTCP), cotton companies (Cottco, Cargill, Olam, Alliance Ginneries), the Central Statistical Office and the Biodiversity Project of the French Agricultural Research Centre for International Development (CIRAD).

In addition, to relate the effect of land use change on wildlife population in this unprotected area, we used data of the aerial censuses conducted by WWF for the years 1982, 1983, 1984, 1986, 1988, 1989, 1992, 1996 (all provided by Cumming and Lynam, 1997), 1997 (Mackie, 1998), 1999 (Davies, 1999) and 2001 (Mackie, 2002) and data of the aerial census conducted by African Wildlife Foundation (AWF) for the year 2003 (Dunham, 2004). WWF and AWF censuses used similar strata: Chapoto, Masoka Hills, Kanyurira, Chisunga, Dande Safari Area and Kadze, the study area being encompassed by the last 4 strata. WWF and AWF censuses also used the same general survey methodology, with sampling done around September in parallel transects with a fixed-wing aircraft at a speed of about 160 km h^{-1} and about 300 feet above ground (Dunham, 2004). The surface surveyed from one year to another was not always the same (varying between 905 and 1032 km^2 for the years 1982, 1983, 1984 and 1986; between 2331 and 2465 km^2 for the years 1988, 1989 and 1992; and between 3623 and 4611 km^2 between the years 1995 and 2003), but always centred around the Dande Safari Area. We also use wildlife count data of the Biodiversity Project coordinated by CIRAD (Gaidet et al., 2006). This data was collected along transects covered by observers on bicycles and can be used to estimate densities or indices of abundance.

2.2.4. Participatory Rural Appraisal: leader and community meetings.

To gain an understanding of the processes that governed land use change in the area since independence and of the biophysical and socio-economic heterogeneity in the study area, participatory rural appraisal (PRA) sessions were conducted. PRA is an approach and a set of techniques designed for local people to share, enhance and analyse their knowledge of life and conditions, but also to plan and to act (Chambers, 1994). PRA sessions were held in West Ward 2, East Ward 2 and Wards 3 and 9.

In each site, the PRA was divided into two half-days: a leaders meeting, and a community meeting. Participants of leaders meetings included, amongst others, traditional leaders, elected representatives of the local government, extension officers, representatives of churches, representatives of clubs, etc (between 10 and 30 people). Community meetings included all members of the community who wished to participate (between 100 and 250 people). Leaders meetings focused on broad issues related to the history of the area (e.g. human immigrations), the spatial organization of the area (e.g. land use), the social organization of the area (e.g. access rules and management of natural resources) and institutional linkages and support (e.g. credit, extension, non-governmental organizations, marketing, input supply, farmer cooperatives). Community meetings discussed issues raised during the leaders meeting in more depth. These meetings also produced tangible outputs such as area resource maps and household self-categorizations (such as a wealth ranking), as we expected that different farms and resource use practices influence the rate of expansion of farmland.

2.2.5. Individual interviews

To better understand the dynamics at farm level and their spatial footprints, as suggested by the PRA sessions, we surveyed a sample of farms representative of the heterogeneity found in the area. We assumed that the distance from the main rivers was a major factor differentiating farms and spatial footprints because of two features. (1) The PRA sessions revealed that soil types differ with distance to the river. Soils close to the rivers are deep sandy loam soils (locally named “*bandate*”), while in the interfluves loamy sand soils (locally named “*shapa*”) or shallow sandy clay loam soils (locally named “*mutapo*”) occur. These different soil types have different production potentials, which have an impact on farmland expansion (2). The PRA sessions also revealed that there was a relationship between the farmer’s origin (i.e. autochthon versus immigrant) and distance of the farm from the rivers. The first settlers preferentially occupied land along the major rivers on the fertile alluvial terraces, while land further away from the rivers was settled later. For these reasons, we decided to sample farms using transects perpendicular to the major rivers, i.e. designed to include the fixed effect of distance to the main rivers, whereas other factors occur at random. We thus walked three transects of 30 to 40 km from the

Mana Pools-Chewore-Sapi complex towards more populated areas to the south-east-east (Figure 1). We also hypothesized that the distance from the protected areas would influence livelihood options. Moreover, with Mushumbi Pools growth point being the centre of the district and hosting cotton depots and other agro-services, the three transects were oriented along a gradient of increased access to markets i.e. better accessibility to farm inputs and reduced transport costs for the purchase of farm inputs and/or sale of farm outputs.

Farms that had at least one cultivated field on one of the transects in the 2006-7 growing season, were selected for the survey. This resulted in a sample of 176 farms, of which some could be located several kilometres away from their field on the transect. Household heads of these farms were interviewed using a standardised questionnaire (with open questions). The questionnaire addressed size, composition and history of the household, production capital (e.g. land, equipment), crop and livestock management, income generating activities, cash needs, food security, and interactions with wildlife. A more detailed characterization of a sub-sample of 40 farms was conducted, in particular to gather information on farm history and farm development pathways.

2.2.6. Statistical analysis

Quantitative data was tested for normal distribution using Kolmogorov-Smirnov tests, and was log-transformed when needed. When testing for differences between geographic zones or farm types, means of quantitative data were compared by Fisher tests and medians using Kruskal-Wallis (non-parametric) tests. When testing for correlations between quantitative data, Pearson correlations were used. For the qualitative data, proportions were compared using *Chi*-square tests. All analyses were carried out with the software Statgraphic (Version XV).

2.3. RESULTS

2.3.1. Pattern of land use change

The area of farmland, calculated using remote sensing, expanded dramatically since 1980 (Figure 2b-f). Farmland is concentrated along the major rivers. From the PRA we learned that riverbank cultivation is crucial for food security in the area. Between

1980 and 1990 farmland expanded mainly along the major rivers, but from 1990 onwards agriculture stretched into the interfluves (Figure 2b-f).

Between 1980 and 1993 the proportion of farmland in Ward 2 increased relatively slowly from 1% to 3% of the total area, followed by a sharp increase up to 14% of the total area by 2007 (Figure 3). A similar trend was observed in Ward 3, but with greater proportions of farmland: an increase from 5% to 15% of the total area between 1980 and 1993, followed by a rapid expansion thereafter to 47% of the total area in 2007. In both wards, an exponential relationship describes the expansion of farmland over the years.

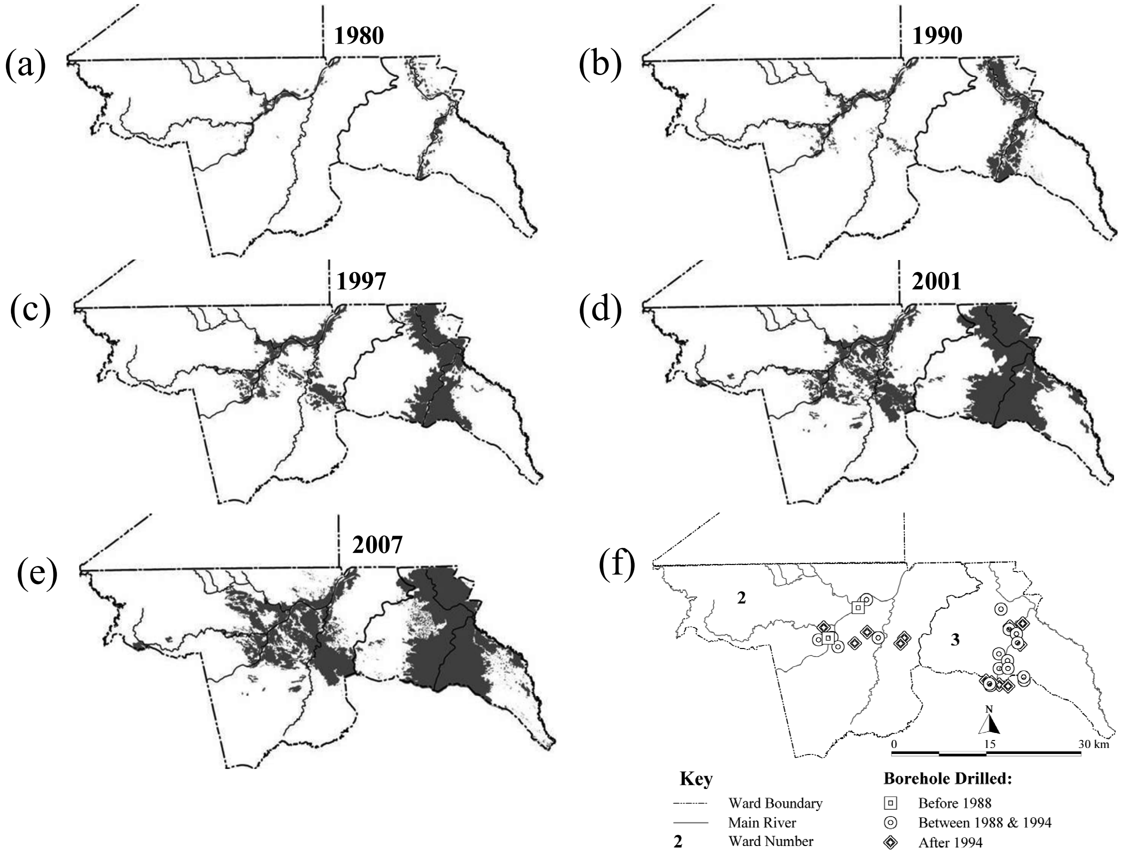

Figure 2. (a) Farmland in Wards 2 and 3 in 1980; (b) farmland in Wards 2 and 3 in 1990; (c) farmland in Wards 2 and 3 in 1997; (d) farmland in Wards 2 and 3 in 2000; (e) farmland in Wards 2 and 3 in 2007; and (f) location of the boreholes in Wards 2 and 3.

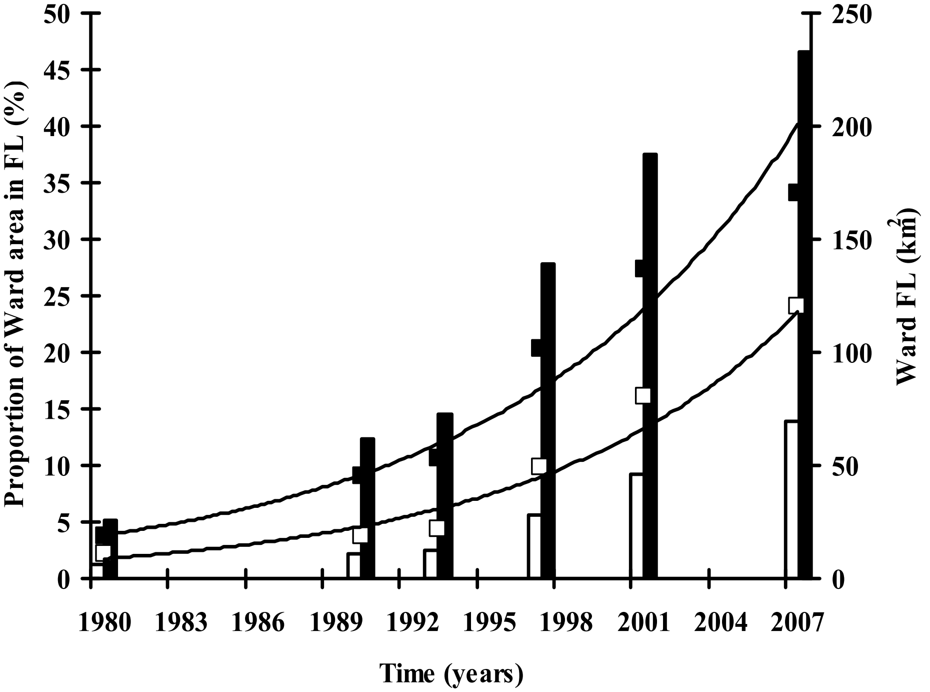

Figure 3. Increase in the area of farmland (FL) in Wards 2 and 3, and of the proportion of the total Ward surface it represents. Open symbols: Ward 2, closed symbols: Ward 3, bars: proportions, squares: FL. The lines represent exponential models: $FLwd2 = \exp(-195 + 0.10 \times T)$, $R^2 = 0.95$; $FLwd3 = \exp(-175 + 0.09 \times T)$, $R^2 = 0.95$; with $FLwd2$ the surface in km^2 of agricultural land in Ward 2, $FLwd3$ the surface in km^2 of agricultural land in Ward 3 and T the time in years.

2.3.2. Immigration, planned settlements and spontaneous settlements

To assess the relative importance of different drivers of land use change in the study area, we first looked at human population growth and its consequences for land use. The population in Dande Communal Area almost doubled between 1992 and 2002 (Table 1). This increase varied between the different wards, and was 1.5 times greater in Ward 3 and 9 than in Ward 2 (Wards 3 and 9 were a single ward in 1992).

Table 1. Population figures and associated densities in 1992 and 2002 in the study area (CA: Communal Area; Source: Central Statistic Office, Harare)

Years	Population (number of inhabitants)			Densities (inhabitants km^{-2})		
	Ward 2	Wards 3 and 9	Dande CA	Ward 2	Wards 3 and 9	Dande CA
1992	2,707	7,762	36,074	3.1	14.3	8.8
2002	4,886	18,362	71,096	5.7	33.9	17.3

The majority of interviewed household heads (64% of the 176 farms sampled) were immigrants, that is they were not born in Dande Communal Area (Table 2). We found a statistically significant difference in the proportion of immigrants in the three geographic areas ($P < 0.01$): 35% in West Ward 2, 61% in Wards 3 and 9 and 86% in East Ward 2.

Table 2. Numbers and proportions (%) of planned vs. spontaneous settlements and of migrants vs. long-term residents in the three geographic areas (total sample $n = 176$): West Ward 2 ($n = 26$; 15% of the total sample), East Ward 2 ($n = 49$; 28% of the total sample) and Wards 3 and 9 ($n = 101$; 57% of the total sample).

	West Ward 2		East Ward 2		Wards 3 and 9		Whole area	
	No. of farms	%	No. of farms	%	No. of farms	%	No. of farms	%
Planned settlements[a]	0	0	0	0	51	51	51	29
Spontaneous settlements	26	100	49	100	50	49	125	71
Migrants[b]	9	35	42	86	62	61	113	64
Long-term residents	17	65	7	14	39	39	63	36

[a] Settlements recognized and demarcated by the Mid-Zambezi Valley Resettlement and Development Project

[b] Heads of households who were not born in Dande Communal Land

Immigrant farmers cultivated significantly larger areas than autochthons, 3.2 and 2.2 ha respectively (differences statistically significant in the mean log-transformed values; $t = -2.88$; $P < 0.005$). Similarly, immigrant farmers tended to cultivate larger areas of cotton than autochthons (2.0 ha and 1.4 ha respectively, with a statistically significant difference in the mean log-transformed values; $t = -2.25$; $P < 0.05$). From the sample of households, 38% had been resettled by the state-sponsored Mid-Zambezi Resettlement Development Project, or MZRDP (Table 2). The majority of settlements in the study area, however, were of unplanned spontaneous origin by the time of the study in 2007. In particular, all the immigrants who settled in East Ward 2 and West Ward 2, areas not targeted by the MZRDP, were spontaneous immigrants who may be recognized by the traditional authority, but not by state institutions. We did not find any significant difference in area cropped, number of livestock or number of months the household is food secured between spontaneous and state-sponsored planned resettlements. Through our PRA, we found that the five eastern-most villages of East Ward 2 (of a total of 10 villages) were all created between 1985 and 2002 by spontaneous immigrants originating mostly from Masvingo Province, in Southern Zimbabwe.,

2.3.3. Increase in cattle population and expansion of plough-based agriculture

As the use of animal traction allows farmers to cultivate larger areas, we need to consider changes in the numbers of cattle as a potential driver of land use change. The livestock population in the Dande Communal Area increased tremendously since the late 1980s, with particularly high annual growth rates (above 15%) in 1990, 1991, 1992, 1994 and 2006 (Figure 4). Similarly, results from aerial censuses carried by WWF and AWF illustrate a linear increase in cattle population from 1995 onwards (Figure 5a). The population of sheep and goats also increased tremendously since 1992, but seemed to plateau by 1999 (Figure 5b).

As expected, the average number of cattle per farm increased from West Ward 2 to East Ward 2 and Wards 3 and 9, as tsetse fly density decreased (F = 10.32; $P < 0.0005$): the average number of cattle per farm was 0.00, 0.91 and 2.65 heads respectively (Figure 6a).

The relative mortality rate of draught animals due to trypanosomiasis is of prime importance in explaining the heterogeneity of farming systems across the study area. Selected characteristics of households in West Ward 2, East Ward 2 and Wards 3 and 9 from the 176 questionnaires administered along the 3 transects, are presented in Table 3. The average surface per farm increased from an average farm surface of 1.56 ha in West Ward 2 to 3.03 ha in East Ward 2 and 3.66 ha in Wards 3 and 9 (Figure 6b; differences statistically significant between the means of the log-transformed values; F = 20.82; $P < 0.0001$).

Hence, whereas tsetse eradication enabled ox-drawn ploughing – and thus a further expansion of farmed land per households in Wards 3 and 9, and to a degree in East Ward 2, it had no impact on the expansion of the area of farmland in West Ward 2.

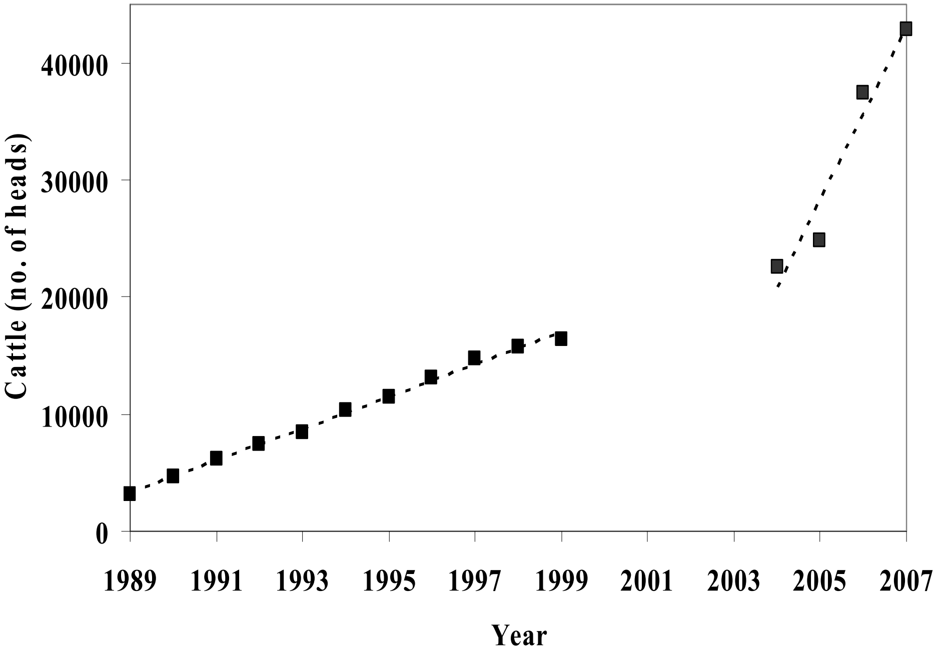

Figure 4. Increase in the cattle population in Dande Communal Area. The dotted lines represent linear regression: $C = 1371 \times T$ between 1989 and 1999, $R^2 = 0.99$; $C = 7371 \times T$, between 2004 and 2007, $R^2 = 0.94$; with C the cattle population in number of heads and T the time in years. Source: Department of Veterinary Services, Mushumbi Pools. (Cattle numbers were not recorded during the years 2000, 2001, 2002 and 2003 due to internal problems in DVS during these years of political instability.)

2.3.4. Animal draught power and cropping pattern

During the PRA sessions, participants mentioned the number of spans of draught animals and the surface area dedicated to cotton farming as the major determinants of farm heterogeneity in the study area. Therefore, we divided the total sample of 176 interviewees into 4 groups: a group of farmers without draught power using hand-hoes who do not grow cotton (49 farmers), a group of farmers without draught power using hand-hoes who grow cotton (29 farmers), a group of farmers owning less than 4 draught animals and growing cotton (38 farmers), and a group of farmers owning 4 draught animals or more and growing cotton (60 farmers). We found statistically significant differences between these four groups for the mean (log-transformed) total land area cultivated (F = 19.49; *P* < 0.0001) and the mean (log-transformed) land area under cotton (F =105.66; *P* < 0.0001) (Figure 7a). However, no differences were found for the (log-transformed) land area under cereals (Figure 7a). There were also significant differences between the 4 farm classes in the (log-transformed) number of adult cattle (F = 117.77; *P* < 0.0001) and the (log-transformed) number of sheep and goats (F = 19.49; *P* < 0.0001), both of which are good indicators of wealth (Figure 7b). Finally, we found statistically significant differences between the 4 farm classes in the number of months the household is food secured (F = 5.44; *P* < 0.0001).

The difference between farms in cultivated area per farm was also apparent when comparing the three geographic areas – West Ward 2, East Ward 2 and Wards 3 and 9. Cotton farming was less developed in West Ward 2, with a mean area of cotton per farm of 0.31 ha, than in East Ward 2 and Wards 3 and 9 which had 1.74 and 1.82 ha respectively (Figure 6c). These differences were statistically significant (F = 29.78; *P* < 0.0001).

The positive interaction between cotton farming and cattle numbers suggested by our data is confirmed by the fact that 15 respondents out of a sample of 17 interviewees representative of the heterogeneity of immigrants in the study area came to Dande Communal Area without cattle or donkeys, but purchased them with income generated from cotton or to a lesser extent, from maize cropping (data not shown). Cotton is the major source of income for 76% of the farms in the study area (Table 3). The area each farm cropped with cotton was also significantly correlated with the number of months during which the farm was food secure (r = 0.22; *P* < 0.005)

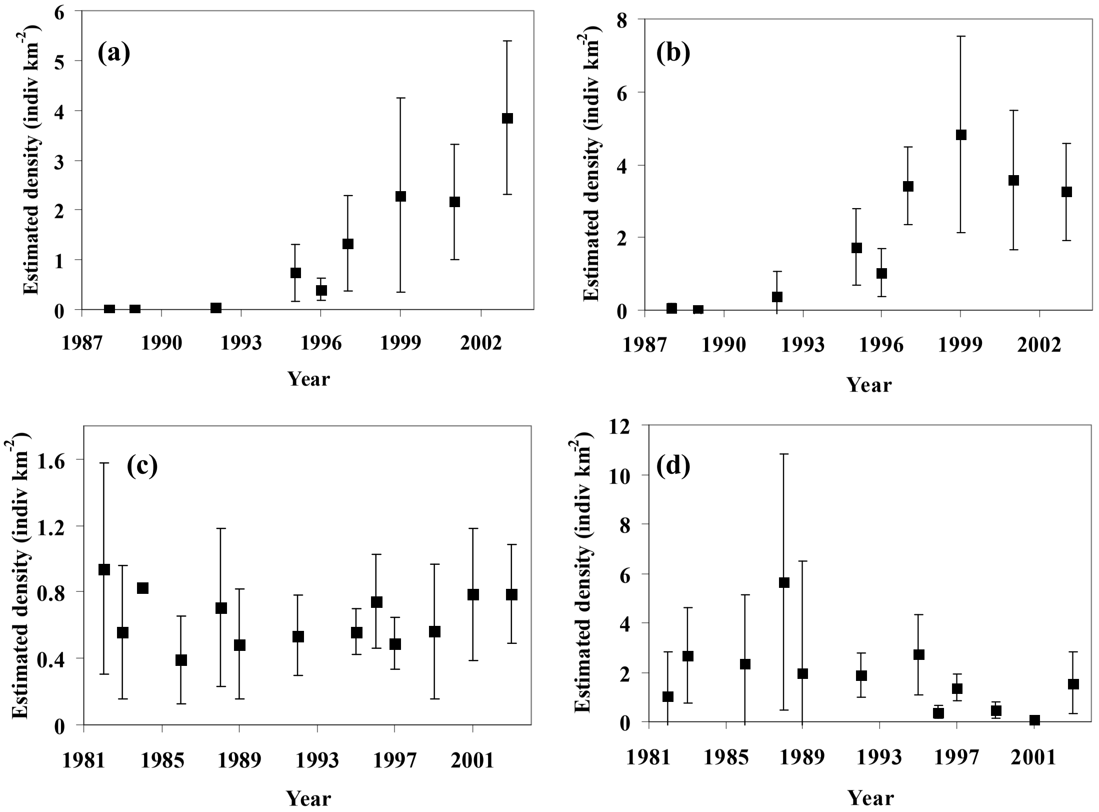

Figure 5. Changes in animal density in Dande Communal Land and Dande Safari Area (a) for cattle between 1986 and 2003, (b) for sheep and goats between 1986 and 2003, (c) for elephant between 1981 and 2003 and (d) for buffalo between 1981 and 2003 (vertical lines represent 95% confidence intervals).

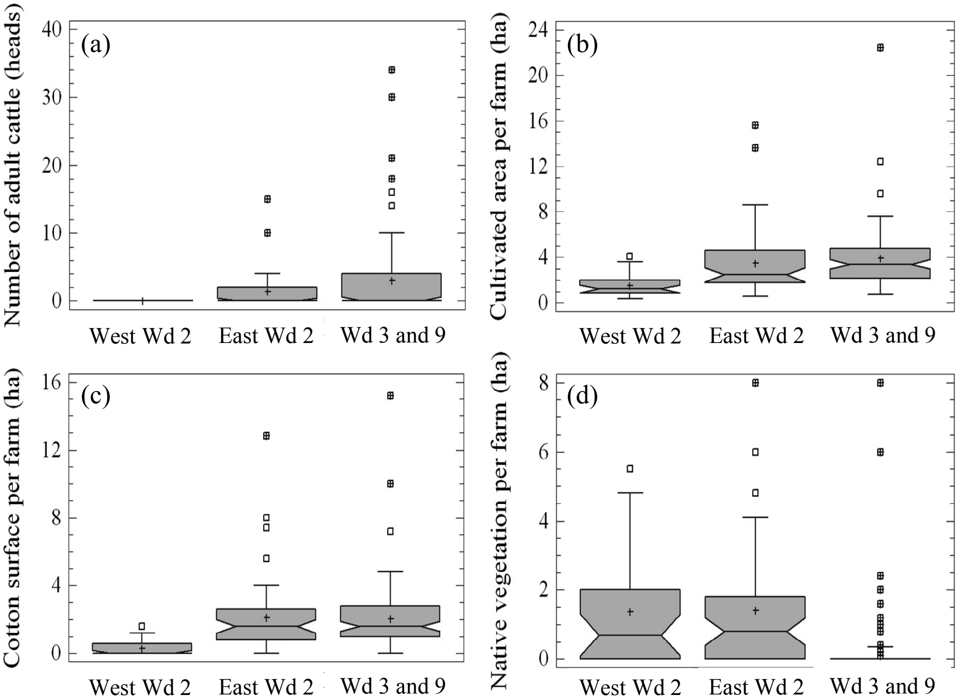

Figure 6. Box and whisker plots comparing: (a) number of adult cattle per household, (b) cultivated area per household, (c) land area cropped with cotton per household and (d) surface area under native vegetation per household, in the three geographic areas; West Ward 2, East Ward 2 and Ward 3 and 9 (boxes are drawn extending from the lower quartile to the upper quartile; whiskers are drawn from the edges of the box to the largest and smallest data values, excluding outside points i.e. points that are more than 1.5 times the box width above or below the box limits; outside points are represented by squares, medians are represented by vertical lines; means are represented by crosses).

Table 3. Numbers and proportions (%) of farms with various qualitative characteristics noted during the participatory rural appraisal in the three geographic areas (total sample *n* = 176): West Ward 2 (*n* = 26; 15% of the total sample); East Ward 2 (*n* = 49; 28% of the total sample); and Wards 3 and 9 (*n* = 101; 57% of the total sample).

Characteristics	**Geographic areas**							
	West Ward 2		**East Ward 2**		**Wards 3 and 9**		**Whole area**	
	No. of farms	**%**	**No. of farms**	**%**	**No. of farms**	**%**	**No. of farms**	**%**
Cotton as the main source of income	7	27	46	94	80	79	133	76
Crops destroyed by wildlife	26	100	42	86	58	57	126	72
Fields guarded	26	100	36	73	55	54	117	66
Crops destroyed by elephants[b]	25	96	21	43	31	31	77	44
Crops destroyed by buffaloes[b]	19	73	11	22	4	4	34	19

[a] Permanent or temporary

[b] Household heads who mentioned elephant/buffalo in their answer to the open question “which animal species do destroy your fields?”

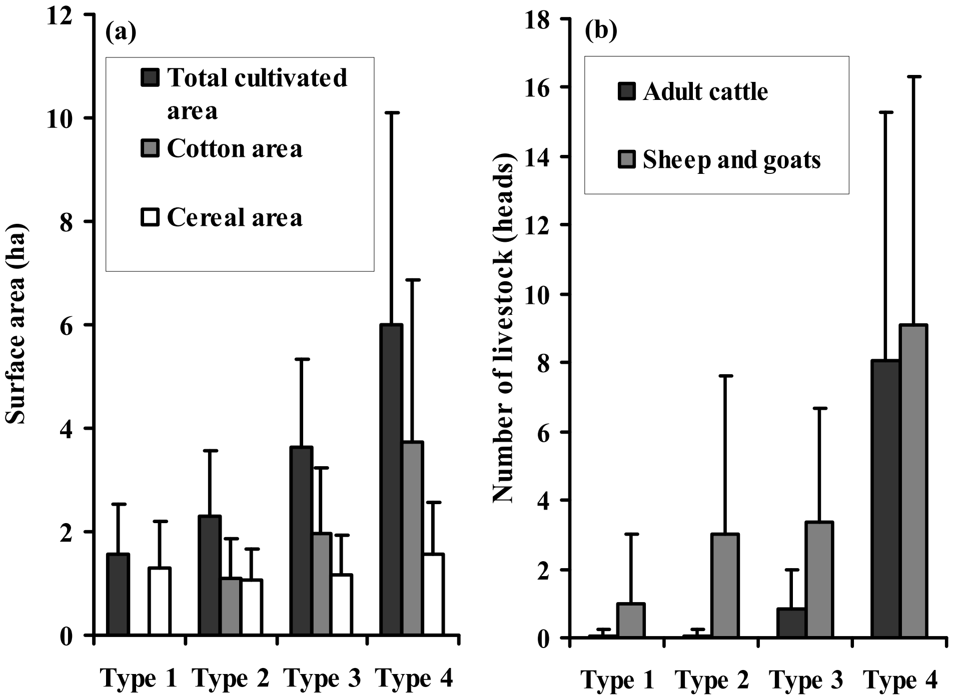

Figure 7. (a) Mean total cultivated area, cotton area and cereal area for 4 farm groups of increasing production capacity (n = 176; Type 1: manual farms not growing cotton; Type 2: manual farms growing cotton; Type 3: farms owning less than 4 draught animals and growing cotton; Type 4: farms owning 4 draught animals or more and growing cotton); (b) mean number of cattle and sheep and goats for the same farm classes.

2.3.5. Trends in wildlife populations

The relative abundance of wildlife across the study area can be assessed by the proportion of farmers reporting human-wildlife conflicts, which we found to be statistically different between the three geographic areas ($P < 0.01$). In West Ward 2, all heads of households interviewed reported crop losses due to wildlife, whereas only 86% of the farmers in East Ward 2 and 57 % in Wards 3 and 9 reported such losses (Table 3). This suggests a clear decrease in the intensity of crop destruction by wildlife from West Ward 2 to Wards 3 and 9. Not surprisingly, the proportion of farmers guarding their fields against wildlife was statistically different between the three geographic areas ($P < 0.01$): in West Ward 2, all interviewed farmers indicated that they guarded their fields against wildlife every night of the cropping season, compared with, respectively, 77% and 54% of the farmers in East Ward 2 and Wards

3 and 9. The interviewees mentioned elephant and buffalo as the major species causing crop destruction (Table 3).

Data from counts on bicycle transects carried out in the study area in 1999 (Gaidet et al., 2003) – and re-conducted in 2002 according to the same protocol – demonstrates significantly ($P < 0.05$) higher elephant and buffalo densities in Ward 2 compared with the more deforested Ward 3 (Table 4). Aerial census results (Cumming and Lynam, 1997; Mackie, 1998; Davies, 1999; Mackie, 2002; Dunham, 2004) surveying an area larger than the study area (an area encompassing the Dande Communal Land and the Dande Safari Area) do not show any significant trend in elephant populations between 1982 and 2003 (Figure 5c). In contrast, the density of buffalo appears to have decreased in the same area and during the same period (Figure 5d). An analysis of species with a smaller home range - zebra, kudu and sable – showed no trends (data not shown).

Table 4. Density estimates and their 95% confidence intervals for elephant and buffalo, for the years 1999 and 2002 in Ward 2 and Ward 3, based on observations from six bicycle transects.

Stratum	Estimate	95% Confidence Interval	
Elephant			
1999			
Ward 2	1.93	1.39	2.68
Ward 3	0.59	0.34	1.03
2002			
Ward 2	1.48	0.93	2.34
Ward 3	0.88	0.49	1.58
Buffalo			
1999			
Ward 2	6.09	3.95	9.39
Ward 3	1.02	0.63	1.67
2002			
Ward 2	7.02	3.76	13.13
Ward 3	1.12	0.68	1.85

2.4. DISCUSSION

2.4.1. Expansion of farmland from the major rivers into the interfluves

Between 1980 and 2007, farmland expanded exponentially in the study area (Figure 3). This was driven, at least in part, by the migration-fuelled growth in the human population. Since independence, the area can be described as an agricultural frontier (Cumming and Lynam, 1997; Biodiversity Project, 2002; CIRAD, 2004).

We found farmland to be concentrated along the major rivers, which is consistent with the findings of Cumming and Lynam (1997), who observed that 74% of household activities in 1997 occurred within 1 km of the major rivers. Easy access to water is probably a major factor that determines the pattern of settlements in the study area. Rivers not only provide freshwater for people and livestock but also a number of natural resources, such as wild fruits (in particular "masau": *Ziziphus mauritania* Lam.), reeds for making mats, fish, as well as wildlife that is attracted to these permanent water sources during the dry season. Riverbanks also provide deep, fertile soils that are easy to till manually and that hold receding moisture during the dry season. Despite the legal interdiction to "cultivate (…) land within thirty metres of the naturally defined banks of a public stream" (Natural Resource Protection Regulations, 1991), cultivation of river banks, and even of the river beds during the dry season, remains a common practice in Dande Communal Area (Laigneau, 1999).

Since the 1990s, farmland started to expand into the interfluves. This "herring-bone" pattern of expansion differs from that found in the Brazilian Amazon where land clearing occurs from roads outwards (Laurance et al., 1998). The difference arises probably because the Mid-Zambezi Valley is a semi-arid area where access to water limits agricultural expansion more than access to markets via roads. Drilling of boreholes in the interfluves between 1988 and 1994 has no doubt been an important driver of the expansion of settlements there (Figure 2a). This must have been particularly the case in Ward 2, where boreholes have been drilled away from the major rivers. In Wards 3 and 9, boreholes were drilled close to the Manyame river by the MZRDP, and such increased access to water would have been a less important driver of land use change (Figure 2a).

In the following sections we discuss the main drivers of this expansion of farmland considering immigration and land use planning, the expansion of plough-based agriculture (due to tsetse eradication), and the expansion of cotton production.

2.4.2. Immigration and the Mid-Zambezi Valley Resettlement and Development Project

Between 1992 and 2002, the human population increased 6% per annum in Ward 2 and 9% per annum in Wards 3 and 9 (Table 1), mainly due to immigration. Less important immigration in Ward 2 may be the consequence of a number of factors, among which the very partial control of tsetse fly, the abundance of destructive wildlife and the remoteness from input and output markets. Exclusion of Ward 2 from the MZRDP is another factor that led to this differentiation between wards.

The MZRDP started in 1986, and was funded by the African Development Bank and the Government of Zimbabwe. It sought to develop the Mid-Zambezi Valley by resettling 3,000 families from crowded and degraded Communal Lands elsewhere in the country, in addition to an estimated 4,600 resident families (Derman, 1996). Each family, resettled or resident, was provided with a 0.5 ha residential plot, 4.5 ha arable land and 0.1 ha of vegetable garden area in demarcated residential and farming blocks. In addition, each family was restricted to own a maximum of two livestock units (LU), one head of cattle being equivalent to 0.7 LU and one goat to 0.09 LU (RTTCP, 1995; Ivy, 1998).

However, the programme's planning and implementation was problematic. Firstly, land capability classifications for crop and livestock production were only compiled after resettlement, from 1993 onwards, and financial difficulties within the AGRITEX Planning Branch prevented the development of proper planning in several areas, for example the area between the Manyame and Angwa rivers (RTTCP, 1995). Secondly, the MZRDP under-estimated the resident population, in particular by overlooking the demographic consequences of the liberation war: numerous residents of the Valley had fled the war and were coming back gradually, a number of freedom fighters remained and settled after independence, and many former commercial farm workers had settled in the Valley around 1980 when the (colonial) state's control over land use was minimal and openly contested. (Derman, 1996). Thirdly, the resident population was reluctant to move to their newly-allocated plots (RTTCP, 1995; Spierenburg, 1995). Many of the autochthons continue to cultivate their old plots illegally until the present day. Fourthly, many resident households were not recorded and even entire villages (in particular the whole of Ward 2), were not recognized by the MZRDP. Their inhabitants were identified as “squatters”, permanently under threat of being chased away by government authorities (Aubin, 1997). Illegal settlements, regrouped in illegal villages, welcomed spontaneous settlers, possibly driven by the assumption that large villages would be harder to evict. Local leaders turned a blind eye to spontaneous immigration as the population size of one’s constituency is a basis of political power, and can be used to argue for the development of new infrastructures (e.g. schools, clinics, roads, buses) and to scare away animals (Derman, 1996). Fifthly, planning took no account of natural population growth. Official settlements were not meant to be sub-divided and the next generation was expected to seek employment away from the settlement scheme (Chimhowu and Hulme, 2006). Finally, settlers found several ways to circumvent the rules and access more land than the 4.5 ha which was set as the maximum per household, for example by having unmarried sons applying for a 4.5 ha plot and adding the surface to the parental farm. The confusion thus created by the MZRDP resulted in the plans not being respected, and only accelerated spontaneous immigration, both in villages targeted by the MZRDP and in “illegal” villages. Government planning thus contributed to land use change.

Immigrants tend to farm larger surfaces than autochthons: on average the total area they cultivate is almost 50% larger than that of autochthons. However, spontaneous immigrant households and MZRDP resettled households do not differ in this respect, nor in other resource endowment indicators, despite of the fact that MZRDP resettled households received inputs and tillage services during their first year under the programme, and despite that spontaneous immigrant household where considered to be illegal. This supports the conclusion of Chimhowu and Hulme (2006): “in some cases state-sponsored resettlement has merely been an expensive way of reproducing the livelihoods of communal lands”. That both types of immigrants seem to strategically appropriate land (Demont et al., 2007), is also suggested by a socio-economic survey conducted in the area in 1997. It found that 83% of the interviewees who migrated to Dande after 1993 mentioned “accessing more crop land” as their primary reason for moving (RTTCP, 1997).

State planned and spontaneous immigration thus explains an important part of the land use change observed in Dande Communal Area. However, the area of farmland increased much faster than the human population, and far beyond the area planned by the MZRDP. In Ward 2 for example, farmland increased by 263% between 1993 and 2001 (Figure 3), whilst its population grew by only 80% from 1992-2002 (Table 2). This suggests land use change in the Mid-Zambezi Valley cannot be reduced to immigration-fuelled population growth. We have to consider other drivers to understand the rapid changes in land use. In the following sections we discuss changes in farming practices: the increase in plough-based agriculture and the expansion of cotton farming.

2.4.3. Increased cattle population and expansion of plough-based agriculture

The increased use of animal draught power may be a driver of land use change, since this labour-saving technology increases the area that a farming household can cultivate. Similarly to the area of farmland, the livestock population in Dande Communal Area increased faster than the human population: the average number of cattle per person was 0 in 1980, 0.20 in 1992 and 0.28 in 2002. High annual growth rates (above 15%) in 1990, 1991, 1992 and 1994, suggest that residents of Dande purchased cattle after the tsetse eradication campaigns of the 1980s, and/or that new immigrants came with their cattle. The first factor is likely to have been more important, as we found that most immigrants in the study area came to Dande Communal Area without cattle or donkeys, and purchased them with income generated from cropping (data not shown). The exceptionally rapid growth rate of the cattle herd in 2006 may be understood as the combined effect of: a massive purchase of cattle by residents, errors in data capture by the DVS, a change in the zoning used by the DVS (e.g. addition of villages) or a reduction in cattle off-take (less sales, slaughter and/or mortality).

Spatially heterogeneous interventions of tsetse control generated a gradient of tsetse fly abundance, from west to east. The successful tsetse eradication in the Wards 3 and 9 area has probably been a consequence of both active control measures and the large expansion of farmland that reduced the habitat of wildlife (the vector of the fly) and of the fly itself.

The distribution of tsetse fly across the study area has a great impact on the possibility to use plough-based agriculture. However, we found that the rates of increase in the area of farmland between 1980 and 2007 were similar in Ward 2, which is still tsetse infested, and in Ward 3, which is tsetse free: 0.10 and 0.09 km^2 per year respectively (Figure 3). We therefore conclude that tsetse control was not paramount in driving the expansion of farmland in the study area. Other factors must have had a stronger influence. Other authors (such as Barrett, 1994 and Derman, 1996) have argued that the presence of tsetse flies has not been a barrier to the expansion of livestock, as cattle were present in the Valley in the 1920s, long before any tsetse control operation. According to Barrett (1994), the cattle population peaked in 1972. Moreover, the fact that growth in the cattle population followed the same trend as the sheep and goat population (Figure 5b), more tsetse-resistant domestic species, suggests that the increase in cattle population happened more as a result of wealth accumulation than tsetse control. Cattle breeds found in the Mid-Zambezi Valley before independence may have been different from those found today in the area, probably smaller and more tsetse resistant.

2.4.4. The development of cotton farming

We suggest that the development of cotton farming has been the major driver of both land use change and the growth in cattle numbers. This cash crop has allowed households to accumulate livestock (cattle, sheep and goats) and to purchase farm inputs and implements. Figure 7a demonstrates that land use change was driven by cotton production rather than cereal production (maize and sorghum being the two other major crops): as the wealth of a farming household increases (in terms of production assets), so does investment in cotton production rather than cereal production. Similarly, the average area per farm of cotton, not cereals, increases along a gradient from West Ward 2 to Wards 3 and 9; and immigrants cultivate significantly more cotton than autochthons whilst no difference in the average cereal surface can be observed. Our PRA sessions also suggest that farmers consider the clay soils in the interfluves (locally named "*mutapo*"), which have a high permanent wilting point, to be more suited for cotton production than the alluvial soils (locally named "*bandate*"). This is another demonstration of the role of cotton, rather than cereal production, driving the expansion of farmland, as it occurred mainly in the interfluves since 1990 (Figure 2b-f).

We found positive interactions between cotton farming and livestock numbers. Cotton generates the cash needed to purchase cattle, and cattle provide the draught power necessary for cotton expansion (Figure 7a). Moreover, household needs are covered primarily by cash generated through cotton production, reducing the need to sell cattle, sheep and goats and allowing further accumulation of livestock (Figure 7b). Having 2 spans of cattle or donkeys rather than one significantly accelerates livestock accumulation in cotton farms. Farms that have more than 4 draught animals own on average more than 8 times more cattle than farms with less than 4 draught animals (8.1 and 0.9 respectively; Figure 7b). Similarly, farms with more than 4 draught animals own on average almost three times as many sheep and goats than farms with less than 4 draught animals (9.1 and 3.4 respectively; Figure 7b). Cash generated by cotton may also allow investment in inputs (e.g. fertiliser, hybrid seeds), implements (e.g. ploughs, cultivators) and other production factors, improving not only cotton productivity, but also that of other crops. The positive correlation between the land area per farm on which cotton is cultivated and the number of months the farming household is food secure supports this conclusion. It exemplifies the complementarity of cash and food crops that has been demonstrated in many other parts of sub-Saharan Africa (see, for example, Demont et al., 2007). A number of spill-over effects of cotton production on cereal production (Govereh and Jayne, 2003) may occur at household level (e.g. access to fertilisers on credit benefiting cereals in the rotation cycle or being used directly on cereals; use of knowledge acquired in cotton promotion activities for the production of cereals) and at regional level (e.g. market infrastructures developed by cotton companies and benefiting markets of other commodities).

Therefore, our conclusion supports the RTTCP (1997) report that sees tsetse control as only one of the factors that “may have facilitated or accelerated” land use change in Dande Communal Area. Tsetse control enhanced the presence of cattle in the area, but cotton farming was the main driver of increased cattle numbers as well as the clearing of natural vegetation for agriculture.

2.4.5. Implications for wildlife conservation in the Mid-Zambezi Valley

The decrease in crop damage by wildlife (mainly buffalo and elephant) along the anthropogenic gradient from West Ward 2 area to Wards 3 and 9 suggests lower wildlife densities in the eastern part of the study area compared with its less deforested western part (Table 3). This is consistent with the findings of Hoare (1999) who demonstrated a positive correlation between a “problem elephant index”, defined as the average number of incidents in a ward per surface of cropped land, and the distance from a protected area. Similar findings have been reported in the neighbouring district of Muzarabani (Parker and Osborne, 2001).

Results from counts on bicycle transects point to the same conclusion, with significantly less elephant and buffalo sightings in Ward 3 than in the less deforested Ward 2 in both 1999 and 2002 (Table 4). However, no changes were seen between the two sampling times for either species or area.

Data from aerial censuses from WWF and AWF cover a longer period, but are less precise (variances are high due to the small number of transects per stratum) and can only detect large mammals. However, conclusions may still be drawn for species with a large home range such as elephant and buffalo. Results from these aerial censuses do not point to a decline in the population of elephants in the study area (Figure 5c), despite the increase in human settlements and in the area under farmland. It may be that changes in elephant population couldn’t be detected by aerial censuses, due to the large scale at which they were conducted, and the large confidence intervals of the estimated densities. It may also be that a critical threshold of human density affecting elephant populations has not yet been reached. Taylor (1999) estimates this threshold to be around 15 to 20 inhabitants per km^2 (and up to 30 inhabitants per km^2 under intensely managed conditions) whilst the human density for the whole of Dande Communal Area in 2002 was 17 inhabitants per km^2. Finally, the elephant population may also have remained stable due to the presence of large protected areas in the western part of the study area that act as wildlife reservoirs.

Despite the limitations of the methods, data from aerial censuses suggest that buffalo densities have diminished between 1982 and 1992 (Figure 5b). Reduction of habitat is only one possible cause of declining buffalo numbers. Poaching for bushmeat is common in the study area (Murindagomo, 1988, Chardonnet, 1995) and buffalo is sought after. Poorly managed sport hunting in the area may also have contributed to the decline in buffalo population: a recent study has shown that hunting quotas were too high and that the industry was targeting animals that were too young on average for sustainable management of the buffalo population (Taylor, 2005). We cannot link directly the decline of buffalo population in the study area to land use change. However, analysis of satellite images clearly shows increasing isolation of the Angwa and Manyame rivers from uncultivated areas. Wildlife thus became excluded from dry season water sources and key riparian habitats. Fritz et al. (2003) found negative correlations between dry season frequentation of both the Angwa River and Manyame River by wildlife and the intensity of cultivation along these rivers. Cumming and Lynam (1997) also argued that cultivation along the rivers reduces the effective use by wildlife of large unsettled areas away from rivers that are unsuitable for agriculture. From the 1990s to date, the expansion of farmland into the interfluves reinforced this barrier effect.

2.4.6. What future for the Mid-Zambezi Valley, “wildlife-friendly farming” or “land sparing”?

Farmers in the study areas use fallows to renew farmland productivity. This extensive form of agriculture could be typified as “wildlife-friendly farming”, a form of agriculture based on the use of little or no external input and the retention of patches of natural and semi-natural extensively cultivated patches (Green et al., 2005). Wildlife-friendly farming is strongly supported in Europe, through agri-environmental payments (Potter and Burney, 2002), as this set of practices was demonstrated not only to be benign for European wildlife, birds in particular, but also to be necessary for their survival. Most European landscapes are man-made, and the majority of wildlife species surviving in these areas have evolved within the heterogeneous farmland habitats created and maintained by low-input agriculture and extensive livestock rearing (Benton et al., 2003).

The situation is different in most countries of sub-Saharan Africa, where the history of farming is shorter and most wildlife species are “agriculturally naïve” i.e. they cannot be maintained in farmland, even at low farming intensity (Green et al., 2005). This is probably the case for the emblematic African mega-fauna in the Mid-Zambezi Valley. Fritz et al. (2003), for instance, found the number of individuals recorded per segment of riverbed to decrease with increasing cultivated areas for all the major ungulate and small and medium-sized carnivore species. Moreover, African mega-herbivores and large carnivores, the main species of interest to conservation in the Mid-Zambezi Valley, generally represent a threat to human lives and their presence in farmland may be undesirable. Finally, although wildlife-friendly farming is beneficial for farmland biodiversity, it often results in less production and therefore requires a larger area of farmland to meet any production target (Green et al., 2005).

The alternative approach to wildlife-friendly farming is “land sparing” i.e. increasing yield on existing farmland, reducing at the same time the need to expand on remaining wild nature. The validity of a land sparing approach is confirmed by country-based evidence of yield increases and declines in cultivated areas (Rudel et al., 2005). For instance, US farmers, by raising grain yields, have spared about 150 million hectares since 1940 (Ausubel, 2000). Similarly, increases in crop yields in developing countries (Green et al., 2005), have reduced deforestation rates (Ewers et al., 2009). Therefore, land use intensification, i.e. yield increase, may constitute an opportunity for the conservation of wildlife in the Mid-Zambezi Valley, especially if the human population continues to increase.

2.5. CONCLUSIONS

The image of the Mid-Zambezi Valley that emerges from our research is that of an agricultural frontier that attracted opportunity-seeking farmers, and where large-scale land use changes were mainly driven by cotton farming. Tsetse control has played an important role in catalysing these changes, but they would not have been as fast and extensive without the presence of a cash crop such as cotton. We argue that this situation is common in agricultural frontiers in developing countries – i.e. that land use change is driven by cash cropping and the economic revenue derived, and not only by alleviation of farming constraints (e.g. deforestation in Sumatra driven by coffee prices, Gaveau et al., 2009; deforestation of the Amazonia driven by beef and soyabean prices, Barona et al., 2010). Farmers’ response to changing economic conditions, mediated by institutions and increasingly influenced by global forces, is a major driver of global land use and land cover changes worldwide (Lambin et al., 2001).

Although direct effects of land use change on wildlife density could not be proven, our study suggests that the consequences for elephant and buffalo numbers are negative. Other factors – and in particular poaching and sport hunting – may contribute to wildlife decline. In any case, if the observed rates of change – in terms of human demography, farmland and cattle population - are to continue unabated, the consequences for the role the Dande Communal Area in the maintenance of wildlife in the wider Mid-Zambezi Valley ecosystem will probably be negative. For Dande Communal Area to continue to support wildlife population without jeopardizing agricultural production, intensification of land use will be needed in order to “spare” land for wildlife. This will require an integrated approach including technical and institutional innovation and the development and enforcement of policies and regulations to promote sustainable intensification and constrain further clearance of land for agriculture.

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Chapter 3

What kind of farming can save wild nature? Environmental footprint of farms in the Mid-Zambezi Valley, Zimbabwe

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ABSTRACT

Environmental footprints of producing food or cash crops adjacent to a conservation area of global importance were compared using ten indicators: cropped area, fallow area, pesticide use, plant diversity loss, C loss, N, P and K removal, calorific deficit and forage deficit. The study was conducted across a gradient of increasing farming intensity in Mbire district, Northern Zimbabwe. The environmental footprint of the farms increased strongly along a continuum of cereal-based to cotton-based farms. A kilogram of seed cotton required about 60% more land, removed twice as much N, 50% more K and 20% more P than a kilogram of cereal grain. Except for pesticide use and N removal, one man-day invested in cotton production had a smaller environmental footprint than a man-day invested in cereal production. Consequently, if farmers specialised in cereal production, the cropped area would increase by more than 20% and the fallow area by more the 35%. In contrast, if all farmers were to specialise in cotton production, the total cropped area would decrease by more than 30% and the fallow area by more than 20%. Therefore, maintaining the relative profitability of cotton may 'spare land' for nature. For this 'land sparing' to be effective, however, further immigration and land clearance would have to be regulated.

Keywords: Zimbabwe; cotton; cereal; footprint; productivity; efficiency.

3.1. INTRODUCTION

Over the last four decades of the twentieth century, the total area of cropland decreased in the developed world but increased by 20% in the developing world (Green et al., 2005). Production of agricultural commodities is a major contributing factor for this expansion and overrules the effect of population growth (Angelsen, 1999; Lambin et al., 2001, Searchinger et al. 2009). For instance, deforestation is partly driven by oil palm production in Indonesia and Malaysia (Koh and Wilcove, 2008), by beef cattle production and soya farming in the Amazon (Barona et al., 2010), and by cotton farming in the African savannahs (Baudron et al., 2009; Chapter 2). These regions of the developing world are some of the last biodiversity-rich areas on the planet (Myers et al., 2000; Gibbs et al., 2010). As our understanding of the role of biodiversity in maintaining ecosystem processes improves (Chapin et al., 2000), the urgency to reduce current rates of deforestation becomes more evident (Pimm et al., 1995). Moreover, cash cropping relies more heavily on external inputs of pesticides and fertilisers than food cropping (Bamire and Manyong, 2003; Erenstein, 2006), which may represent an environmental threat locally and regionally (Matson et al., 1997). Cotton – the main cash crop in the African savannahs – is considered to be one of the most polluting annual crops due to use of pesticides such as endosulfan and deltamethrin that are classified as hazardous by the World Health Organization (EJF, 2007; WWF, 2007).

Cash cropping has driven major shifts in land use in several parts of the developing world previously dominated by food production (Lambin et al., 2001). This may affect the environmental impact of farming, as different crops require different land area, labour, and external inputs, and hence differ in their environmental impacts. This article focuses on a region of the Mid-Zambezi Valley, in northern Zimbabwe, where smallholder farming has expanded rapidly. In the late 1980s, this biodiversity-rich region was hit by a cotton boom that transformed the farming systems that were previously dominated by cereal farming. Cotton farming permits access to external inputs on credit (mineral fertiliser and pesticides) and generates income to purchase draught power and implements (Baudron et al., 2009; Chapter 2). Depending on resource endowment (e.g. labour), the agro-ecological circumstances in which they farm (e.g. abundance of tsetse fly determining the possibility to keep draught animals, see below), and when they first engaged in cotton farming, farmers did not benefit equally from the cotton boom. Moreover, no farm fully specialised in cotton farming, as being self-sufficient for one's food requirement is a strong socio-cultural force in many rural societies (van Donge et al., 2001). Therefore, the study area presents a continuum of farms, from cereal-based to cotton-based systems.

The concept of ‘ecological footprint’ allows for an integrated evaluation of the environmental impact of a social unit, such as a farming community. It is defined as “*the amount of biologically productive land and sea area needed to regenerate the resources a human population consumes and to absorb and render harmless the corresponding waste*” (Wackernagel and Rees, 1996). In this paper, a slightly different interpretation of the environmental footprint is used. Environmental impact from farming was not expressed as a land area, but assessed using locally-relevant environmental indicators i.e. adapted to the assessment of the environmental footprint of rainfed farming by African smallholder farmers. For example, the risk of pollution by pesticides was simply estimated through the quantity of pesticides used. The indicators used can be divided in indicators of direct and indirect impact on the environment. Direct impacts include the conversion of natural vegetation into farmland (cropped land and fallow land), the loss of *in situ* plant biodiversity, the pollution by synthetic biocides and the depletion of nutrient stocks (e.g. N, P, K). Indirect impacts have effects on the environment outside the farm boundaries. In this study, this included an indicator of the household food requirements that are not fulfilled by on-farm production, and that must be fulfilled by food produced off-farm (natural resources from neighbouring wild lands or food produced in other farms, sometimes even in other farming areas or other countries); and an indicator of livestock forage requirements that are not fulfilled by on-farm production, and that must be fulfilled by off-farm grazing in the neighbouring natural vegetation and/or on other farms.

The objectives of this paper were (i) to assess the current environmental footprint of farming in the Mid-Zambezi Valley, along a continuum of farms from cereal-based to cotton-based farming, and (ii) to explore possible consequences on the environmental footprint of farming under various scenarios including change in farm distribution along this continuum and increased cotton or cereal specialisation.

3.2. MATERIALS AND METHODS

3.2.1. Study area

The study area covers three wards (Ward 2, Ward 3 and Ward 9) of Mbire District located in northern Zimbabwe between 30°00 and 31°45 longitude East and 16°00 and 16°30 latitude South (Figure 1). Human population is still relatively sparse and there is no land scarcity: in 2002 a total of 23,250 people lived in these three wards that cover a total area of 1,400 km^2. It is part of the Mid-Zambezi Valley, which is formed by the former floodplains of the Zambezi River between the Victoria Falls and Cabora Bassa Lake, at an average altitude of 400 m above sea level. It has a dry tropical climate, with low and very variable annual rainfall (on average between 450 and 650 mm year^{-1}) and a mean annual temperature of about 25°C. Two seasons are clearly defined: a rainy season from December to March and a long dry season from April to November. Smallholder agriculture abuts wildlife conservation areas comprised of national parks and safari (hunting) areas. Cotton, sorghum and maize are the major crops grown in the region. Minor crops include groundnut, cowpea and sunflower. Since the post-2000 economic crisis, the cultivation of maize diminished, and remained mostly concentrated along river banks, while more drought-tolerant sorghum became the major cereal grown on the interfluves.

The study area is characterised by an agricultural intensification gradient, from north-west-west to south-east-east. Along this gradient, three geographic zones can be distinguished: 1) 'West Angwa', on the western end of the gradient, corresponds to the western part of Ward 2 and is a sparsely populated zone, where tsetse fly remains abundant, large wild mammals are numerous, cattle is absent and cotton is cultivated on relatively small areas; 2) 'Mushumbi Pools', on the eastern end of the gradient, corresponds to Ward 3 and Ward 9 and is a more densely settled zone where tsetse fly has been eradicated, large wild mammals are few, cattle population is comparatively large, and cotton is cultivated on relatively large areas; 3) 'East Angwa', in the middle of the gradient, corresponds to the eastern part of Ward 2 and represents an intermediate situation (Chapter 2; Figure 1).

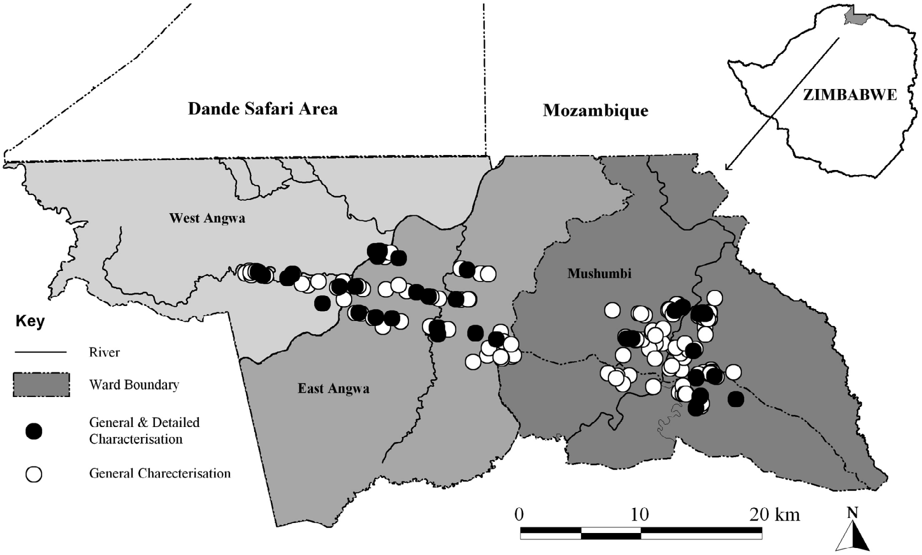

Figure 1. Map of the study area indicating the three geographic zones located on an agricultural intensification gradient oriented north-west-west to south-east-east, and the locations of farmers interviewed during the general and detailed farm characterization surveys.

3.2.2. A continuum of farms: from cereal-based to cotton-based systems

To describe and analyse the continuum of farms between the two ideal-typical ends – cereal-based farming that is poorly linked to the market and market-oriented cotton-based farming – a farm typology was constructed and the functioning of each farm type was analysed, following a two step methodology. The first step aimed at describing broadly, and mainly from a structural point of view, a relatively large sample of farms (*n* = 176). The aim of the second step was to describe in more detail and from a functional perspective a sub-sample of 37 farms chosen to represent the diversity of farms identified in step one.

3.2.2.1. General characterisation

Farms were surveyed along three transects of 30 to 40 km cutting across the study area in a direction parallel to the agricultural intensification gradient (Figure 1). We hereby assumed that the position on the gradient was a major factor influencing the farm types. Land uses were classified into four categories: cropland (fields and homestead surroundings), fallow land (fallows, grazing areas and degraded woodlands), natural vegetation and other types of land uses (e.g. main river beds). Along the three transects, coordinates of the transitions between different land uses were recorded using a global positioning system and distances between two contiguous transitions were calculated. From the proportion of total transect length under different land covers, the proportions of the area occupied by fields, fallows and natural vegetation in the three geographic zones were estimated. Using the transect lengths under cropland and the total length of transect under fallow land as proxies, Ruthenberg coefficients (R) were calculated as $R = C/(C+F)$; where C is the area under cultivation and F the surface under fallow at any time (Ruthenberg, 1980). Farms that had at least one cultivated field on one of the transects in the 2006-07 growing season were selected for the general farm characterisation (Figure 1). This resulted in a sample of 176 farms, of which some homesteads were located several kilometres away from their field on the transect, with 26 farms in West Angwa, 49 in East Angwa and 101 in Mushumbi Pools. Household heads were interviewed using a standardised questionnaire, which addressed size, composition and history of the household, production capital (e.g. land, equipment), crop and livestock management, income generating activities, cash needs, and food security. For each farm, some secondary variables were calculated, such as the total livestock per farm (in tropical livestock units) or the land:labour ratio (in ha. person^{-1}).

3.2.2.2. Detailed characterisation

From the data gathered during the survey for the general farm characterisation, a simple typology made of four farm types of increasing resource endowments was developed. The surveyed farms were first grouped into farmers that were not growing cotton (Type 1) versus farmers growing cotton. The latter group was further divided in hand-hoe farmers (Type 2) and ploughing farmers using oxen or donkeys. The group of ploughing farmers was finally divided in farmers owning less that two pairs of draught animals (Type 3) and farmers owning two pairs or more (Type 4). The terms ‘Type 1’, ‘Type 2’, ‘Type 3’ and ‘Type 4’ are used in the rest of the paper to describe this typology. The typology was used to select a stratified sample of farmers in each geographic zone. In total, 37 farmers were selected and interviewed during the 2008-09 cropping season, which received above average rainfall (around 1000 mm) well distributed over the growing season. The interviews aimed at gathering detailed information on farm history, crop management and productivity and resource allocation in space and time, with an emphasis on indicators of environmental impact. The area of each field at the selected farms was first measured using a global positioning system. Information was then gathered on the nature and quantity of external inputs applied and the amount of labour invested in each field. For each farm, the crop harvests and the proportions of crop residues kept as mulch, ploughed in, burnt, grazed by livestock, grazed by wildlife and being decomposed on the soil surface during the dry season, were estimated with the corresponding farmer. Finally, the farm history was discussed with a focus on major events - such as shift in cropped area and technological changes (e.g. cultivation of new crops, use of animal traction, use of pesticides) – and on changes in the labour available on-farm, the number of draught animals (adult cattle and donkeys) and the areas for the cultivation of the different crops.

3.2.3. Indicators of environmental footprint

A total of ten indicators were used in this study, namely: ‘cropped area’, ‘fallow area’, ‘pesticide use’, ‘plant diversity loss’, ‘C loss’, ‘N removal value’, ‘P removal value’, ‘K removal value’, ‘calorific deficit’, and ‘forage deficit’. The description and calculation for these indicators are given in Table 1. To calculate these indicators, only the fields cultivated to cotton, maize and sorghum were considered. As the areas dedicated to other crops (e.g. cowpea, groundnut, sunflower) were minor in comparison, these were ignored in the analyses.

3.2.3.1. ‘Cropped area’

The indicator ‘cropped area’ corresponds to the sum of land (in ha) occupied by cotton, maize and sorghum in a given farm, and the indicator ‘fallow area’ correspond to the land area (in ha) that is under fallow. Land areas were measured directly during the detailed characterisation.

3.2.3.2. 'Pesticide use'

The indicator 'pesticide use' denotes the sum of the quantities of active ingredient (in g) being used by a given farm. The quantity of each active ingredient was calculated as the product of the rate of application of a pesticide (in L or g) and its concentration in active ingredient (g L^{-1} or g g^{-1}). Cotton was the only crop treated with pesticides. Rates of application of the different pesticides were obtained during the detailed characterisation. Concentrations of active ingredients were obtained from cotton companies or manufacturers. Active ingredients used included carbaryl, carbon sulphate, fenvalerate, lambdacyhalothrin, acetamiprid, and dimethoate.

3.2.3.3. 'Plant diversity loss'

The indicator 'plant diversity loss' was calculated as the mean value of the plant diversity loss (in species ha^{-1}) in the different fields, weighed by the area of these fields. The value of plant diversity loss in cotton, maize and sorghum fields was obtained by measuring plant diversity per area in the fields of nine farms (three in each of the three geographic zones) using a reference value of 19 (the measured value of the maximum plant diversity per surface area in a field). In each cotton, maize and sorghum field of these nine farms, 5 m × 5 m quadrats were placed randomly. The number of quadrats set in each field depended on the size of the field, with the aim of sampling roughly 1% of the total field area. Samples of plants that could not be identified in the field were dried and identified with a reference herbarium at the Harare Botanical Garden.

Table 1. Summary of the indicators of environmental impact, their meanings and units and the way they were calculated for each farm.

Indicators	Meaning and unit	Calculation
Cropland area	Land area occupied by crops (ha)	$\sum_{i} SURF_i$ with $SURF_i$ the surface area of the ith crop (directly measured).
Fallow land area	Land area occupied by fallow land (ha)	Directly measured.
Pesticide use	Total quantity of active ingredient used (g)	$\sum_{i} RATE_i \times CONC_i$ with $RATE_j$ and $CONC_j$ the application rate and the concentration in active ingredient of the ith pesticide.
Plant diversity loss	Cropland loss of plant diversity compared with a reference of 20 (species ha^{-1})	$(1/CL) \times \sum_{i} (SURF_i \times (19 - DIV_i))$ with $SURF_i$ and DIV_i the surface area and the number of plant species per surface area of the ith crop; 19 is the maximum number of plant species attainable in an field
C loss	Annual loss of total soil carbon to a depth of 40 cm in the whole farm i.e. cropland and fallow land (kg y^{-1})	$(5535 - ((1/n+m) \times (\sum_{i} TSCC_i - \sum_{j} TSCF_j)))/40$ with n the number of sections of cropland of different age, m the number of sections of fallow land of different age, $TSCC_j$ the total soil carbon to a depth of 40 cm in the section of cropland i, $TSCC_j$ the total soil carbon to a depth of 40 cm in the section of fallow land j; 5535 is the estimated value of the total soil carbon at a depth of 40 cm under natural vegetation (kg ha^{-1}); 40 is the approximate life-time of a farming unit in the study area (years).
Nutrient (N, P, K) removal value	Annual removal of nutrient (kg ha^{-1} y^{-1})	$- \sum_{i} (\sum_{j} IN_j - \sum_{k} OUT_k)$ with IN_j the nutrient input through the jth use in the ith field and OUT_k the output through the kth use in the ith field.
Calorific deficit	Annual quantity of energy required by the household and not fulfilled by on-farm cereal production (kcal y^{-1})	$(HH \times 3450 \times 365) - (3690 \times \sum_{m} PCRL_m)$ with and HH the total number of people in the household and PCRL the production of the mth cereal crop; 3450 is the estimated daily energy requirement per person (kcal d^{-1}) and 3690 is the estimated quantity of energy delivered by cereal (kcal kg^{-1}).
Forage deficit	Annual quantity of dry matter required by the livestock owned by the household and not fulfilled by on-farm grazing of residues and the primary productivity of fallow land (kg y^{-1})	$\sum_{p} (\alpha_p \times LVS_p \times 2050) - FL \times 3000 - (\sum_{i} FLVS_i \times RES_i)$ with α_p and LVS_p the conversion coefficient in Tropical Livestock Unit and the number of livestock for the pth species, FL the surface area under fallow, $FLVS_i$ and RES_i the fraction of the residues grazed by livestock and the quantity of residues produced by the ith crop; 2050 is the estimated forage requirement of one Tropical Livestock Unit (kg dry matter y^{-1}); 3000 is the estimated primary productivity of fallow land (kg dry matter ha^{-1} y^{-1}).

3.2.3.4. 'C loss'

The indicator 'C loss' is an estimate of the mean annual loss of total soil organic carbon to a depth of 40 cm for the whole farm after 40 years (the approximate lifetime of a farm in years). For each farm, the proportion of land under cultivation, based on the measured cropped area and fallow area, was first calculated. This proportion was assumed to be equal to the frequency a given piece of land was put to cultivation, and each farm was further assumed to neither expand nor reduce its cropped area and fallow area from on year to the next. For example, in a farm where 2/5th of the total farm area was occupied by crops, it was assumed that any given piece of land was being cultivated for two years and put to fallow for 3 years. Thus we assumed for this example that the farm consisted at any given time of one section cultivated for one year, one section cultivated for two years, one section put to fallow for one year, one section put to fallow for two years and one section put to fallow for three years. For each of these sections the long-term total soil carbon to a depth of 40 cm - i.e. after ten crop-fallow cycles - was then estimated, assuming an exponential decline in soil organic carbon in fields and a linear increase in fallow.

The exponential decline function of soil organic matter for cultivated fields was obtained by fitting an exponential model to the measured data from a sample of 33 fields (including 3 plots under natural vegetation) representing a chronosequence of 22 years of cultivation. Three pits were dug in each field of the chronosequence, and three undisturbed samples were collected at 0-10, 10-20 and 20-40 cm depth. For each field, the nine samples from each depth (each about 100 g) were bulked together to form a composite sample that was air-dried and sieved to pass 2 mm. Total carbon content was measured in laboratory using a CN auto-analyser (Thermoscientific Flash EA 1112 series). Under fallow, the annual rate of total soil organic carbon increase to a depth of 40 cm was estimated to be 0.6 t ha^{-1} year^{-1} (Piéri, 1991). For the whole farm, the total soil organic carbon to a depth of 40 cm after 40 years was then calculated as the mean value of the total soil organic carbon to a depth of 40 cm considering the different sections of fields and fallows of different ages. Annual 'C loss' was calculated by subtracting this value from 5535 kg ha^{-1} (the measured value of the total soil organic carbon at a depth of 40 cm under natural vegetation in the most common soil type in the study area) and dividing the result by 40, the number of years.

3.2.3.5. 'N, P, K removal'

The indicators 'nutrient removal' (for N, P, K) are calculated from partial nutrient balances for the whole farm i.e. the aggregation of the balances of the different fields. For a given field, nutrient removal is defined as the difference of the sum of all nutrient outputs and the sum of all inputs. In this study, nutrient balances are partial in the sense that losses through erosion, leaching and under gaseous forms and input through atmospheric deposition and nitrogen fixation (symbiotic and non-symbiotic) were not considered. Thus, nutrient input used in our calculations was only through mineral fertilisers and animal manure, whilst nutrient output was exclusively as harvested products of the crops and removal of residues by fire, livestock, wildlife and decomposition. It was assumed that all N contained in residues was lost in gaseous form during burning, while P and K was retained in the field as ashes. During the 2008-09 season, none of the farmers included in the detailed characterisation used animal manure and only four farmers used mineral fertiliser: Compound L (4% N, 7.48% P, 9.13% K), Compound D (7% N, 6.16% P, 5.81% K), ammonium-nitrate (34.5% N) and/or Folifert (51 g N L^{-1}, 34.76 g P L^{-1}, 17.43 g K L^{-1}). Harvest indexes of 0.25, 0.5 and 0.43 were used for cotton, maize and sorghum, respectively, and mean N, P and K contents provided by Nijhof (1987) were used for residues and harvested products.

3.2.3.6. 'Calorific deficit'

The indicator 'calorific deficit' is defined as the difference between calorific requirements and production of a given farming household. The calorific requirement per person and per year was estimated at 3450 kcal $person^{-1}$ $year^{-1}$ (which is the daily average energy requirement of men aged between 30 and 60 years, weighing 60 kg and having a vigorously active lifestyle, after FAO (2001)). Annual on-farm calorific production was estimated solely on the basis of annual cereal production, considering 3690 kcal kg^{-1} cereal grain (http://www.fao.org/docrep/003, visited 20 March 2011). Although farming households consumed other minor crop products (e.g. cowpea, groundnut) and animal products (milk and occasionally meat), these are negligible on-farm sources of energy compared with cereals, which are consumed in the form of a thick porridge (‘*sadza*’).

3.2.3.7. Forage deficit

The indicator ‘forage deficit’ is defined as the difference between the amount of dry matter required by the livestock on a given farm and the amount of dry matter available for grazing on this farm. For each farm, cattle, goat and sheep numbers were converted into tropical livestock units (TLU), which is defined as a hypothetical animal of 250 kg live weight, and which is equivalent to 1.5 cattle, 12 goats or 10 sheep (Le Hourou and Hoste, 1977). The annual forage requirement per TLU was estimated at 2050 kg DM TLU^{-1} year^{-1} (Breman and de Ridder, 1991). Biomass production in fallows was estimated at 3000 kg DM ha^{-1} year^{-1} (Baudron et al., unpublished). The amount of crop residues available for grazing was calculated from data of crop biomass production and residue use (i.e. fraction grazed by livestock) that were collected during the detailed characterisation.

3.2.4. Environmental footprint at different scales

The environmental footprint for a farm was estimated using the ten indicators described above. The same indicators – except ‘plant diversity loss’, ‘calorific deficit’ and ‘forage deficit’ - were used to estimate the environmental footprint for cotton and cereal production on each farm, by respectively only considering the cotton and cereal fields. By dividing the indicator values by the corresponding economic yield (kg ha^{-1}) or quantity of labour invested per area (man-day ha^{-1}), the environmental footprint of cotton and cereal per unit of output and per unit of labour were obtained.

Finally, average indicator values per farm type were aggregated for each geographic zone, from the distribution of farm types in each zone (obtained from the general characterisation data) and the number of farm units in each zone in 2007 - i.e. at the time of the general characterisation. The latter was estimated from census data of 1992 and 2002, assuming that population increased with the same rates between 2002 and 2007, and assuming that the number of farms of West Angwa represented 1/3 of the total number of the farms of Ward 2.

3.2.5. Scenario analysis

The environmental footprints per geographic zone in 2007 are referred to as ‘current’ footprints. These ‘current’ footprints were compared with four scenarios. ‘Scenario 1’ assumed a general loss in wealth that would shift all farmers down one farm type in the typology (Type 1-4). ‘Scenario 2’ assumed a gain in wealth that would shift all farmers up one type in the typology. In these two scenarios, environmental footprints were recalculated using alternative distributions of farm types, but assuming that the footprint per farm type remained unchanged. Scenario 1 is informed by the farm development that occurred in the late 1980s and in the 1990s, whilst Scenario 2 is informed by the increased vulnerability observed since 2000. ‘Scenario 3’ assumed that all farms would shift to growing cereals only, while under ‘Scenario 4’ it was assumed that all farms would grow only cotton. In these two scenarios, the distribution of farm types in each geographic zone was assumed to be unchanged, whilst indicators per farm type were recalculated as follows. First, the total labour used in farming (in man-day), the labour requirements of cereal production and cotton production (in man-day ha^{-1}) were calculated for each farm, from data obtained during the detailed characterisation. Second, for each farm, the surface area in cereal and in cotton was recalculated under ‘Scenario 3’ and ‘Scenario 4’, assuming that all available labour was used to produce only cereal or cotton. Finally, the value of each indicator of the environmental footprint was recalculated for each farm, assuming that cropped area:fallow area ratios, fertilisation and pesticide application rates, and residues utilisation for each crop remained unchanged. Scenario 3 was informed by the increased tendency of farm units to specialise in cotton production since the late 1980s, while Scenario 4 simulated the long-term decline in cotton profitability and the recent liberalisation of the national cereal market, creating a new opportunity for cereal as a cash crop. The study area is still sparsely populated and can be considered an agricultural frontier, as farming is limited by labour (manpower and animal draught power) more than by land (Chapter 5). Therefore, a change in the profitability of cotton vs. cereal may trigger a change in labour allocation, which may in turn trigger a change in cropping patterns.

3.3. RESULTS

3.3.1. Description of the farm typology

There were significant ($P < 0.001$) differences in the mean total area cultivated and the area under cotton ($P < 0.001$), both increasing significantly from Type 1 to Type 4 farms (Table 2). The four farm types also differed significantly ($P < 0.01$) in the size of the household, Type 4 farmers having a family with significantly ($P < 0.01$) more members than other types, and in the number of implements owned, which increased significantly ($P < 0.001$) from Type 1 and 2 (hand-hoe farmers) to Type 3, and to Type 4. The land:labour ratio was significantly ($P < 0.001$) different between the four farm types, increasing from Type 1 (0.40 ha person^{-1}) to Type 2 (0.50 ha person^{-1}), Type 3 (0.64 ha person^{-1}) and Type 4 (0.81 ha person^{-1}). There were also significant differences in livestock ownership: the number of sheep and goats ($P < 0.001$) and cattle ($P < 0.001$) increased significantly from Type 1 to 4 (Table 2). Most farmers of Type 1 (72%) sold their labour out, whilst only few of them hired external labour. The opposite was observed for Type 4 farmers, most of them (73%) hired labour. Type 2 and 3 were in an intermediate situation. Although the average farm in the study area experienced a calorific deficit of 3.0 10^6 (± 4.3 10^6) kcal year^{-1}, which is equivalent to 0.81 (± 1.66) t cereal year^{-1}, Type 3 and 4 farmers (ploughing farmers) were food self-sufficient during a significantly ($P < 0.001$). longer period of the year than Type 1 and 2 farmers (hand-hoe farmers).

The distribution of the different farm types varied along the intensification gradient (Table 2). Types 3 and 4 were confined to East Angwa and Mushumbi Pools, and their proportion was greater in Mushumbi Pools than in East Angwa. West Angwa hosted only Type 1 and 2, farmers and the proportion of Type 1 and 2 farmers decreased from West to East in the three geographic zones along the intensification gradient (Figure 1). The presence of cattle is a fundamental factor determining farming type in the study area. No cattle was found in the tsetse infested area of West Angwa (cf. Figure 2b), limiting farm diversity to Types 1 and 2 (cf. Table 2). Along the intensification gradient, the maximum area cultivated per farm – in particular cotton – is constrained by the availability of animal draught power, whilst the number of livestock per farm was to a large extent controlled by animal diseases – in particular trypanosomiasis and tick-borne diseases (Figure 2a and 2b).

Table 2 – Main characteristics (proportions and means ± standard errors) of the four farm types identified in the study area, from data collected through general characterization during the 2006-07 season (*n* = 176).

Farm characteristics	Farm types			
	Type 1	Type 2	Type 3	Type 4
Composition of the smallholder community				
In West Angwa	62 %	38 %	0 %	0 %
In East Angwa	33 %	14 %	20 %	33 %
In Mushumbi Pools	17 %	12 %	28%	44%
Proportion of farms				
Selling labour out	72 %	58 %	49 %	22 %
Hiring labour in	12 %	25 %	56 %	73 %
Nr. of household members*	5.1 ± 2.2	5.4 ± 2.7	6.3 ± 3.2	7.7 ± 4.1
Area under cotton (ha)	0.0	1.1 ± 0.7	2.0 ± 1.3	3.7 ± 3.1
Area under maize (ha)	0.6 ± 0.2	0.6 ± 0.6	0.6 ± 0.6	0.9 ± 0.8
Area under sorghum (ha)	0.7 ± 0.3	0.5 ± 0.4	0.5 ± 0.5	0.7 ± 0.8
Number of adult cattle (heads)	0.0	0.0	0.9 ± 1.1	8.1 ± 7.2
Number of sheep and goats	0.7 ± 1.1	3.0 ± 4.6	3.4 ± 3.3	9.1 ± 7.3

*Living and eating within the farm household

Beyond the differences in resource availability between farm types, the magnitude of resource flows and use efficiencies were also different. From the data gathered during the detailed characterisation (n = 37), the mean cereal and cotton yields differed between Type 1 and Type 4 (Table 3). No farm type applied P and K fertiliser on cereals, and only Type 4 applied very small amounts of fertiliser N on the cereal crop (mean of 0.7 kg ha^{-1}). All farm types applied limited amounts of fertiliser N, P and K on their cotton crops. The main difference in nutrient resource management between the four farm types was through residue management (Figure 3). Between 57 and 76% of cotton residues were burnt, as cotton residues have to be destroyed for phytosanitary reasons in Zimbabwe. In West Angwa, the fraction of cotton residues not burnt was almost entirely grazed by wildlife, whilst in Mushumbi Pool they were almost entirely grazed by livestock (Figure 3). Cereal residue management was not only influenced by the presence of wildlife and livestock, but also by the mode of land preparation: between 13 and 18% of cereal residues were incorporated into the soil through ox- or donkey-ploughing in East Angwa and Mushumbi Pools;

whilst hand-hoe farmers burnt a greater fraction of cereal residues – around a quarter – than ploughing farmers did. Moreover, grazing of cereal residues by wildlife was only important in West Angwa – about a third – and to a lesser extent in the fields of hand-hoe farmers of East Angwa. Grazing of cereal residues by livestock was negligible in West Angwa, small in the fields of hand-hoe farmers in East Angwa and more important in the fields of ox- and donkey-ploughing farmers in East Angwa and in Mushumbi Pools – between 40 and 50 %. Between 19 and 24% of cereal residues were decomposed on the soil surface during the dry season.

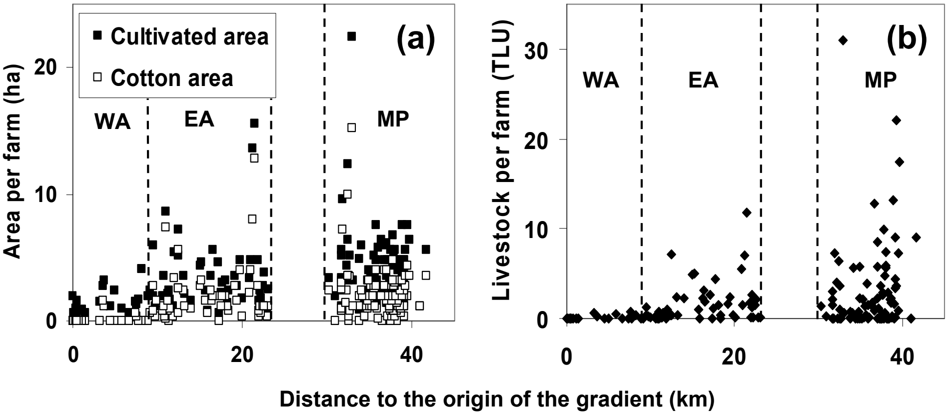

Figure 2. (a) Total cultivated area and area under cotton, and; (b) number of livestock, along the intensification gradient (WA: West Angwa; EA: East Angwa; MP: Mushumbi Pools).

Table 3. Yields and N, P and K fertiliser input rates (means ± standard errors) on cereal and cotton fields for the four farm types (Type 1-4) recorded from the detailed characterization (*n* = 37).

Farm	Yield (kg.ha^{-1})		N input (kg.ha^{-1})		P input (kg.ha^{-1})		K input (kg.ha^{-1})	
	Cereal	Cotton	Cereal	Cotton	Cereal	Cotton	Cereal	Cotton
Type 1	945 (± 471)	-	0	-	0	-	0	-
Type 2	1258 (± 674)	631 (± 480)	0	4.7 (± 12.3)	0	0.7 (± 1.8)	0	0.7 (± 1.7)
Type 3	1364 (± 635)	835 (± 499)	0	1.4 (± 3.8)	0	0	0	0
Type 4	1494 (± 998)	1033 (± 299)	0.7 (± 2.6)	4.2 (± 8.4)	0	1.0 (± 1.6)	0	1.0 (± 1.6)

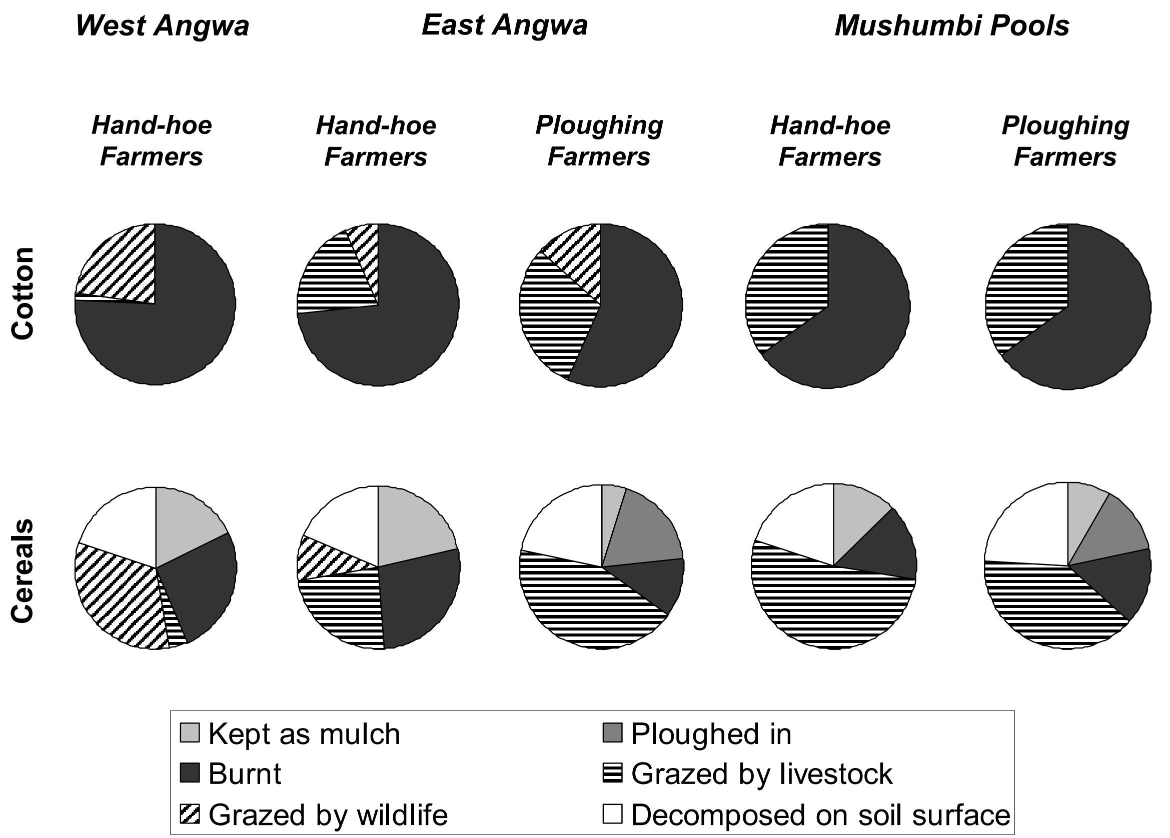

Figure 3. Fate of cotton and cereal crop residues in the three geographic zones by farmers ploughing or practicing hand-hoeing, estimated from a sample of 37 farms (Note: ploughing is not practised in West Angwa).

3.3.2. Impact of farming on the environment

3.3.2.1 Cropped and fallow area

The proportion of fallow land was found to be identical in the three geographic zones (Figure 4). However, the proportion of cropland was three times greater in Mushumbi Pools than in East Angwa and West Angwa. R values of 0.37, 0.40 and 0.67 were found for West Angwa, East Angwa and Mushumbi Pools, respectively. While R values comprised between 0.33 and 0.66 indicate fallow cultivation, i.e. fertility renewed through fallowing, values above 0.66 indicate permanent cultivation, implying that soil fertility has to be renewed by nutrient inputs (Ruthenberg, 1980).

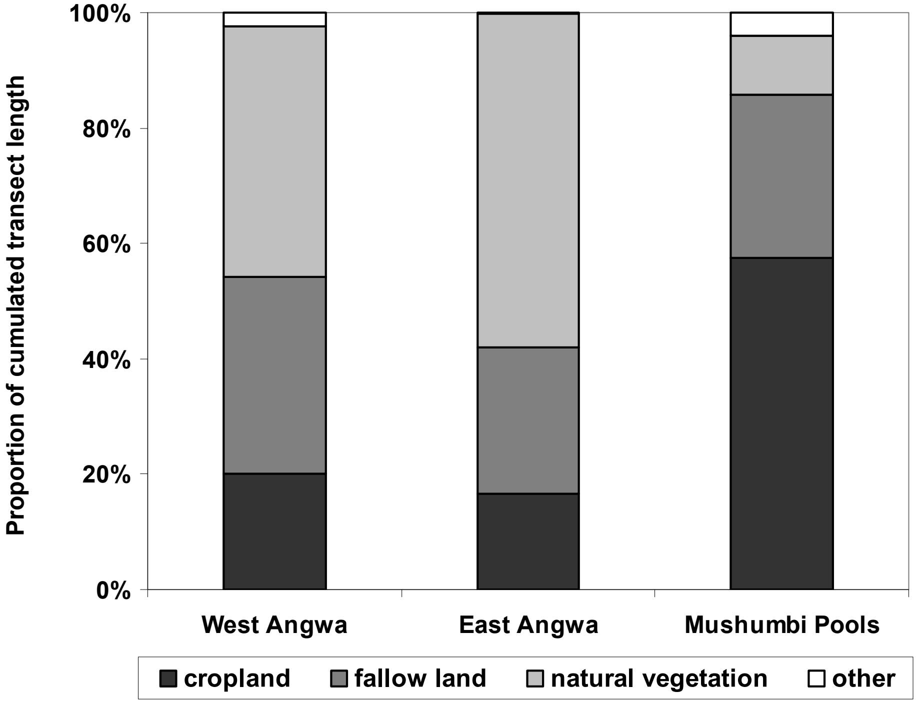

Figure 4. Relative distribution of land cover types inventoried along three transects (of 44, 35 and 33 km length) across the three geographic zones of the study area (figures are mean percentages for the three transects; see text for details).

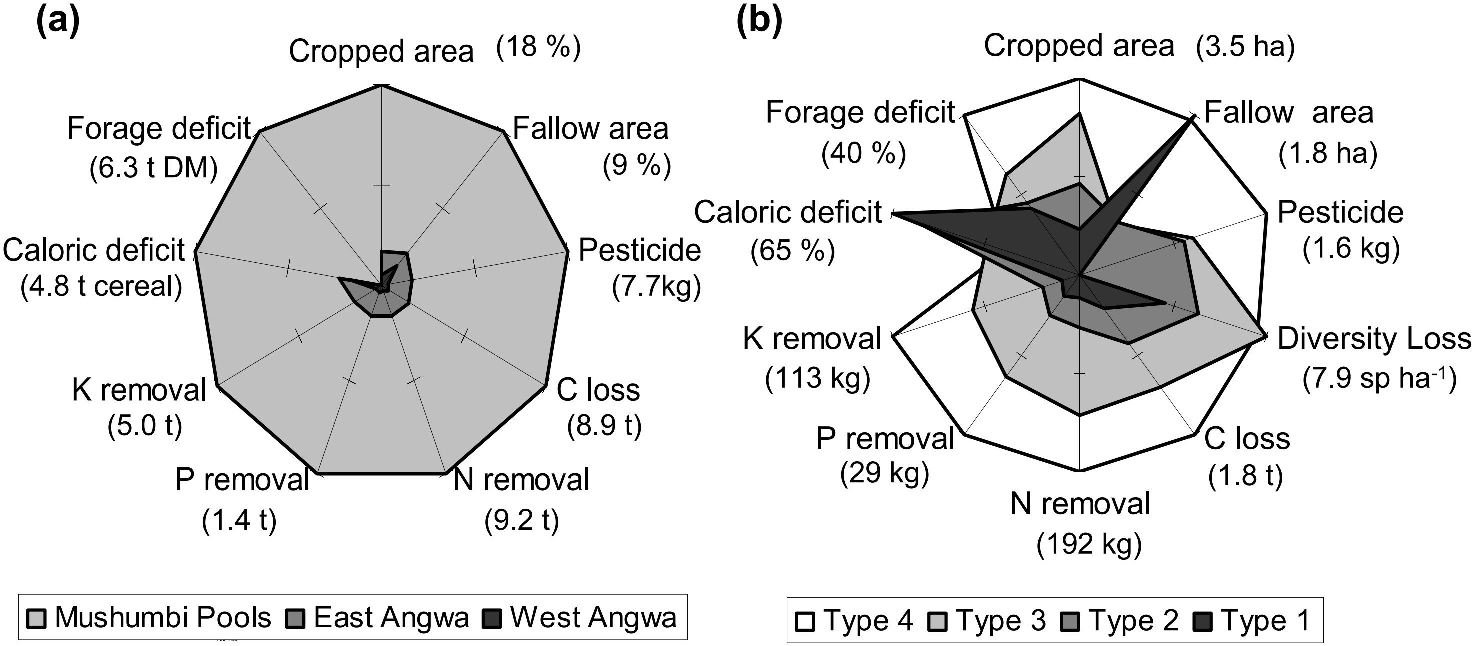

Figure 5 – (a) Representation of the environmental footprint per unit area (km^2) for the three geographic zones along the agricultural intensification gradient. See text for details on the construction of the various indicators. Maximum values of indicators before standardization are given in parentheses; and (b) representation of the environmental footprint per farm for the four farm types found in the study area (Types 1-4), using standardised average values of the environmental indicators.

3.3.2.2 Pesticide use

In the study area, 0.3, 1.2 and 7.7 kg active pesticide ingredient km^{-2} year^{-1} were estimated to be released in West Angwa, East Angwa and Mushumbi Pools, respectively (Figure 5a). Cotton was the only crop treated with pesticides. The average intensity of pesticide use per unit of cropped area was 428, 415 and 377 g active ingredient ha^{-1} year^{-1} in West Angwa, East Angwa and Mushumbi Pools, respectively. As a reference, the average national intensity of pesticide use per unit of arable land in 2001 was 135, 280, 365, 455, 1420 and 5900 g active matter ha^{-1} year^{-1} in France, the United Kingdom, Brazil, the United States of America, the Netherlands and Japan, respectively (FAOSTAT, http://faostat.fao.org/site/423/default.aspx#ancor, visited 20 March 2011).

3.3.2.3 Plant species diversity

While the geographic zone had no influence on the plant diversity per unit of cropped area, the crop cultivated in the field ($P < 0.05$) and the mode of land preparation ($P < 0.1$) had a statistically significant influence. Plant diversity was largest in maize fields planted with hand-hoes (mean of 18.7 species) and lowest in ploughed sorghum fields (mean of 8.6 plant species). Ploughing decreased plant diversity significantly in maize and sorghum fields, but not in cotton fields (Table 4).

Table 4 – Mean in-field plant diversity (number of plant species per hectare) as a function of mode of land preparation, measured on fields cultivated with cotton, maize or sorghum. Standard errors are given in parentheses.

Present crop	Unploughed	Ploughed
Cotton	12.3 (±4.0)	12.1 (±1.7)
Maize	18.7* (±2.6)	12.9* (±3.4)
Sorghum	14.4** (±2.0)	8.6** (±0.8)

* indicates differences in means statistically significant at $P < 0.1$
** indicates differences in means statistically significant at $P < 0.05$

3.3.2.4 Soil carbon stocks

Total soil carbon to a depth of 40 cm decreased exponentially with the period of cultivation (time since land clearance) along a chronosequence of 22 years (Figure 6). Such changes were described by the function $TSC\ (t\ ha^{-1}) = 34.4 + 15.9 \times$

0.7945^T (RMSE = 5.6 t ha^{-1}; R^2 = 38%; $P < 0.001$) – where *TSC* is the total soil carbon and *T* the period of cultivation in years. According to this model, around 15 t ha^{-1} of total soil carbon to a depth of 40 cm was lost before an apparent equilibrium was reached, after about 10 years of cultivation. Using the fitted function of exponential decrease of total soil carbon in fields (above) and assuming a linear increase of 0.6 t ha^{-1} $year^{-1}$ in fallow, an estimated 0.4, 1.5 and 8.9 t soil organic carbon km^{-2} $year^{-1}$ was lost in West Angwa, East Angwa and Mushumbi Pools, respectively (Figure 5a).

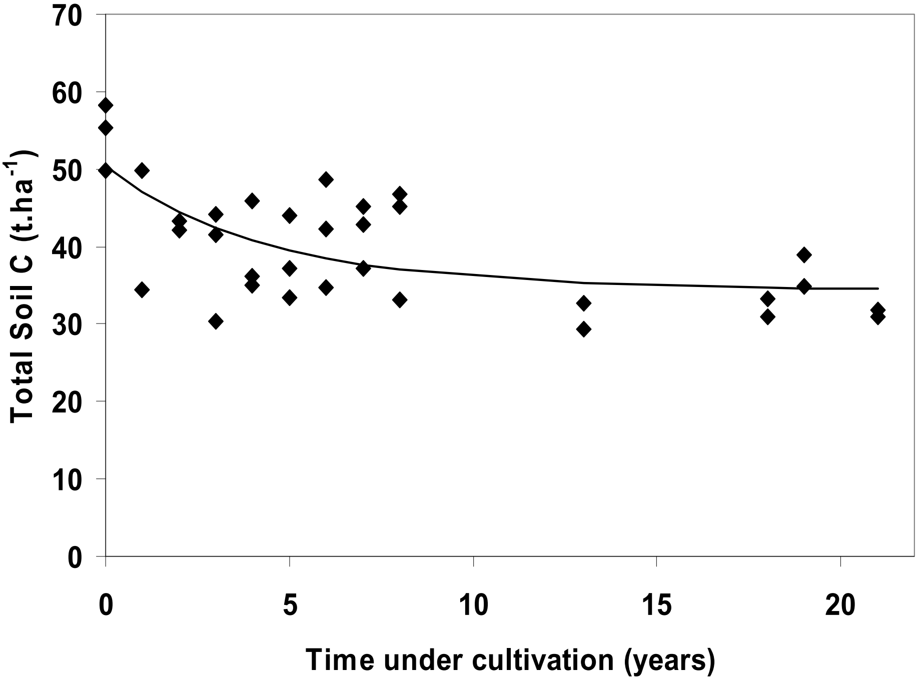

Figure 6 – Change in total carbon content in the surface 40 cm of the soil profile (*TSC*) against length of period under cultivation (*T*) on a typical sandy loam soil for the study area. The line represents the fitted exponential function: $TSC = 34.4 + 15.9 \times 0.795^T$ (root mean squared error = 5.6; R^2 = 0.38; $P < 0.001$).

3.3.2.5 Soil nutrient depletion

Due to low fertilisation rates, partial nutrient balances were negative in the study area (Table 5). Cotton, maize and sorghum have different total biomass and economic yields, and N, P and K concentrations in their harvested products and residues, all of which determine their respective partial nutrient balances. Although cotton received far more N fertiliser than maize or sorghum (cf. Table 3), it is the crop which removed the largest quantities of N, partly due to burning of its crop resides (cf. Figure 3). The three crops removed similar quantities of P and K nutrients. The estimated removal of N due to farming was 0.3, 1.5, and 9.2 t km^{-2} year^{-1} in West Angwa, East Angwa and Mushumbi Pools, respectively (Figure 5a). The estimated removal of K was about half these values: 0.1, 0.8, and 5.0 t km^{-2} year^{-1} in West Angwa, East Angwa and Mushumbi Pools, respectively. The estimated removal of P was very small compared to N and K: 0.0, 0.2, and 1.4 t km^{-2} year^{-1} in West Angwa, East Angwa and Mushumbi Pools, respectively.

3.3.2.6 Caloric deficit

Over the 37 farms included in the detailed characterisation, only 7 experienced a caloric deficit, up to 100% of their annual requirements. For the three geographic zones, the aggregated caloric deficit equivalent in cereal grain was found to be 0.8, 1.0, and 4.8 t km^{-2} year^{-1} in West Angwa, East Angwa and Mushumbi Pools, respectively (Figure 5a).

3.3.2.6 Forage deficit

Fourteen of the 37 farms experienced a forage deficit, up to a maximum of 15 t DM year^{-1}. For the three geographic zones, there was no aggregated forage deficit for East Angwa and West Angwa, and an estimated forage deficit of 6.3 t DM km^{-2} year^{-1} in Mushumbi Pools (Figure 5a).

Table 5 – Main characteristic (means ± standard errors) of the major crops cultivated in the study area, calculated from a sample of 37 farms.

Crop	Economic yield (kg ha^{-1})	Primary productivity* (kg ha^{-1})	Labour productivity (kg manday^{-1})	Partial nutrient balance (kg ha^{-1})		
				N	P	K
Cotton	0.79 (± 0.46)	3.15 (± 1.86)	3.79 (± 2.13)	- 47 (± 34)	- 6 (± 4)	- 20 (± 12)
Maize	1.28 (± 1.35)	2.55 (± 2.69)	5.21 (± 4.20)	- 29 (± 31)	- 8 (± 8)	- 16 (± 16)
Sorghum	1.32 (± 0.90)	3.11 (± 2.08)	7.89 (± 0.46)	- 38 (± 27)	- 7 (± 5)	- 24 (± 19)

*Above ground

3.3.3. Diverse farms, diverse environmental footprints

The environmental footprints of the different farm types are shown using radar diagrams that represent the 10 indicators. For graphical reasons, the indicators ‘calorific deficit’ and ‘forage deficit’ were set to be equal to zero when negative (i.e. when a surplus was realised). All indicators were expressing negative impact on the environment; thus, the greater the surface in these diagrams the greater the corresponding environmental footprint.

3.3.3.1. Environmental impact per farm type along the intensification gradient

Differences in cropping patterns and livestock endowment (Table 2, Table 4, Table 5), crop yields, fertilisation rates (Table 3), residue management (Figure 3), and the mode of land preparation (Table 4) are the causes of different environmental footprints for the different farm types. Values of all environmental indicators increased along the cereal-based/cotton-based continuum, from Type 1 to 4, except for the indicator ‘area under fallow’, while the value for the indicator ‘caloric deficit’ decreased in the same direction (Figure 5b). Both Type 1 and Type 4 farmers had a mean fallow area of 1.8 ha, whilst Type 2 and Type 3 farmers had less than half of this amount (mean of 0.6 ha). Type 1 and Type 2 farms showed a greater calorific deficit (65 and 57% respectively) than Type 3 and Type 4 farms (32 and 25%). There was a clear trade-off between food self-sufficiency and environmental footprints.

3.3.3.2. Environmental impact per cropping system along the intensification gradient

Figure 7a and 7d show that for Type 2 and Type 3 farmers, and except for the indicator of pesticide use, cereal production per farm had a smaller environmental footprint than cotton production per farm. For Type 4 farmers, and except for the indicator of pesticide use and N removal, the opposite was found, with cereal production per farm having a greater environmental footprint than cotton production per farm.

A unit output (kg) of cereal had a smaller environmental footprint than a unit output of cotton (Figure 7b and 7e). On average, a kilogram of cereal produced in the study area used 13 m^2 of land, led to a loss of 392 g C, removed 27 g N, 6 g P, 17 g K and received no pesticide. For the production of a kilogram of seed cotton 20 m^2 of land were used, 598 g C were lost , 53 g N, 7 g P and 25 g K were removed and 2.6 g of active pesticide ingredient were released. The magnitude of the environmental footprint of a kilogram of cereal grain differed amongst farm types; for example a kilogram of cereal grain produced by Type 1 and 2 farmers required 4 m^2 more cropped land than a kilogram of cereal produced by Type 3 and 4 farmers. However, in general the variation in environmental footprints of a kilogram of cereal grain produced by the different farm types was small compared with that of a kilogram of seed cotton (Figure 7b). The environmental footprint of a kilogram of seed cotton was markedly different for the different farm types (Figure 7e). For example, a kilogram of seed cotton produced by Type 2 farmers used more than twice the amount of pesticides, occupied more than twice the area of land and lost more than twice the amount of soil carbon, than a kilogram of seed cotton produced by Type 4 farmers. On the other hand, a kilogram of seed cotton produced by Type 4 farmers removed more N, P and K from the soil than a kilogram of seed cotton produced by Type 2 farmers: the net removal was 30, 54 and 25% larger for Type 4 farmers than for Type 2 farmers for N, P and K, respectively. There was thus an apparent trade-off in the production of a kilogram of seed cotton between, on one hand, the quantity of pesticide used, the surface area required and the quantity of carbon lost, and on the other hand the quantity of N, P and K removed. From Type 2 to 4, increased pesticide use efficiency (i.e. less pesticide per unit output) was found, as well as increased land productivity (i.e. less surface area required per unit output – which can also be deduced from yield data in Table 3).

Except for pesticide use, a labour unit invested in cereal production had a larger environmental footprint than in cotton production (Figure 7c and 7f). On average, a man-day invested in cereal production consumed 68 m^2 of land, 2.3 kg C, 198 g N, 41 g P, 124 g K and no pesticide, whilst on average, a man-day invested in cotton production consumed 54 m^2 of land, 1.9 kg C, 265 g N, 31 g P, 109 g K and required 6.7 g of active pesticide ingredient. The difference between farm types was small for the environmental footprint of a labour unit invested in cotton production, but large for cereal production. The environmental footprint of a unit of labour invested in cereal was especially large for Type 4 farmers and, to a lesser extent, for Type 3 farmers.

3.3.4. Exploring scenarios: change in wealth and change in cropping patterns

A comparison of the outcome of Scenario 1 (in which all farms shifted down one farm type in the typology) with the current situation shows that a general loss in wealth has a small impact on the environmental footprint of farming in the three geographic zones, particularly for West Angwa (Figure 8a). On the contrary, Scenario 2 shows that a general gain in wealth greatly increases the environmental footprint of farming in the three geographic zones (the value of most indicators would be approximately doubled in each geographic zone; Figure 8a).

Scenario 3 and 4 show that a theoretical shift in cropping patterns towards specialisation in cereal (Scenario 3) or cotton production (Scenario 4) has little impact on the environmental footprint of West Angwa, except for pesticide use (Figure 8b). In East Angwa and Mushumbi Pools, a specialisation in cereal production (Scenario 3) does not affect P removal, but decreases N removal and K removal, and increases cropped area and fallow area. In particular, it increases the cropped area by more than 20% and the fallow area by more than 35% (Figure 8b). In East Angwa and Mushumbi Pools, a specialisation in cotton production (Scenario 4) drastically reduces the environmental footprint of farming, except for the indicator of pesticide use (which increases). In particular, it reduces the cropped area by more than 30% and the fallow area by more than 20%.

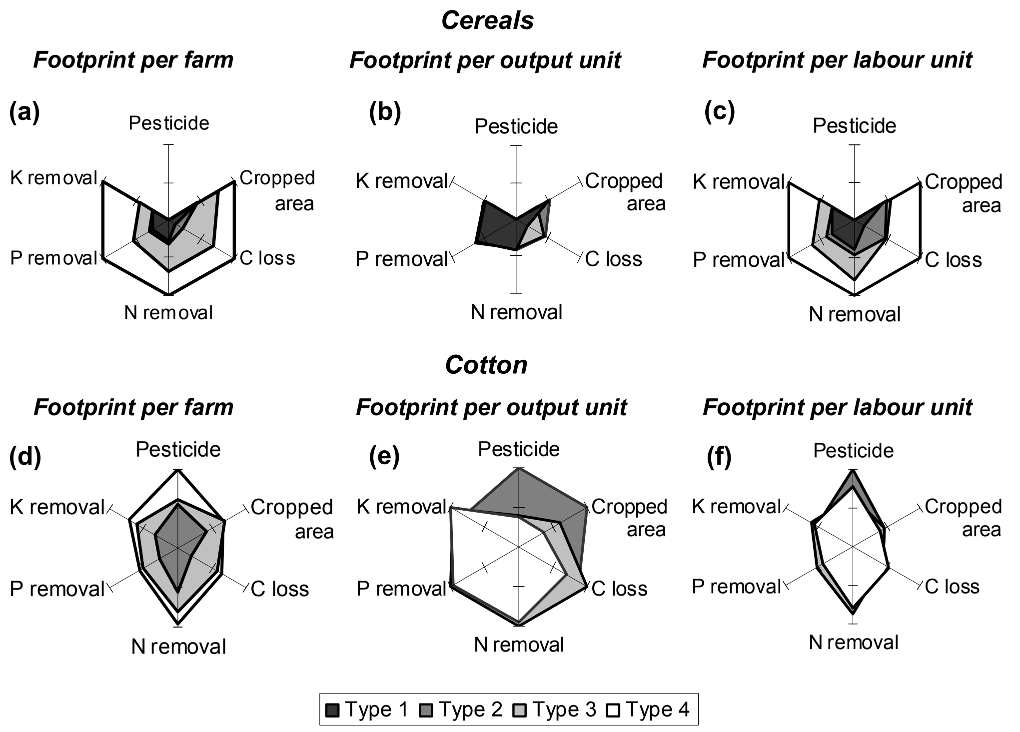

Figure 7. Representation of the environmental footprint of cereal production (a, b, c) and cotton production (d, e, f) expressed on a per farm basis (a, c), per unit of output (b, c) or per unit of labour invested (e,f), for the four farm types identified in the study area (Types 1-4), using standardised average values of environmental indicators. See text for details on the construction of the various indicators. Radar diagrams in each row (farm, output, labour) use the same scale for cereals and cotton, to allow for comparison.

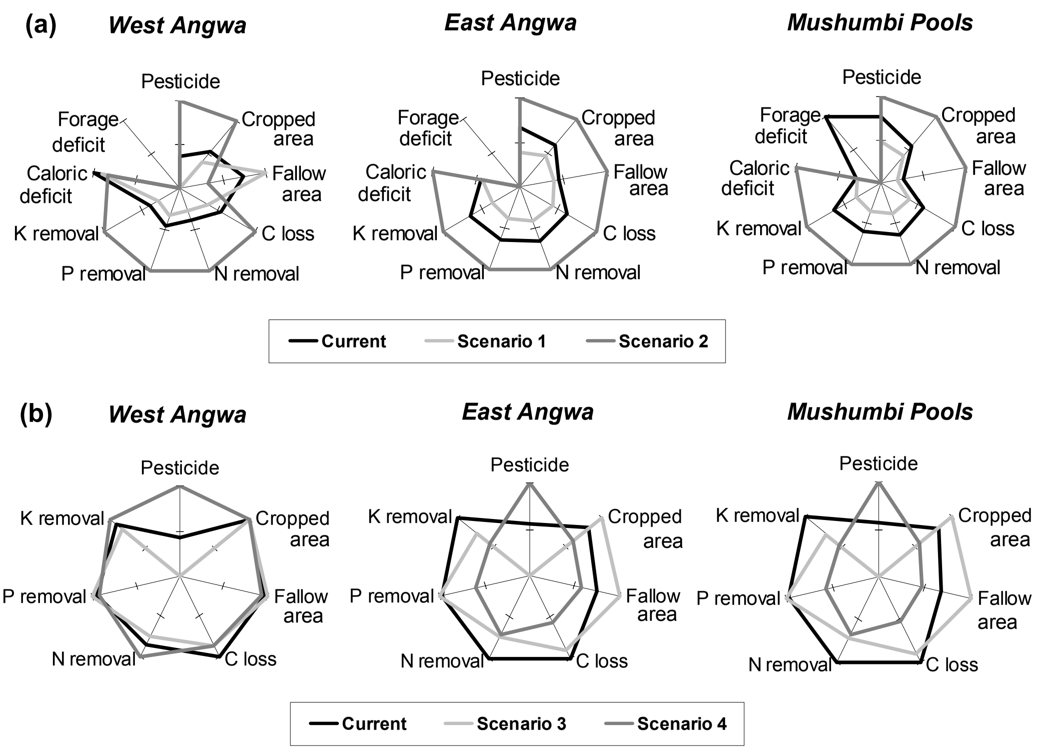

Figure 8. Representation of the total footprint per unit area (km^2) for the three geographic zones (a) according to three scenarios: current situation (Current), general decrease in wealth (Scenario 1) and general increase in wealth (Scenario 2); and (b) according to three scenarios: current situation (Current), full specialization in cereal production (Scenario 3), and full specialization in cotton production (Scenario 4). Each indicator was standardized. The diagrams use different scales.

3.4. DISCUSSION

3.4.1. Competition of farming with environmental objectives

Our study highlights the existing tensions between agriculture and environmental conservation in the Mid-Zambezi Valley ecosystem. Farming covers a large proportion of the land of the study area, particularly in Mushumbi Pools (Figure 4, Figure 5a). Cultivation reduces total soil organic carbon in the surface 40 cm of the soil profile (Figure 6). Around 15 t C ha^{-1} was estimated to be lost after 10 years of cultivation. This can probably be explained by the small quantities of organic materials that are returned to the soil (when compared with a natural ecosystem), destruction of protective aggregates by tillage and accelerated erosion (cultivated fields having a sparse ground cover compared to natural ecosystems). Farming also reduces *in situ* plant diversity. Ploughed fields had less plant diversity than fields planted after hand-hoe minimum-tillage. Ploughing is indeed known as an effective way to control 'weeds' (Vogel, 1996; Lal, 2009). Maize fields were found to have a greater plant diversity than cotton and sorghum fields. This is likely because of cotton being weeded more frequently than maize and sorghum, as it has a longer phenological cycle, whilst sorghum is known to have allelopathic properties (Cheema and Khaliq, 2000).

Although the environmental indicators of our study provide a useful illustration of the impact of farming on the Mid-Zambezi Valley ecosystem, they are based on a number of assumptions, except for cropped area and fallow area that were accurately measured. For instance, only a fraction of the quantity of the active pesticide ingredients sprayed represents an environmental threat: this fraction is affected by a complex interaction of factors such as the properties of the active ingredient considered, the spraying method, atmospheric conditions during and after spraying and soil conditions (Pimentel, 1995; Wijnands, 1997; Beulke et al., 2000). Our estimates of C loss do not take into account the facts that : (1) for a given farm, the proportion of the land area occupied by crops may change from one year to another, depending on rainfall, input availability (e.g. planting seeds) and labour availability. Whilst some farmers are in a phase of expansion (young farmers), others are in a phase of decline (elderly farmers); and (2) not all sections of the farm have the same fallow regime; particular sections– e.g. riverbanks or rich alluvial soils are farmed more intensively. Moreover, actual values of N removal, P removal and K removal may be larger, as we ignored losses through erosion, leaching and gaseous forms. On the other hand, we also ignored inputs through atmospheric deposition and nitrogen fixation (by e.g. legume weeds).Values for food self-sufficiency also ignored on-farm sources of energy other than cereals (e.g. pulses, milk) whilst cereal harvested on the farm where considered to be used for household consumption only, ignoring sales, bartering, support to other dependant households and the use of cereals to hire food-unsecured labour. Finally, estimates of forage deficits were based on the assumption that farm residues are only accessible by livestock from the same farm, ignoring communal grazing.

3.4.2. Environmental footprints along the cereal-based/cotton-based continuum of farms

Figure 9 represents schematically the four farm types – Type 1 to Type 4 - identified along the cereal-based/cotton-based continuum of farms. During the late 1980s and the 1990s, farms who benefited from the ‘cotton boom’ ‘moved up’ along this continuum: from the 37 farmers interviewed, 17 were migrants, from which 15 had settled in the study area with no cattle or donkey (i.e. as Type 1 or 2 farmer) but since their settlement they had purchased some animals with their cotton income (i.e. they had became Type 3 or 4 farmers). From Type 1 to Type 4, the area under cereals did not change but the cotton area expanded significantly (Table 2). This was the result of the increase in the higher land:labour ratio, due to more animal draught power, less family labour being sold, and more external labour being hired in (Table 2). Type 4 farmers were also endowed with significantly more family labour (Table 2). From Type 1 to Type 4, crop yields also increased for both cereal and cotton (Table 3). Therefore, moving up the continuum in Figure 3 can be seen as both ‘intensification’, defined as the adoption of yield increasing technologies (which are land-saving technologies), and ‘extensification’ as the adoption of labour-saving technologies (Erenstein, 2006).

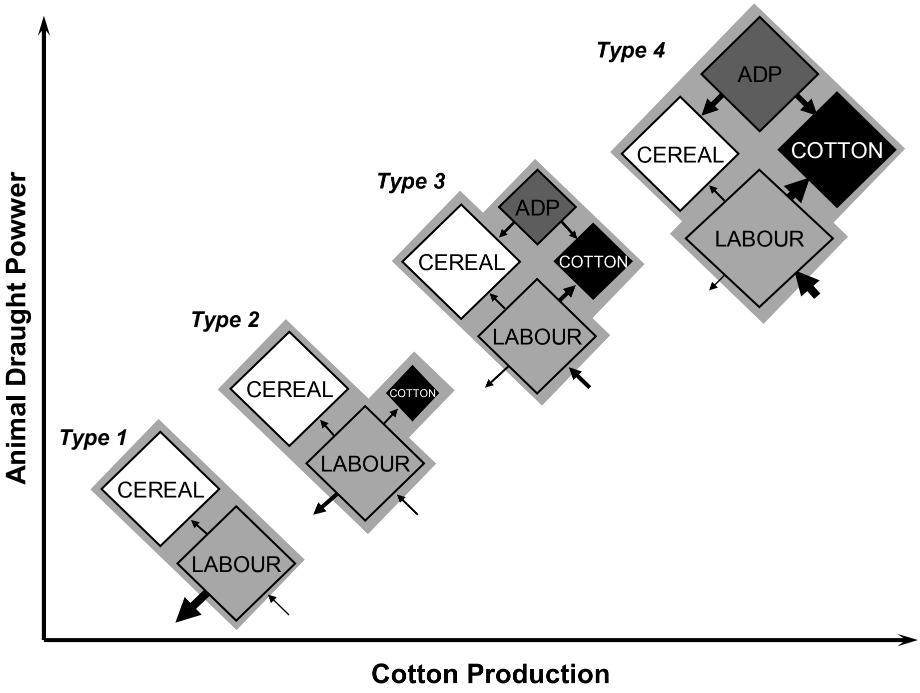

Figure 9. Schematic representation of the four farm types identified in our study, along the cereal-based/cotton-based continuum (arrows represent labour: manpower and animal draught power). Moving up this continuum from Type 1 to Type 4, animal draught power increases, cotton area increases, labour sold out decreases, and hired labour increases. Cereal area does not change (although cereal yield increases, see text). Type 4 farms are also endowed with significantly more family labour than other types.

Resource endowment (equipment, cattle, small ruminants) and food security increased from Type 1 to Type 4. Thus, enabling farms to move up the cereal-based/cotton-based continuum appears to be a pathway for improving rural livelihoods in the study area. However, this ‘development objective’ appears to conflict strongly with the objective of environmental conservation, as the environmental footprint per farm increased significantly for Type 1 to Type 4 (except for caloric deficit and fallow area; Figure 5b). Thus, gain in wealth would increase the environmental footprint in all three geographic zones (Scenario 2, Figure 8a). The value of most indicators would roughly double in each zone, as better endowed farmers cultivate larger areas, with more area under cotton that requires more pesticides. Better endowed farmers also have a larger forage deficit.

Can these strong tradeoffs between improving rural livelihoods and minimising environmental degradation be turned into a win-win situation? As explored below, maintaining the profitability of cotton production may offer a possibility.

3.4.3. Cotton: friend or foe of conservation?

In the entire district of Mbire, about 10,000 t of seed cotton are purchased by the cotton industry every year, implying that the aggregated annual environmental impact of the industry for the district represents the use of about 200 km^2 of land, the loss of about 6000 t C, the removal of about 530 t N, 70 t P, and 250 t K and the use of 26 t of active pesticide ingredient. From the results of this study, a kilogram of seed cotton requires on average about twice as much N, about 50% more land, C and K, and about 20% more P than a kilogram of cereal grain. Therefore, can the replacement of cotton by cereal as a cash crop be regarded as desirable? This question is explored through Scenarios 3 and 4. As cereal and cotton production have different labour productivities (Table 5) and different environmental footprints (Figure 7), a change in cropping pattern would have important consequences on the overall environmental footprints of the different farm types.

Specialisation of farmers into cereal production (Scenario 3) would cut out pesticide use completely, but would increase the cropped area by more than 20% and the fallow area by more than 35% in East Angwa and Mushumbi Pools. Thus, the replacement of cotton as the main cash crop by cereals appears to be a direct threat for wildlife conservation areas. By contrast, specialisation of farmers into cotton production would not change the environmental footprint of farming in West Angwa substantially (except for pesticide use), but would drastically reduce the environmental footprint of farming in East Angwa and Mushumbi Pools (except for pesticide use). In particular, it would reduce the cropped area by more than 30% and the fallow area by more than 20% in Mushumbi Pools and East Angwa. Therefore, it appears that maintaining or increasing the relative profitability of cotton compared with cereals is an opportunity for conservation rather than a threat, provided the risk of pollution from pesticides is controlled. In particular, maintaining or increasing cotton production appears to ‘spare land’ for nature compared with specialisation in cereal production (Green et al., 2005). Of course, a major assumption under

Scenario 3 and Scenario 4 was that the shift in crop would not be accompanied by an increased investment in labour or in labour-saving technologies, resulting in an expansion of the cropped area. Moreover, full specialisation to produce only a single crop such as cotton is unlikely, as farmers rarely abandon cereal production for food security reasons.

Improved access to mineral fertilisers (on credit) from cotton companies may reduce the environmental footprint of cotton farming, and of the farm as a whole, by compensating for nutrient removal and soil depletion. Ruthenberg coefficients indicate that fallowing is insufficient to rebuild soil fertility in Mushumbi Pools. Not burning cereal residues would only improve the current partial nutrient balances by less than 5 % (data not shown). Similarly, using manure available on-farm would only represent a substantial nutrient input for Type 4 farmers (improvement of 23% of the current partial nutrient balance) but is insignificant for other farm types (improvement of less than 4% of the current partial nutrient balance; data not shown). Therefore, increased use of mineral fertiliser represents the only option to maintain the productivity of croplands in Mushumbi Pools. The closest input agricultural markets are located more than 100 km from the study area, implying that virtually the only viable way for local farmers to access mineral fertilisers is through input credit schemes from cotton companies. At the time of this study, however, farmers were using little mineral fertiliser in their cotton fields, as cotton companies were providing limited quantities of mineral fertilisers through credit schemes (Table 3). The situation has since then improved, with the passing in August 2009 of a new legislation under which cotton companies have to provide adequate input packages to the farmers they contract.

3.4.4. Towards ecological intensification of cotton production

Cotton farming requires substantial quantities of pesticides compared with cereal farming, and these may become a threat to off-site biodiversity. Type 4 and Type 3 farmers demonstrated higher pesticide use efficiencies than Type 2 farmers (Figure 7e). This may simply be a result of the fact that pesticides are packed in units for a hectare, whilst many Type 2 farmers cultivate cotton fields much smaller than one hectare (Table 2). The differences in the pesticide use efficiencies between Type 3 and 4 farmers and Type 2 farmers may also be caused by better management of inputs by farmers specialised in cotton farming. Pesticide use efficiency could be further increased by use of ultra-low volume (ULV) spraying techniques (Cauquil, 1987), or through spraying only when a certain threshold of pest attack is reached (Silvie et al. 2001), which would have positive consequences for both the environment and profitability.

Specialisation in cotton farming may also lead to increased efficiency of use of other production inputs. Fertiliser use efficiency can be enhanced by increasing the fraction of nutrient captured by the crop and/or reducing the fraction lost by leaching, through use of improved germplasm, precision application in time and space, mulching, and recycling of nutrients by cover crops or agroforestry species. Deployment of these technologies could ultimately lead to what is sometimes referred to as ‘ecological intensification’ or ‘eco-efficient agriculture’ – agriculture that achieves high crop production, in terms of quantity and quality, and uses all resources as efficiently as possible, minimising environmental damage (Cassman, 1999; Keating et al., 2010).

3.5. CONCLUSIONS

Cotton has been the major driver of land use change in the Mid-Zambezi Valley (Chapter 2). For a particular farm, moving along the cereal-based/cotton-based continuum increases wealth and food security, but also increases the environmental footprint of the farm. Thus, cotton may be seen as the single biggest threat to the Mid-Zambezi Valley ecosystem. On the other hand, cotton farming is more labour intensive than cereal farming. Therefore, in areas were production is limited by labour more than by land, a farming unit specialised in cotton production occupies less space than a farming unit specialised in cereal production. Under circumstances where the profitability of cotton farming declines relatively to the profitability of cereal farming, encouraging cotton farming may provide an opportunity for conservation rather than a threat. However, for ‘land sparing’ to be effective, control of immigration is the first requirement (Scholte, 2003), and further clearance of ‘spared land’ will have to be prevented. Indeed, the greater environmental footprint of farming along the agricultural intensification gradient of our study area is not only due to a larger proportion of farmers specialised in cotton production, but also to the greater human population. For intensification through cotton production to be a net benefit for the Mid-Zambezi Valley ecosystem, inputs must be used as efficiently as possible. The cotton sector has the potential to reduce the environmental footprint of farming by improving the effectiveness of pesticides and fertilisers which could be achieved with technologies aiming at ‘ecological intensification’.

Acknowledgements

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Chapter 4

Comparative performance of conservation agriculture and current smallholder farming in semi-arid Zimbabwe

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Chapter 4

ABSTRACT

Conservation Agriculture (CA) is currently promoted in sub-humid and semi-arid areas of sub-Saharan Africa as a means to increase crop water use efficiency and stabilize yields. In this study, conducted during three consecutive seasons in a semi-arid area of Zimbabwe, the short-term performance of CA and current farming practice (CP) were compared in two multi-locational experiments: (1) unfertilised on-farm trials with a cotton-sorghum rotation, and (2) farmers' cotton fields receiving fertiliser provided on credit by cotton companies. In both cases, residues for mulch were produced *in situ*. In addition to biophysical measurements, farmers' perceptions of the technology were appraised. CA did not affect cotton productivity during the first two years of experiment, which received average or above average rainfall. During the drier 2009-10 season CA had a negative effect on crop yield both in the on-farm trials (average yield of 730 and 820 kg ha^{-1} under CA and CP, respectively) and in farmers' cotton fields (average yield of 1220 and 1440 kg ha^{-1} under CA and CP, respectively). There was no difference in water runoff between CA and CP on a relatively fine-textured soil, but significantly more runoff with CA on a coarser-textured soil (14 mm during the wetter 2008-09 season), due to soil surface crusting. Most soils in the study area fall into this latter category. For these reasons, farmers perceived ploughing as necessary during drier years to maximize water infiltration, but perceived CA as beneficial during wetter years as a means to 'shed water' and avoid water-logging. This challenges the common description of CA as a water-harvesting technology. Soil crusting may be avoided by the production of greater quantities of mulch than achieved in this study (average of 770 kg ha^{-1} in on-farm trials). The retention of sorghum residues and the inclusion of N_2-fixing legumes resulted in less N being exported by cropping from the CA fields compared with the CP fields. This may result in long-term beneficial effects of CA on crop yields. The possibility to improve the sorghum-intercrop association to increase short-term benefits of CA is discussed.

Key words: conservation agriculture; smallholder; semi-arid area; cotton; soil crusting.

4.1. INTRODUCTION

Conservation agriculture (CA) is a set of cropping principles aiming at sustaining high crop yields with minimum negative consequences for the resource base - i.e. water, soil, and surrounding natural environment (Hobbs et al., 2008; Gowing and Palmer, 2008). It is defined as the simultaneous application of minimal soil disturbance, permanent soil cover through a mulch of crop residues or living plants, and crop rotations (www.fao.org/ca). CA has received increasing attention in sub-Saharan Africa, as a means to increase food security and minimize environmental degradation, particularly in sub-humid and semi-arid areas that are characterised by frequent droughts and dry spells. More specifically, CA enables early planting, as land preparation is simplified and often carried out before the first effective rains (Haggblade and Tembo, 2003), which may result in more efficient use of rainfall, reducing the risk of crop failure when receiving below-average rainfall and stabilizing yields when rains are poorly distributed (Friedrich, 2008; Erenstein, 2002; 2003).

Whilst the effect of mulching with crop residues on reducing water runoff and increasing infiltration is well known (e.g. Mannering and Meyer, 1963 and Thierfelder and Wall, 2009 for CA in southern Africa), it has been suggested that minimum tillage also increases water infiltration (McHugh et al., 2007; Rockström et al., 2009). The resulting increased soil water availability under CA is, for example, believed to extend the flowering period and yield of cotton in semi-arid areas (Naudin et al., 2010). Such arguments led international donors to vigorously promote CA in southern Africa. For example, during the 2009-10 growing season, respectively 180,000 and 110,000 smallholders were financially supported to adopt some form of CA in Zambia (www.conservationagriculture.org) and Zimbabwe (www.prpzim.info),.

While from on-station experiments there is ample evidence of the long-term positive impact of CA on crop water use efficiency (e.g. Nyamgumbo, 2002), less is known about the short-term impact under typical smallholder conditions. Filling this knowledge gap is crucial as smallholder farmers are concerned with meeting their immediate needs, and are therefore easily deterred from adopting technologies that entail no yield benefits in the short term (Giller et al., 2009). The inability to anticipate the poor adoption of technologies that perform well in research stations often resides in the poor understanding of smallholders' contexts and constraints.

Most measurements of water runoff and infiltration as a function of mulch cover in southern Africa were done under controlled conditions, with amounts of mulch that are not feasible under typical smallholder conditions. For example, Thierfelder and Wall (2009) measured in experiments in Zimbabwe and Zambia water infiltration rates under CA that were at least twice those under current farm practices, but the amounts of mulch they used - more than 3 t ha^{-1} of maize stover – were produced due to high rates of mineral fertilizer applications and fencing the experimental plots to protect the biomass from grazing animals. In contrast, typically about 1 t ha^{-1} of crop residues are produced under smallholder conditions in southern Africa and these are become a public good available for communal grazing after harvest (Mtambanengwe and Mapfumo, 2005), leaving a sparse soil cover. In addition, importing residues from outside the field for mulching is often not an option because of the huge labour efforts it would entail. Also, whilst in CA research or demonstration plots the quantities of mineral fertilisers used are generally high (165 kg ha^{-1} basal fertiliser and 200 kg ha^{-1} ammonium nitrate in the study of Thierfelder and Wall, 2009), no or little fertiliser is being used by smallholder farmers (average of 8 kg ha^{-1} in sub-Saharan Africa according to Groot, 2009). As a result, comparisons between CA and current farmers' cropping practices are often questionable, as the effect of CA *per se* (i.e. soil cover and minimum-tillage) is confounded with the effect of increased nutrient applications (Haggblade and Tembo, 2003).

In this study, the performance of CA during its first years of implementation was compared under the farming conditions of the local smallholders in the semi-arid Mid-Zambezi valley of Zimbabwe against the current farmers' cropping practices. The comparison was done for the production of the two major crops of the region - cotton (*Gossypium hirsutum* L.) and sorghum (*Sorghum bicolor* (L.) Moench). Mulches under CA were produced *in situ*. On-farm trials were conducted during three consecutive seasons and farmers' cotton fields were monitored during two seasons. The on-farm trials did not receive fertiliser, while the farmers' cotton fields were fertilised at various rates, depending on farmers' judgements and their access to fertilizer through the cotton company. .

4.2. MATERIAL AND METHODS

4.2.1. Study area

The study area is located in Mbire District, and is part of the Mid-Zambezi Valley in northern Zimbabwe, between 30°00 and 31°45 East and 16°00 and 16°30 South. The Mid-Zambezi Valley is characterized by the former floodplains of the Zambezi River between the Victoria Falls and Cabora Bassa Lake, at an average altitude of 400 m above sea level. The area is part of the agro-ecological zone 'Natural Region IV' of Zimbabwe, which is characterized by low rainfall (450-650 mm), periodic seasonal droughts and severe dry spells during the growing season, resulting in a low agricultural potential (Vincent and Thoms, 1961; modified by Surveyor-General, 1980). There are two clearly defined seasons: a short rainy season with between 110 and 140 days of rainfall from December to March (Figure 1) and a long dry season from April to November. Rainfall is highly variable within seasons and across small distances due to localised storms (Figure 1) and mid-season dry spells of more than 30 days often occur (see Figure 1, 2007-08 season). Cotton, sorghum and maize are the main crops. Sorghum is the major cereal crop and is grown on the interfluves, while maize is grown mostly along river banks. Farming takes place on three major soil types known in vernacular language as '*shapa*' (sandy clay loam to sandy loam), '*bandate*' (sandy loam to loamy sand) and '*mutapo*' (loamy sand) (Table 1).

The study area has been an agricultural frontier since independence, when it was targeted with resettlement projects, tsetse fly control operations and promotion of cotton cropping (Chapter 2). However, these interventions were concentrated in the western part of the study area, which created a gradient of agricultural intensification from west to east: over a relatively short distance (30-40 km) the area under cultivation, cotton production, use of animal-drawn ploughs and livestock densities increase substantially (Chapter 2).

Table 1. Soil characteristics (means ± standard errors) of the three major soil types used for agriculture in the study area in Mbire District, Mid-Zambezi Valley (SOC: soil organic carbon determined through the dry combustion method; N: total nitrogen determined through the dry combustion method; P: phosphorus concentration determined through the Olsen method; K: potassium exchange capacity determined through pH 7 ammonium acetate procedure; proportions of clay, silt and sand were determined through sedimentation)

Soil type*	Depth (cm)	pH KCl	SOC (g/kg)	N (g/kg)	P (mg/kg)	K (cmol/kg)	Clay (%)	Silt (%)	Sand (%)
Shapa	0-10	5.9 (± 0.8)	8.40 (± 2.33)	0.66 (± 0.19)	8.82 (± 3.96)	0.39 (± 0.21)	12.3 (± 2.9)	12.6 (± 5.1)	75.2 (± 7.3)
	10-20	5.7 (± 0.7)	7.18 (± 2.36)	0.56 (± 0.13)	5.12 (± 3.05)	0.39 (± 0.22)	13.3 (± 3.9)	12.2 (± 4.0)	74.5 (± 7.0)
Bandate	0-10	6.2 (± 0.5)	10.0 (± 3.20)	0.79 (± 0.25)	17.3 (± 13.4)	0.68 (± 0.27)	13.6 (± 4.0)	18.2 (± 11.2)	68.2 (± 14.6)
	10-20	5.9 (± 0.6)	8.73 (± 2.77)	0.69 (± 0.21)	11.7 (± 11.8)	0.54 (± 0.25)	15.5 (±5.3)	18.0 (± 10.8)	66.4 (± 15.3)
Mutapo	0-10	6.1 (± 0.5)	7.73 (± 3.04)	0.63 (± 0.24)	11.8 (± 8.20)	0.80 (± 0.33)	14.9 (± 3.0)	17.5 (± 5.5)	67.7 (± 7.5)
	10-20	5.9 (± 0.5)	7.43 (± 2.63)	0.59 (± 0.18)	8.26 (± 5.73)	0.69 (± 0.30)	16.5 (± 3.9)	17.9 (± 5.6)	65.6 (± 8.5)

* local names

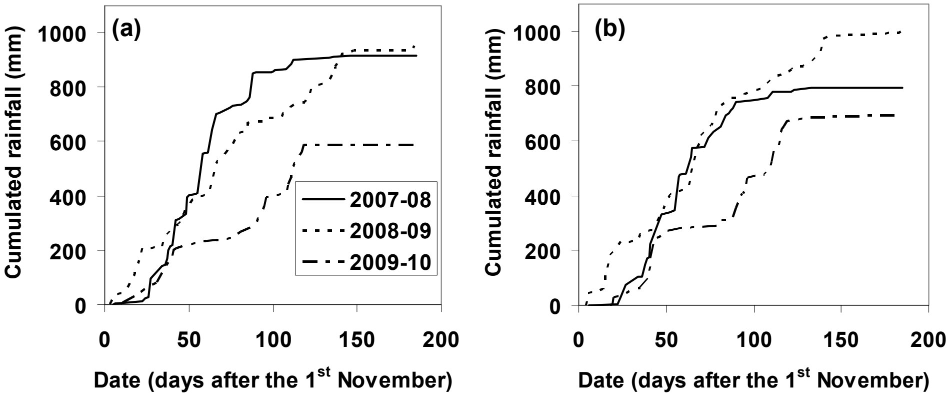

Figure 1. Rainfall distribution during three seasons, measured on two farms 5.3 km apart: Farm 1 (a) and Farm 2 (b) in Mbire District, Mid-Zambezi Valley.

4.2.2. On-farm trials and farmers' cotton fields

During each of three consecutive seasons: 2007-08 (the first season), 2008-09 (the second season), and 2009-10 (the third season), a number of farms were selected to host trials that compared the performance of CA with farmers' current cropping practices (CP). The population of cotton producers in the study area can be divided into hand-hoe farmers and ox- or donkey-ploughing farmers. The latter group can be subdivided into farmers owning less than two pairs of draught animals and those owning two pairs or more. A sample of farmers was selected to represent these different farmer types, the diversity of soil types ('*shapa*', '*bandate*', '*mutapo*'), and the range of positions on the agricultural intensification gradient mentioned above. Trials were planted by 24 farmers during the first season, 35 during the second season and 25 during the third season. Due to poor management and/or destruction by pests, livestock (e.g. free roaming goats) or wild animals (e.g. elephants), data was collected only from 12 farms during the first season, 28 during the second season (including 9 farms selected during the previous season) and 23 during the third season (all continued from the previous season). On-farm trials were a simple comparison of CA and CP for a sorghum-cotton rotation (Table 2). For sorghum, the CP treatment was a pure stand of sorghum sown after either ox- or donkey-drawn ploughing or hand-hoe minimum-tillage, depending on the mode of land preparation used by the hosting farmer. Hand-hoe minimum-tillage – i.e. opening of planting stations at the onset of the rainy season using a hand-hoe - is a common practice for farmers in the study area who have no access to draught animal power and ploughs.

The CA treatment consisted of sorghum sown in shallow planting holes made with a hand-hoe in association with a legume crop that was planted two to six weeks after the sorghum crop. Mixing crops is an important principle of CA; sorghum was intercropped with legumes to increase biomass production and N input through atmospheric N_2-fixation. Four grain legumes - cowpea (*Vigna unguiculata* (L.) Walp.), jackbean (*Canavalia ensiformis* (L.) D.C.), lablab (*Dolichos lablab* (L.) Sweet), and pigeonpea (*Cajanus cajan* (L.) Millsp.) - and two green manures - sunnhemp (*Crotalaria juncea* (L.)) and velvet bean (*Mucuna pruriens* var. *utilis* (L.) DC.) were compared. Cotton under CP consisted of sole cotton sown after ox- or donkey-drawn ploughing or hand-hoe minimum-tillage, depending on the usual mode of land preparation used by the hosting farmer. For this treatment, residues of the previous sorghum crop were removed from the plot before planting, mimicking farmers' practice of residue export, residue grazing and/or burning. The CA treatment consisted of cotton sown in shallow planting holes made with a hand-hoe. When the trial was in its second or third year, sorghum and legume residues from the previous year were retained as mulch in this treatment. After harvest of cotton, stalks were slashed, removed from the plot and burnt for both treatments, such practice being compulsory for phytosanitary reasons in Zimbabwe. In the CA treatment, the sorghum-legume phase of the crop rotation can be considered a phase of *in situ* biomass production for the following cotton crop. Each of the four plots in each trial had an area of 100 m^2. As most farmers currently use little or no mineral fertiliser, no fertiliser was applied in any of the trials. Although the trials were not fenced, farmers chased roaming herds of livestock from them (as far as possible), both during the rainy and the dry seasons. Farmers were free to choose planting dates and the number and date of pesticide treatments. All plots were maintained weed free – i.e. weeds where hand pulled and/or removed by superficial hand hoeing before they reached a height of 10 cm.

Table 2. Agronomic management under current farm practice (CP) and conservation agriculture (CA), as compared in pairs in on-farm trials.

Management factor	CP		CA	
	Cotton	Sorghum	Cotton	Sorghum
Crop	Sole	Sole	Sole	Intercropped with legumes
Land preparation	Ploughing or minimum-tillage	Ploughing or minimum-tillage	Minimum-tillage	Minimum-tillage
Soil cover	Bare soil	Bare soil	Mulch of sorghum and legume residues	Bare soil

Data was also collected from the main cotton field of a large sample of farmers in the study area over two seasons – 195 fields in 2008-09 and 346 in 2009-10. The area of the fields ranged between 0.1 and 5.2 ha. Farmers obtained external inputs – cotton seeds, fertilisers and pesticides – on credit from a cotton company. During the 2008-09 season, the mean N, P and K fertilisation rates were 38 (± 31), 6 (± 7) and 6 (± 8) kg ha^{-1} respectively. During the 2009-10 season, they were 11 (± 20), 2 (± 4) and 2 (± 5) kg ha^{-1} respectively. A subset of these fields (120 fields in 2008-09 and 170 fields in 2009-10) was sponsored by the EC-funded project PARSEL (Public-Private-Community Partnerships to improve food security and livelihoods in South East Lowveld and Mid-Zambezi Valley). In these fields, farmers received technical assistance (e.g. equipment) and training to apply CA. Cotton was planted following either a cereal crop or an herbaceous fallow. All cereal crop residues and/or herbaceous biomass present in the field at the onset of the rainy season were retained as mulch. Cotton was planted either: (1) with an ox- or donkey-drawn Fitarelli direct-seeder, without any previous land preparation; (2) by hand after ripping with an ox- or donkey-drawn Magoye ripper; or (3) after hand-hoe minimum-tillage. The other subset of fields included in this analysis (75 fields in 2008-09 and 176 fields in 2009-10) was managed using CP and used as control. In these fields, all crop residues and the herbaceous biomass were burnt prior to planting, and planting was done either after ploughing with an ox- or donkey-drawn mouldboard plough or after hand-hoe minimum-tillage.

4.2.3. Measurements

In the on-farm trials, planting dates, dates of first weeding, total number of weeding operations and total number of pesticide treatments were recorded for each crop in farmers' books. In 2007, soil was sampled in each trial (for each trial one 0-10 cm and one 10-20 cm depth composite sample bulked from 3 cores), oven-dried for 48 hours at 60°C, sieved and stored for analysis. Crop yields and the amount of residues from the three crops (cotton, sorghum and legume) at harvest and at the end of the dry season were measured in each plot of each trial and samples were oven-dried for 48 hours at 60°C. During the 2008-09 season, grain and residue samples of sorghum, cotton and legumes were collected from 20 trials to determine their N and P concentrations using a colorimeter after Kjeldahl digestion with sulphuric acid (Parkinson and Allen, 1975).

Four on-farm trials were selected to measure water runoff in the CP and CA cotton plots. Owners of these trials were equipped with a rain gauge and recorded rainfall on a daily basis. In each plot, water runoff from a 10 m × 0.9 m subplot was directed by iron sheets into a 200 L plastic drum buried below the soil surface. The drums were emptied with a hand-pump after each intense rainfall event (i.e. intense enough to generate over-land flow). The volume of water in each drum was measured and converted to cumulative water runoff in mm. Due to the destruction of the experimental set-up by a stormy rainfall at one site and theft of the iron sheets and drum at another site, runoff data from only two trials could be analysed. Both were located on a *bandate* soil with somewhat different soil textural characteristics: 10% clay, 12% silt, 78% sand versus 14% clay, 17% silt, 69% sand.

Disappearance of sorghum residues during the dry season (November to April) was measured in three on-farm trials using litter bags. Litter bags of 1 and 5 mm mesh were filled with 150 g of oven-dried sorghum residues chopped into pieces no longer than 5 cm. The litter bags of 5 mm mesh size were expected to allow macro-fauna (e.g. termites) to enter, whilst those of 1 mm mesh size to exclude macro-fauna from the sorghum residues. Litter bags were placed on the soil surface of the sorghum CA plots of the three selected trials on the 1st of May 2008 i.e. when all harvesting was done. Every 1.5 month, two litter bags of both 1 mm and 5 mm mesh size were removed from each trial. The content of the litter bags was oven-dried during 48 h at 60°C and its ash content was determined by combustion in a muffle furnace (up to a temperature of 550°C) to determine organic matter loss.

On the farmers' cotton fields managed through CA, the proportion of soil covered by cereal residues and/or herbaceous biomass was estimated at five different locations in the field at the time of planting. An average value was calculated per field. All farmers from the sample of cotton fields (both under CP and CA) were interviewed about 2-3 months after planting to obtain information on soil type (five soil types were locally identified, with increasing clay content: *shapa, bandate-shapa, bandate, mutapo-bandate, mutapo*), the number of years of cultivation since forest clearance, the mode of land preparation, the type and quantities of fertilisers used in the field, and the date of first weeding operation. The same farmers were also interviewed after harvest on the cotton yield from the field (which was cross-checked with the records from the cotton companies' officers), the total number of weeding operations and the total number of pesticide treatments. Each field area was measured using a global positioning system (GPS) to obtain the fertiliser applications and crop yields in kg ha^{-1}.

At the end of each growing season, group discussions with farmers were organized for a participatory evaluation of the performance of CA in comparison with CP. These discussions were organized at four locations along the intensification gradient of the study area: Masoka, Angwa, Mazambara and Mushumbi Pools. Farmers who had hosted the on-farm trials and chairpersons of farmers' groups (groups of 15 to 20 farmers) created by the PARSEL project were invited. Thus, each group discussion gathered between 30 and 50 individuals. Discussions focused on the benefits and problems associated with each component of CA, when compared with CP: minimum-tillage, mulching, and legume intercropping. Interactions between cropping practices, soil types and rainfall were also discussed.

4.2.4. Calculations of N and P partial balances

For the 20 on-farm trials that were sampled for analysis of N and P concentration in the grains and residues of sorghum, cotton and legumes, partial N and P balances considering the entire cotton-sorghum rotation were calculated. A nutrient balance is defined as the difference of the sum of all nutrient inputs and outputs. In this study, partial nutrient balances (kg ha^{-1}) were calculated in the sense that only the readily-measured input and output flows were included. Losses through erosion, leaching and in gaseous forms and inputs through atmospheric deposition and non-symbiotic N_2-fixation were not accounted for. Since no manure or fertiliser was used, the only nutrient inputs were atmospheric deposition (which is generally very small in Africa) and N_2-fixation from the legumes, whilst nutrient outputs occurred via harvest (of seed-cotton, cereal and legume grains) and burning of residues (cotton residues present at the end of the dry season for CA and CP and sorghum residues present at the end of the dry season for CP). It was further assumed that (1) 80% of the N contained in legume biomass and grain originated from N_2-fixation, (2) all the N and P contained in mulch of sorghum and legume residues in the cotton CA plot was retained in the field, (3) all the N contained in the residues burnt was lost in gaseous form and (4) all the P contained in the residues burnt was retained in the field as ash. ‘N export’ and ‘P export’ are defined as the absolute value of the N and P partial balances when these were negative.

4.2.5. Statistical analysis

Generalized linear mixed models (GLMM) were used to assess the source of variability in cotton and sorghum yields (e.g. trial, season, soil) from the on-farm trials. The effect ‘trial’ is defined as the particular circumstances of a given experimental unit on a particular soil type and during a particular cropping season, chosen from a wider pool of experimental units on the same soil type and during the same cropping season i.e. the effect ‘trial’ in the models below is a random effect nested in the interaction season × soil. The effect ‘trial’ can be considered as the repetition. The effect ‘season’ was considered as a fixed rather than random effect due to the fact that there are only three cropping seasons in our dataset and that these three levels may not be representative of all the possible levels in the study area. The effect ‘soil’ was considered a fixed effect because the levels of this factor consist of the entire population of possible levels.

Model 1 was used to describe both cotton and sorghum yields, Model 2 to describe cotton yield and Model 3 to describe sorghum yield. Model 1 aims at testing the general effect of the factor ‘treatment’ i.e. CA or CP on cotton and sorghum yields. In Model 2, the factor ‘treatment’ is further specified using three factors: the factor ‘mode of land preparation’ (i.e. minimum-tillage or ploughing), the factor ‘log-transformed quantity of sorghum mulch' and the factor 'log-transformed quantity of legume mulch', in order to specifically test their effects on cotton yield. In Model 3, the factor 'treatment' is further detailed using two factors: the factor 'mode of land preparation' (i.e. minimum-tillage or ploughing) and the factor 'legume type' (seven levels: no legume and six legume crops). The effect of the previous crop yield was not considered (no inter-seasonal effects) due to the high variability of the other factors. In the three models, cotton and sorghum yields were log-transformed. Kolmogorov-Smirnov test was used to ensure that log-transformed values of yields followed a normal distribution ($P < 0.05$). A probability of 0.05 was used to test the significance of the various factors. In each model, factors that had an F-value less than 0.1 were removed. Models were constructed as follows:

(Model 1) $$Y_{ijklmn} = \alpha + \beta.SS_i + \gamma.SL_j + \delta.TR_{kij}(SS_i \times SL_j) + \varepsilon.WF_l + \zeta.PF_m + \eta.T_n + \theta.PD + \kappa.WD + \lambda.SS_i.T_n + \mu.SL_j.T_n + v.WF_l.T_n + \xi.PF_m.T_n + R$$

(Model 2) $$Y_{ijklmp} = \alpha + \beta.SS_i + \gamma.SL_j + \delta.TR_{kij}(SS_i \times SL_j) + \varepsilon.WF_l + \zeta.PF_m + \pi.LP_p + \rho.MS + \sigma.ML + \theta.PD + \kappa.WD + \lambda.SS_i.LP_p + \mu.SL_j.LP_p + v.WF_l.LP_p + \xi.PF_m.LP_p + R$$

(Model 3) $$Y_{ijklmpq} = \alpha + \beta.SS_i + \gamma.SL_j + \delta.TR_{kij}(SS_i \times SL_j) + \varepsilon.WF_l + \zeta.PF_m + \pi.LP_p + \omega.LG_q + \theta.PD + \kappa.WD + \lambda.SS_i.LP_p + \mu.SL_j.LP_p + v.WF_l.LP_p + \xi.PF_m.LP_p + R$$

where $Y_{ijklmnpq}$ represents the log-transformed value of the yield, SS_j the i^{th} season, SL_j the j^{th} soil type, TR_{kij} the k^{th} trial, WF_l the l^{th} frequency of weeding, PF_m the m^{th} frequency of pesticide treatments, T_n the n^{th} treatment, LP_p the p^{th} mode of land preparation, LG_q, the q^{th} legume species, PD the log-transformed planting date (in number of days since the 1st of November), WD the log-transformed date of first weeding operation (in number of days since planting), MS the log-transformed quantity of sorghum mulch, ML the log-transformed quantity of legume mulch, and R the residual, and where α, β, γ, δ, ε, ζ, η, π, ρ, σ, ω, θ, κ, λ, μ, v and ξ represent fixed and random effects values.

To explain the response of cotton yield (as kg DM seed-cotton ha^{-1} or kg DM seed-cotton per mm seasonal $rainfall^{-1}$) to the various categorical and continuous (predictor) agronomic variables measured in the farmers' cotton fields, classification trees were constructed using the software CART- Classification and regression tree analysis (Salford Systems Inc., San Diego, CA, USA).

To further explore in more detail the contribution of biophysical and management factors to the variability of cotton productivity, the boundary line approach was used as adapted by Fermont et al. (2009). After ordering cotton yields (the target variable) in ascending order for independent variables expected to have a negative effect on productivity (e.g. planting date), and in descending order for independent variables expected to have a positive effect on productivity (e.g. quantity of N applied), boundary points i.e. the maximum cotton yield response for each level of the independent variable were identified. A logistic curve was then fitted through these boundary points (using Genstat 6.1, 2002). Boundary line analysis was performed for CA and CP independently and the curves compared using an F-test.

4.3. RESULTS

4.3.1. Crop productivity

4.3.1.1. On-farm trials

In the on-farm trials, only minor differences were observed between CA and CP for cotton and sorghum yields (Figure 2). There were no significant differences during the first and second season (Table 3). In the third season, cotton yields were significantly greater with CP (average of 820 kg ha^{-1}) than with CA (average of 726 kg ha^{-1}), whilst sorghum yielded significantly less with CP (average of 688 kg ha^{-1}) than with CA (average of 761 kg ha^{-1}). The study area received approximately 30 mm more rainfall in 2008-09 than in 2009-10 with an extra 30 rainy days (Figure 1). Moreover, a marked dry spell was observed during the 2009-10 season, whilst rainfall was well distributed during the 2008-09 season. The 2008-09 seasonal rainfall was considered locally as 'above average' (i.e. wet year) and the 2009-10 seasonal rainfall as a 'below average' (i.e. dry year). The 2007-08 season can be considered as an 'average' season, despite a mid-season dry spell.

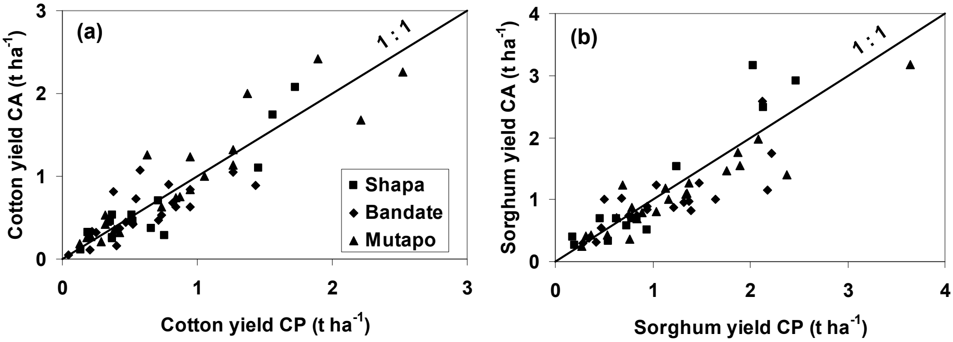

Figure 2. Comparison of crop yields between current farm practices (CP) and conservation agriculture (CA), measured in multi-locational on-farm trials during three consecutive season on the three major soil types of the study area (‘*shapa*’, ‘*bandate*’ and ‘*mutapo*’) for cotton (a) and sorghum (b).

Although there was no significant difference in the mean yield of cotton for the different soil types (whether comparing the three soil types or contrasting one soil type against the other two), the maximum yields attained on *‘shapa’* and *‘mutapo’* (up to 2500 kg ha^{-1}) were larger than on ‘*bandate*’ soils (up to 1000 kg ha^{-1}) (Figure 2a). The random factor ‘trial’ was found to be overruling in the three GLM models, both for cotton and for sorghum, and to some extent masked seasonal, soil and treatment effects (Table 4). For cotton, the interaction between ‘treatment’ and ‘season’ was significant in Model 1 ($P < 0.05$). The least squared mean yield (i.e. the mean adjusted for other factors) was similar between CP and CA during the first season (1051 and 1007 kg ha^{-1} respectively), significantly lower for CP than for CA during the second, wettest season (935 and 1129 kg ha^{-1} respectively), and significantly higher for CP than for CA during the third, driest season (519 and 449 kg ha^{-1} respectively). For cotton, a weakly significant ($P < 0.1$) interaction between land preparation (ploughing or minimum-tillage) and soil type was detected in Model 2. The mulch quantities of sorghum and legumes did not influence cotton yield. For sorghum, there was no significant effect of the mode of land preparation or legume intercropping (i.e. having or not a legume intercropped and the type of species used) on sorghum yield in Model 3.

Table 3. Yield (means ± standard errors; in kg ha^{-1}) of cotton and sorghum in trials and farmers’ fields, following current farm practices (CP) and conservation agriculture (CA) over three seasons.

Season	Cotton				Sorghum	
	On-farm trials		Farmers' fields		On-farm trials	
	CP	CA	CP	CA	CP	CA
2007-08	568 (± 446)	565 (± 524)	NA	NA	1500 (± 745)	1450 (± 951)
2008-09	722 (± 635)	788 (± 616)	1038 (± 430)	1004 (± 451)	1028 (± 809)	975 (± 717)
2009-10	820$^{(a)}$ (± 440)	726$^{(a)}$ (± 492)	1445$^{(b)}$ (± 488)	1219$^{(b)}$ (± 541)	688$^{(c)}$ (± 304)	761$^{(c)}$ (± 333)

(a): significantly different for the log-transformed values ($P < 0.005$)
(b): significantly different for the log-transformed values ($P < 0.001$)
(c): significantly different for the log-transformed values ($P < 0.05$)

Table 4. Summary of the results of the three GLM models (see text) for explaining the variability in cotton and sorghum yields in the on-farm trials. Significant effects (*P* < 0.1) are shown in bold (N° weeding: number of weeding operations; N° Pesticide: number of pesticide treatment; Land Prep: mode of land preparation)

Model	*F*	*P*	*DF*
Model 1			
Cotton	18.68	**0.0000**	65
Season	0.27	0.7625	2
Soil	1.69	0.1943	2
Trial(Season*Soil)	19.95	**0.0000**	49
Nb weeding	1.69	0.1956	2
Nb pesticide	0.42	0.6597	2
Treatment*Season	4.22	**0.0203**	2
Treatment*Soil	1.71	0.1921	2
Treatment*N° weeding	1.82	0.1731	2
Treatment*N° pesticide	1.52	0.2289	2
Sorghum	9.04	**0.0000**	62
Season	1.07	0.3519	2
Soil	0.49	0.6144	2
Trial(Season*Soil)	9.3	**0.0000**	50
Treatment*Season	1.17	0.3194	2
Treatment*Soil	0.54	0.5850	2
Treatment*N° weeding	0.4	0.6745	2
Model 2			
Cotton	16.15	**0.0000**	65
Season	0.17	0.8416	2
Trial(Season*Soil)	16.54	**0.0000**	49
Nb pesticide	0.8	0.4543	2
Log-Mulch sorghum	1.86	0.1756	1
Log-Mulch legume	0.12	0.7265	1
Land Prep	1.5	0.2297	2
Land Prep*Soil	2.5	**0.0923**	2
Land Prep*N° weeding	0.79	0.4561	2
Land Prep*N° pesticide	0.43	0.6518	2
Model 3			
Sorghum	9.53	**0.0000**	62
Season	1.53	0.2244	2
Soil	0.45	0.6398	2
Trial(Season*Soil)	10	**0.0000**	50
Land Prep	0.41	0.5215	2
Legume	0.42	0.8624	6
Land Prep*Season	0.87	0.4241	2
Land Prep*Soil	2.05	0.1338	2

4.3.1.2. Farmers' cotton fields

The variability of farmers' cotton yields (*n* = 541) was explored using classification trees that used management variables (mode of land preparation, planting dates, fertiliser rates, etc.) as partitioning criteria, which allowed to evaluate the effect of CA compared with CP practices on cotton yields. The entire dataset was first split by the variable 'season' (2008-09 vs. 2009-10), indicating an overruling seasonal effect on cotton yields; with an average yield of 1 t ha^{-1} in 2008-09 and of 1.3 t ha^{-1} in 2009-10 (Figure 3). A similar result was obtained when using rainfall use efficiency (kg DM mm^{-1} rain) instead of yield as target variable. The classification tree corresponding to the wettest 2008-2009 season (*n* = 195) was further split by the number of pesticide applications; fields that received more than 5 applications (*n* = 106) produced on average 0.2 t ha^{-1} more seed-cotton than the rest. This group was further split by the rate of K fertilizer application. The performance of the classification was poor for this season, with all terminal nodes having average yields fluctuating around 0.9 and 1.1 t ha^{-1}, and neither the mode of land preparation (direct-seeding, ripping, hand hoe minimum-tillage, or ploughing) nor the proportion of soil covered by mulch appeared as a classification criterion. In contrast, during the driest 2009-10 season (*n* = 346) the mode of land preparation was paramount in explaining cotton yield, with an average yield that was 50% greater with ploughing (1.6 t ha^{-1}) than with the three modes of minimum-tillage (1.1 t ha^{-1}). Ploughed fields (*n* = 111) were further split by the rate of N fertilizer application, with a threshold of 22 kg N ha^{-1}, below which average yield was 1.4 t ha^{-1}, and above which yield was 1.8 t ha^{-1}. The rate of P fertilizer application split the group of fields under minimum-tillage (*n* = 235) into a small group of 17 fields receiving higher application rates and yielding 1.6 t ha^{-1} on average, and a large group receiving less than 7.3 kg P ha^{-1} and yielding 1.1 t ha^{-1}, which was further split by the mode of land preparation; fields managed with hand-hoe minimum-tillage (n = 91) produced on average 0.2 t ha^{-1} more seed-cotton than fields managed through minimum-tillage using animal draught power (direct-seeding or ripping).

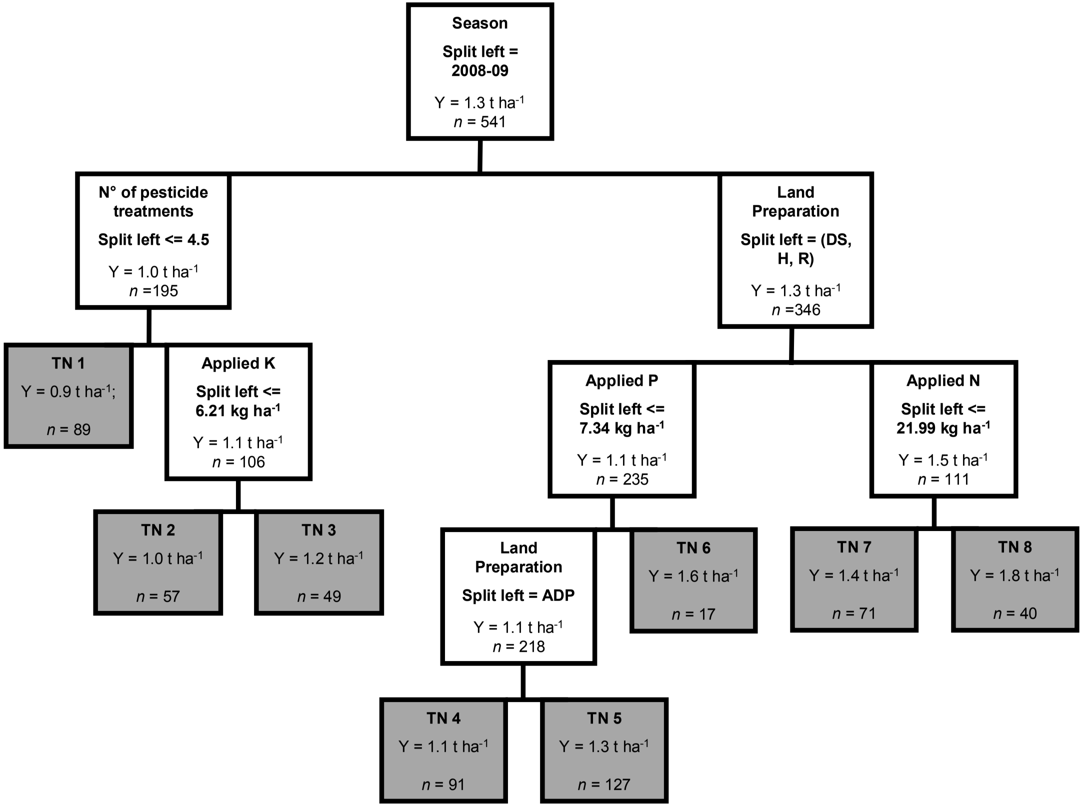

Figure 3. Trees constructed by binary recursive partitioning rules using CART, for cotton yield in 2008-09 and in 2009-10. For each node, the value used as threshold for the next split is given, as well as the average yield (Y) and the number of data records (*n*). (DS: direct seeding, H: hand hoeing, R: ripping, ADP: animal draught power)

Using the data from farmers' cotton fields, boundary line (BL) models were fitted between individual management variables and rainfall use efficiency - RUE (to reduce the effect of season). The analysis was done separately for CA and CP but the data from both seasons was pooled. Nitrogen, P and K fertilisation, fraction of the soil surface covered by mulch, time since vegetation clearance, planting date, date of first weeding operation, total number of weeding operations and total number of pesticide treatments were used as explanatory variables in the different models. Fertiliser application rates were weak explanatory variables due to the fact that most fields received no or little fertiliser (42% of the fields received no N fertiliser and 58% received no P or K fertiliser). The relationship between attainable crop RUE and the fraction of soil surface covered by mulch on the CA plots could be described by a boundary line model (data not shown). For the other factors used as independent variables (planting date, date of first weeding, number of weeding operations and number of pesticide treatments), statistically significant differences in the boundary lines were found between CA and CP (Figure 4). However, the differences between CA and CP in terms of attainable RUE at a given value of the explanatory variable appeared small when compared against the variability of the attainable RUE over the whole range of the explanatory variable (i.e. the shape of the boundary line prevailed over the differences between the CA and CP boundary lines). Both for CA and CP, the boundary line model showed a rapid decline in the attainable RUE with delayed planting and first weeding. Similarly, both for CA and CP, the boundary line shows a rapid increase of the attainable RUE with increasing number of weeding operations and pesticide treatments.

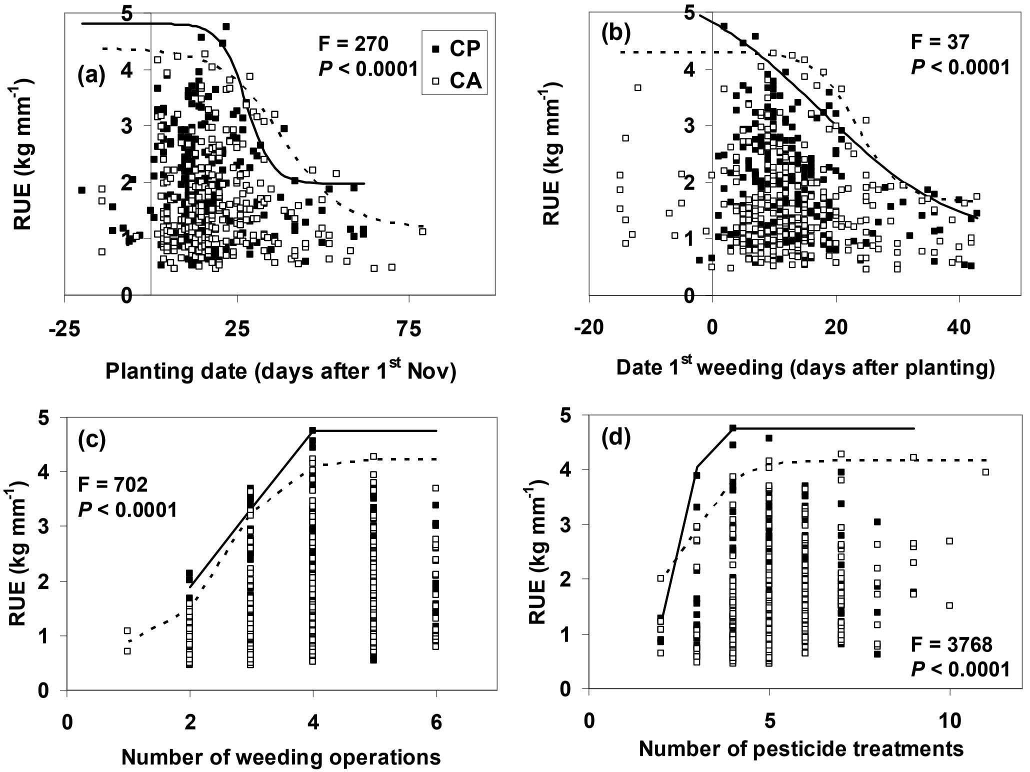

Figure 4. Cotton rainfall use efficiency (RUE, kg DM seed-cotton mm^{-1}) in 2008-09 and 2009-10 under current farm practice (CP) and conservation agriculture (CA), as a function of (a) planting date, (b) date of the first weeding operation, (c) number of weeding operations and (d) number of pesticide treatments. For each graph, a summary of the Fisher test comparing the two curves is given.

4.3.2. Water runoff and surface mulching

In the two selected on-farm trials cumulative water runoff over the growing season ranged from 40 to 80 mm, and there was more runoff in the wetter 2008-09 season than in the drier 2009-10 season. More runoff was observed on the coarser-textured (Farm 1) than on the finer-textured soil (Farm 2) (Figure 5). There was significantly more runoff after each intense rainfall event under CA than CP in both seasons on Farm 1. The difference in cumulative runoff between CA and CP was negligible (2 mm) in the 2009-10 season but greater (14 mm) during the 2008-10 season. No differences in runoff after each intense rainfall event were found on Farm 2 between CA and CP.

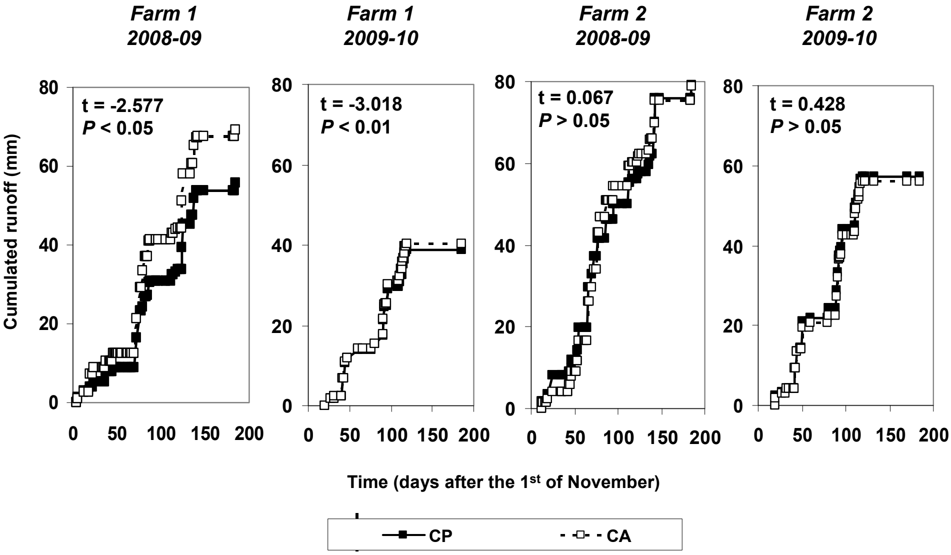

Figure 5. Cumulated water runoff measured from 10 m × 0.9 m subplots in the cotton plots under current farm practices (CP) and conservation agriculture (CA) during two seasons on two on-farm trials on *bandate* soil, one coarse textured (22% clay + silt; Farm 1) and one finer textured (31% clay + silt; Farm 2). On Farm 1, 1110 kg DM ha^{-1} and 820 kg DM ha^{-1} were retained as mulch in the CA plot during the 2008-09 season and the 2009-10 season respectively. On Farm 2, 810 kg DM ha^{-1} and 550 kg DM ha^{-1} were retained as mulch in the CA plot during the 2008-09 season and the 2009-10 season respectively. The CP plots were ploughed and cotton was planted on a bare ground. For each graph, a summary of the paired T test comparing runoff under CA and under CP is given.

The mean quantity of mulch (sorghum and legume residues) retained on the soil surface in the on-farm CA trials was small: 830 (± 1092) kg ha^{-1} in 2008-09 and 835

(± 979) kg ha^{-1} in 2009-10. There was no mulch during the first season of the experiment. The amount of sorghum residues had no effect on the yield of the subsequent cotton crop in on-farm trials (Figure 6a, see also GLMM Table 4). However, the ratio of the quantity of sorghum residues remaining in the field at the end of the dry season to the quantity of sorghum residues at harvest was high; ranging from 0.25 to 0.8 depending on the season (Figure 6b). This ratio was higher in the wetter year compared with the drier year (Figure 6b). Since grazing was controlled in the on-farm trials, the loss of residue biomass during the dry season was mainly due to decomposition. In several fields sorghum resprouted after harvest and contributed to the quantity of sorghum residues measured at the end of the dry season. This phenomenon is also noticeable from the fact that the ratio of the quantity of sorghum residues remaining in the field at the end of the dry season to that at harvest is higher than the proportion of sorghum residues that decomposed in litter bags over the dry season (Figure 6c). The disappearance rates of the sorghum residues from the 1 and 5 mm litter bags were similar. Termites were observed in both types of litter bags after only a few weeks. The mass fraction of sorghum residues remaining after 6 months varied between 0.2 and 0.6 (Figure 6c) with fastest disappearance rates during the first three months of the incubation experiment.

Legumes contributed substantially to the quantity of residues present in the field in the CA treatment (Table 5), except during the 2007-08 season when the legume intercrop did not grow due to a mid-season dry spell (Figure 1). The increase in the quantity of residues was observed both at the time of sorghum harvesting and after the dry season (Table 5). When considering the CA plots in the two seasons, 2008-09 and 2009-10, the average amount of residues produced by sorghum was 3284 ± 1320 kg ha^{-1}, whilst the average amount of residue produced by legumes was 825 ±1175 kg ha^{-1}. At the end of the dry season, the amount of sorghum residues remaining was 2025 ± 1065 kg ha^{-1}, roughly two thirds of the amount of harvest time. This amount was greater in 2009-10 than in 2008-2009. The amount of legume residue remaining at the end of the dry season was 773 ±1337 kg ha^{-1} i.e. almost the same amount than at the time of sorghum harvest. This is the net amount following the decomposition of senescent biomass and the production of new shoots, the latter being significant for legume species with a long growing cycle such as pigeonpea. Thus, the quantity of legume residues found in CA plots at the end of the dry season differed between species, and was particularly high for pigeonpea: more than 2000 kg ha^{-1} during both the 2008-09 and 2009-10 seasons. For the other species, it was less than 500 kg ha^{-1} during the 2008-09 season and less than 1500 kg ha^{-1} during the 2009-10 season. No cowpea residues remained in CA plots at the end of the dry season.

4.3.3. Partial nutrient balances

The partial N and P balances calculated for the entire cotton-sorghum rotation for the 2008-09 season indicated net N and P export from most fields (Figure 7). While there was no significant difference between CP and CA in the amount of P exported from the field (Figure 7b), N export was statistically greater under CP than under CA (Figure 7a). The reduced removal of N with CA comes from the retention of a fraction of sorghum residues as mulch and the inclusion of N-rich legumes. Nitrogen concentration was on average 3 times higher in legume residues (2.1 ± 0.9) than in sorghum residues (0.7 ± 0.2 %). Given the small legume grain yield (between 0 and 371 kg DM ha^{-1}), the legume exported little N. Input of N from the intercropped legume is directly linked to its productivity: pigeonpea and velvet bean are therefore the best legumes in terms of contribution to improving the partial N balance (Table 5). Pigeonpea and jackbean are long-duration legumes which almost doubled their standing biomass between the harvest time of sorghum and the end of the dry season. In four fields, positive partial N balances for the sorghum-cotton rotation were actually observed under CA: two fields where pigeonpea was used as the intercropped legume and two fields with velvet bean.

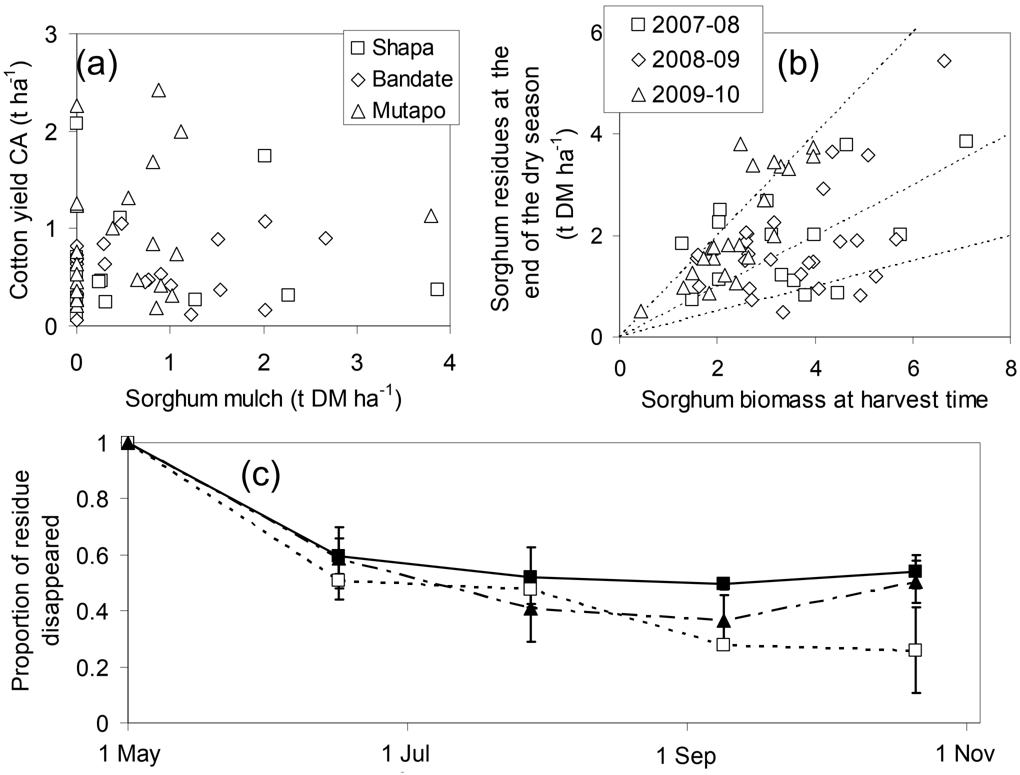

Figure 6. (a) Cotton yield in the conservation agriculture (CA) treatment as a function of the quantity of sorghum residues retained as mulch at the onset of the rainy season; (b) amount of above-ground sorghum biomass retained in CA plots at the end of the dry season, as a function of the amount of above-ground sorghum biomass produced; and (c) disappearance of sorghum residues in litter bags in three on-farm trials during the dry season.

Table 5. Quantity (means ± standard errors; in kg DM ha^{-1}) of sorghum and legume residues in the conservation agriculture (CA) and the current farm practices (CP) plots (sole-cropping) at the time of sorghum harvesting (end of the rainy season) and at the end of the dry season during the 2008-09 and 2009-10 seasons (legume intercrops could not be established during the 2007-08 season due to a mid-season dry spell).

Intercrop	2008-09				2009-10			
	At harvest time		At the end of the dry season		At harvest time		At the end of the dry season	
	Sorghum	Legume	Sorghum	Legume	Sorghum	Legume	Sorghum	Legume
Cowpea	4296 (± 1956)	82 (± 77)	2427 (± 1759)	0	1851 (± 768)	163 (± 104)	1013 (± 60)	10 (± 14)
Jackbean	4069 (± 1108)	64 (± 44)	1965 (± 1215)	437 (± 622)	2613 (± 810)	930 (± 379)	2160 (± 790)	1387 (± 1363)
Lablab	3021 (± 843)	416 (± 538)	1345 (± 662)	140 (± 313)	3169	1100	3464	1109
Pigeonpea	3118 (± 1007)	1062 (± 1746)	1735 (± 1112)	2353 (± 1801)	2282 (± 681)	1700 (± 2226)	2515 (± 1275)	2468 (± 3089)
Sunhemp	4183 (± 1578)	298 (± 393)	1972 (± 1146)	185 (± 215)	3627 (± 578)	469 (± 384)	3337 (± 565)	302 (± 418)
Velvet bean	3286 (± 1229)	2502 (± 1121)	1585 (± 239)	242 (± 247)	2015 (± 389)	712 (± 222)	1706 (± 138)	1441 (± 184)
Sole crop	3740 (± 1402)	-	1561 (± 1226)	-	2768 (± 1344)	-	2573 (± 1402)	-

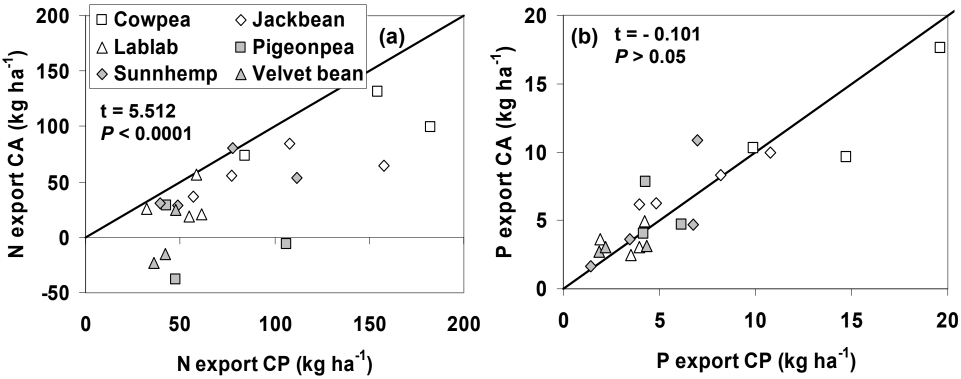

Figure 7. (a) Comparison between conservation agriculture (CA) and current practices (CP) of the quantities of nutrients exported from the field for the entire cotton-sorghum rotation during the 2008-09 season– calculated as the absolute values of the partial nutrient balances – for the different legumes intercropped with sorghum under CA and for (a) N and (b) P. For each graph, a summary of the paired T test comparing export values under CA and under CP is given.

4.3.4. Perceptions by farmers

Farmers perceived minimum-tillage and retention of a mulch of crop residues as having both positive and negative consequences on crop yields, depending on complex interactions with the season and with soil type (Table 6). For example, farmers considered that minimum-tillage reduced loss of soil fertility, but that it led to soil compaction and soil crusting. Similarly, mulching was thought to reduce evaporation, increase infiltration and smother weeds on one hand, but also to carry weed seeds and pests and interfere with weeding activities. Finally, legume intercropping was thought to increase soil fertility and control weeds through the formation of a closed canopy, but also to compete with cereals in some instances and host pests.

Table 6. Perceived impacts of conservation agriculture (CA), ranked by farmers for each technological component of CA during the participatory evaluation in three sites along an anthropogenic gradient in the study area. Ranking was obtained by averaging scores obtained in the three sites.

Perceived impacts
Benefits
Minimum-tillage
1. Controls erosion
2. Saves labour during land preparation
3. Increases precision of input application (e.g. seeds)
4. Maintains fertility
Mulching
1. Reduces water evaporation
2. Increases nutrients available to the succeeding crop
3. Controls weed
4. Reduces erosion
5. Saves labour required for gathering and burning stover
6. Increases infiltration
7. Increases fertility by enhancing termite activity
Legume intercropping
1. Increases nutrients available to the succeeding crop
2. Increases land and labour productivity
3. Reduces weeds through the formation of a closed canopy
Problems
Minimum-tillage
1. Increases abundance of weeds, particularly late in the season
2. Increases soil compaction (particularly of sandy soils) and surface crusting
Mulching
1. Increases termite and millipede destruction on the succeeding crop
2. Increases weeds (maintains seeds of weeds)
3. Complicates planting and weeding/cultivation
4. Exacerbates water-logging during wet seasons
5. Shelters snakes, scorpions and pests (e.g. mice)
Legume intercropping
1. Decreases cereal yield (particularly with velvet bean and creeping cowpea)
2. Hosts crop pests (e.g. crickets)

Important comments were made during the participatory evaluations regarding the local adaptation of CA. First, the advantages of minimum-tillage were said to depend on soil type. Minimum-tillage was said to reduce water infiltration on sandy soils (Table 6), which are poorly structured and prone to surface crusting, but to give good results on heavy clay soils, which form cracks during the dry season. Clay soils are also hard to plough when wet. Second, the benefits of minimum-tillage on soils that crust – i.e. most soils in the study area - will depend on the rainy season. On these soils, ploughing was said to lead to waterlogging and depress yields during wet years, but to maximize water infiltration and improve yields during dry years. Therefore, minimum-tillage was perceived as a way to minimize infiltration and ‘shed’ ‘excess water’ during wet years, whilst ploughing was perceived as a way to maximize water infiltration during dry years. Third – whilst short-term benefits of ploughing were recognized (i.e. weed control, improved water infiltration, avoidance of compaction problems) – long-term benefits of minimum-tillage were also acknowledged (i.e. maintenance of soil structure and soil fertility). This was said to be particularly true for sandy soils, as clay soils were ‘resistant to the plough’. To capture both short-term benefits of ploughing and long-term benefits of minimum-tillage, a rotation between these two forms of land preparation was proposed, with a recommendation of 1-2 years of consecutive ploughing, followed by 2-5 years of minimum-tillage. Ploughing was said to be required after every 2 to 5 years to avoid compaction problems.

4.4. DISCUSSION

4.4.1. Good agronomy is more important than tillage or soil cover

No beneficial or detrimental effect of CA compared with CP could be observed on cotton and sorghum yields in on-farm trials over the three seasons (Figure 2; Table 3; Table 4). In the three statistical models (GLMMs), a compelling effect of the factor ‘trial’ was found on cotton and sorghum yields (Table 4). This factor represents farm-specific circumstances, corrected for tillage, soil cover, legume intercropping, soil type, planting date, time and frequency of weeding and frequency of pesticide treatments. Thus, farm management appeared to have an overriding effect on cotton and sorghum productivity, above factors that differentiate CA and CP.

The diversity of management practices was larger in farmers’ cotton fields than in the on-farm trials, in particular the fertilisation rates and the modes of minimum-tillage: direct-seeding using a Fitarelli seeder, ripping using a Magoye ripper, and opening of shallow planting holes by hand-hoe. Yet, in agreement with the results from the on-farm trials, the analysis of farmers’ cotton fields demonstrated the importance of management factors other than tillage and soil cover in explaining cotton yields. For instance, differences between CA and CP in terms of attainable RUE, though significant, were negligible with respect to the variability of the attainable RUE as a function of planting date, date of first weeding, number of weeding operations or number of pesticide treatments (Figure 4). Similarly, with the exception of land preparation during the wetter 2009-10 season, tillage and soil cover did not appear as import factors explaining the variability of cotton yields using classification trees. Therefore, our results suggest that good agronomy (i.e. adequate fertilisation, timely planting and weeding, adequate frequency of weeding operations and pesticide treatments) had a stronger effect on crop yield than the choice between CA or CP. The only exception was during the wetter season when CA caused decreased yields due to waterlogging.

The lack of differences in cotton and sorghum yields between CA and CP is probably because the current farming practices used by many farmers, and particularly the poorer farmers, do in fact not differ much from CA in terms of tillage management. For instance, many farmers do not plough but plant using a form of hand-hoe minimum-tillage. The lack of differences between CA and CP can also be explained by the fact that water infiltration is not improved with CA under the conditions of our study (Figure 5). The study area is relatively flat, and water losses through runoff do not represent an important component of the water balance. Water runoff rates of 40 to 80 mm per year were recorded (Figure 5) which represented only 6 to 8% of the total rainfall. Only small quantities of crop residues, or no residue at all in some instances, could be retained as mulch. On average there was 770 kg ha^{-1} (± 980 kg ha^{-1}) of mulch in on-farm trials, and only 15% (± 17%) soil cover in farmers' cotton fields managed using CA. Moreover, the residues decomposed rapidly after the first rains, due to the warm moist conditions and the presence of termites. Thus, surface mulches were not thick enough to alter water runoff and evaporation. Derpsch (1988) suggest that 4 to 6 t ha^{-1} of surface residues are required to alter rainwater crop productivity. Other studies in sub-Saharan Africa also noted the importance of mulching, as minimum-tillage on a bare soil often leads to yield penalties (Naudin et al.; 2010; Enfors et al., in press). The soils of the study area are prone to surface crusting, meaning that infiltration may be reduced by minimum-tillage compared with ploughing.

4.4.2. CA 'sheds' rather than harvests rainwater

In this study, the quantities of residues that were retained as mulch were insufficient to avoid soil crusting. As a result, there was higher runoff under CA than under CP on the soil with a coarser texture (Farm 1, Figure 5). On the finer-textured soil less susceptible to crusting, no difference between CA or CP was found in the amount of runoff (Farm 2, Figure 5). Aina et al. (1991) suggested that minimum-tillage may be detrimental on soils susceptible to crusting, regardless of the amount of surface mulch. During the participatory evaluation of CA, farmers indicated that increased soil compaction and surface crusting were problems with minimum-tillage, particularly on sandy soils (Table 6). Farmers perceived CA as better adapted to clay soils. Pillai and McGarry (1999) suggest that naturally-occurring shrink and swell cycles in clay soils can maintain/increase infiltration, even in the absence of tillage.

The proneness of soils in the study area to crusting when not tilled can lead to different crop yield responses to CA, depending on the rainy season. Our results suggest an important interaction between CA and season on cotton yield. During the drier 2009-10 season cotton yielded significantly more under CP than CA, in both the on-farm trials and in farmers' cotton fields (Table 3). In contrast, no differences in cotton yield were observed during the two other wetter seasons, resulting in a significant season by treatment interaction (Table 4). Farmers suggested the same: CA was said to be detrimental – on the soils of the study area prone to crusting and compaction during dry years - i.e. when water is more limiting - due to reduced water infiltration and the resulting water stress. Ploughing was said to lead to better yields during these years, because it maximizes water infiltration. In contrast, the increased water runoff in the absence of ploughing was said to be an advantage during wet years, as it would prevent waterlogging. This goes against the usual claim that CA improves crop water-use efficiency (Scopel et al., 2004; Rockström et al., 2009; Thierfelder and Wall, 2009). For farmers of the study area, CA appears to be rather a 'water-shedding' technology, than a water-harvesting technology. Similarly, Enfors et al. (in press) found a positive effect of CA on maize yield during good rainy seasons (i.e. with high and/or well distributed rainfall) but not during seasons with poor rainfall.

4.4.3. Benefits of residue retention and legume intercropping

More crop residues were produced and retained in the fields managed through CA than through CP (Table 5). In particular, legume intercropping contributed significantly to the production of mulch for the subsequent cotton crop (Table 5). The legumes appeared not to compete with sorghum (Table 4), and legume biomass production can be considered a ‘bonus’ of the CA systems. Other studies in similar agro-ecologies have also demonstrated that crop biomass production can be doubled by intercropping a secondary crop with the cereal, without a yield penalty for the cereal (Naudin et al., 2010).

Amongst the legumes tested, pigeonpea appears to be the legume best-suited for intercropping in CA as it produces large quantities of N-rich biomass during the dry season, most of which is still present in the field at the onset of the succeeding season. It also produces edible grain and the development of pigeonpea farming in Africa offers interesting market opportunities (Odeny, 2007). However, for these benefits to be realized, communal grazing during the dry season needs to be controlled. Legume intercropping may have additional short- and long-term benefits that were not directly measured in this study. First, it enables the formation of a closed canopy to control weeds (Table 6), as observed when crop density is increased (Olsen et al., 2005). Second, the mixing of N rich residues with N poor sorghum residues reduces the C:N ratio of the combined mulch, therefore avoiding potential problems of temporary N immobilization by micro-organisms (Palm et al., 2001). Third, the additional organic input may increase the soil C content in the long-term (Six et al., 2002; Stewart et al., 2007; Corbeels et al., 2006). There is increasing evidence that minimum-tillage alone is insufficient to increase soil C, and that increased inputs of organic material are required (Corbeels et al., 2006; Luo et al., 2010). This is particularly the case in coarse-textured soils such as those prevalent in the study area, as sandy soils offer little structural (aggregate) protection (Chivenge et al., 2006). Minimum-tillage changes the distribution of soil C in the soil profile, concentrating it in the topsoil (Baker et al., 2007; Luo et al., 2010).

The amount of sorghum and legume residues that remained in on-farm trials at the end of the dry season was relatively low- only 2025 ±1065 kg ha^{-1} and 773 ±1337 kg ha^{-1}. Larger quantities of mulch than those achieved may increase the short-term performance of CA, by stimulating macrofauna activity and thus preventing soil crusting (Lal, 1988; Mando et al., 1999). Through higher crop biomass production, it may be possible to increase the quantity of residues left in the field after the dry season, as a large fraction of the residues produced during the rainy season could be retained as mulch despite of the abundance of termites and the high prevailing temperatures in the study area (Figure 6). A prerequisite is the protection of the fields from grazing animals. Moreover, long-duration legumes produced the bulk of their residues during the dry season (Table 5). Therefore, better management (e.g. use of mineral fertilisers, timely weeding, crop protection) with e.g. the use of other intercrops can thus increase the quantity of mulch. For example, in a study conducted under similar agro-ecological conditions in northern Cameroon it was possible to produce up to 5 t ha^{-1} mulch with improved crop management practices (Naudin et al., 2010).

4.5. CONCLUSIONS

Under the existing farm conditions in the Zambezi Valley, CA had in general a neutral to negative effect on cotton and sorghum productivity compared with CP. Good agronomy, and in particular adequate fertilisation and crop protection appeared central for obtaining good yields rather than tillage and soil mulching. CA seems to be only beneficial in relatively intensive cropping systems, as a means to use external inputs and energy more efficiently. As Gowing and Palmer (2008) stated “CA does not overcome constraints on low-external-input systems”. CA reduced water infiltration during wetter years, contrary to what has been stated elsewhere (McHugh et al., 2007; Rockström et al., 2009; Thierfelder and Wall, 2009; Naudin et al., 2010). This was due to the susceptibility of the coarse-textured soils in the study area to surface crusting which resulted in a ‘water shedding effect’ during wet years that was perceived to be an advantage by farmers. During dry years however, a water harvesting effect was obtained with ploughing, not with CA. Such complex interactions between soil types, seasonal effects and tillage demonstrates the necessity of flexibility and pragmatism in the design, evaluation and diffusion of cropping systems based on the principles of CA. CA should not be seen as an alternative to ploughing and other current farm management practices, but rather as an addition to the basket of technical options available to farmers.

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Chapter 5

Failing to Yield? Ploughs, conservation agriculture and the problem of agricultural intensification. An example from the Zambezi Valley, Zimbabwe

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Chapter 5

ABSTRACT

Agricultural intensification, or increasing yield, has been a persistent theme in policy interventions in African smallholder agriculture. This article focuses on two hegemonic policy models of such intensification: (1) the ‘Alvord model’ of plough-based, integrated crop-livestock farming promoted in colonial Zimbabwe, and; (2) minimum-tillage mulch-based Conservation Agriculture (CA), as currently preached by a wide range of international agricultural research and development agencies. An analysis of smallholder farming practices in Zimbabwe’s Zambezi Valley reveals the limited inherent understanding of farmer practices in these models. It shows why many smallholder farmers in southern Africa are predisposed towards extensification rather than intensification, and suggests that widespread CA adoption is unlikely.

Keywords: Zimbabwe; Alvord; conservation agriculture; intensification; extensification; labour.

5.1. INTRODUCTION

"*The Gospel of the Plow means working together with God, in order to get good crop yields while at the same time we take good care of the soil (…) In order to bring this about, a spirit of reverence for the soils must be created, which is… a sort of religion (…) The heathen African dug his land while standing trees, skeletons, stumps and fallen trees were scattered all about. …he planted the seed and trusted to the witchdoctors, rainmakers, ancestral spirits and demons to do the rest. (…) if those people could only be taught the Gospel of the Plow...*" (Emery Alvord, Agriculturalist for Natives in Southern Rhodesia from 1926 to 1950)[1]

"*Conservation Agriculture [CA]… can be difficult for many people to accept because it goes against many of their cherished beliefs. How can crops be grown without plowing the land? Overcoming this mindset of the need for plowing is a major step in achieving successful CA systems.*" (Zimbabwe Conservation Agriculture Taskforce, 2008:5)[2]

"*God has revealed a very simple conservation farming method with an implementation management teaching, which when applied, helps people to apply the Gospel to their lives.*" (Foundations for Farming, formerly Farming God's Way website, 2010)[3]

The above quotes signal two persistent themes in the history of agricultural intervention in the smallholder sector in southern Africa. First, the perception that smallholder farmers' practices are backward, destructive, and in need of revelation. Second, the religious zeal by which (colonial) interventionists have sought to persuade African farmers to adopt more intensive agricultural practices, that is, to increase yield (harvest per surface area). This is most evident in Zimbabwe where an agricultural intensification package was promoted as early as the 1920s. Emery Alvord, an American missionary, turned the plough into a symbol of modern agriculture while promoting a package of integrated crop-livestock farming. It became the hegemonic model for African farming underpinning a wide range of policy interventions in African agriculture in colonial Zimbabwe (Wolmer and Scoones,

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[1] Quote from: E.D. Alvord (not dated) *The Gospel of the Plow or A Guided Destiny (unpublished autobiography of the Agriculturalist for Natives),* National Archives of Zimbabwe (NAZ).

[2] The Zimbabwe Conservation Agriculture Taskforce is a collaborative effort of the FAO, ICRISAT, CIMMYT, the EU, DfID and a number of (faith-based) international donor organizations.

[3] www.foundationsforfarming.org (visited 23 November 2010).

2000; Bolding, 2004). Such interventions initially took the form of 'demonstrations' to African farmers, but religious zeal increasingly made way for compulsion.

Contemporary attempts at agricultural intensification in African agriculture continue to be informed by conservationist concerns. Yet, in contrast to the plough-based Alvord model, current interventions are based on minimum-tillage and retention of a mulch of crop residues, through a technical package referred to as 'Conservation Agriculture'[4], CA. A powerful lobby of international donors, development and agricultural research agencies crusades to extend what has become the current hegemonic policy model for agricultural intensification. Collaborating in a taskforce, NGOs and donors promoting CA have garnered considerable financial and political support in Zimbabwe[5]. The model has even been included in the National Agricultural Policy of Zambia (MACO, 2004), and recognised by Zimbabwe's president as a means to 'make savings on draught power requirements and minimise land degradation'[6].

This article analyses these two hegemonic policy models for agricultural intensification from a comparative perspective. Highlighting some striking similarities in extension approach, notably the invocation of God and the use of science-based demonstration plots, the main focus is on the ideas and inherent assumptions about smallholder farming systems underpinning both models. It is suggested that protagonists of CA have learned little from the earlier, colonial attempts to intensify smallholder agriculture as spearheaded by Alvord. While resource conservation and sustainable production have remained persistent concerns guiding interventions in smallholder agriculture, so remains the disregard for the socio-economic

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[4] The FAO defines Conservation Agriculture as: '…resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment. www.fao.org/ag/ca/1a.html (visited 23 November 2010).

[5] During the 2009-2010 season, 180,000 Zambian smallholders received support to practice conservation agriculture (www.conservationagriculture.org, visited 23 November 2010), while in Zimbabwe a consortium of donors supported more than 110,000 farmers to do so (www.prpzim.info/resources/PRP%20Stories%20of%20Change%20-%20John%20Mhofu.pdf, visited 23 November 2010).

[6] Speech for the official opening of the Parliament of Zimbabwe in July 2010 (Government Intervention Key for Revival of Agriculture Sector, *The Herald*, 20 July 2010).

circumstances and the rationale of African smallholder practices[7]. Like in Alvord's days, interventions take a 'one size fits all' form that ignores the diversity of existing farming practices. Farming Systems Research (FSR) and subsequent participatory approaches – epitomised by the 'Farmer First' approach (Chambers and Ghildyal, 1985) – appear to have had no bearing on the development and extension of CA to smallholder farmers in Africa. Rather than questioning the agronomic merits of the technologies promoted, this article is therefore concerned with the *suitability* of CA technologies to the socio-economic realities of smallholder farming systems in southern Africa.

Malnutrition and population growth (2.3% per annum) underline the need for increased agricultural production in sub-Saharan Africa. As the most suitable areas for agriculture are already cultivated, agricultural intensification seems a logical strategy (World Bank, 2008). Yields in smallholder farming systems of southern Africa remain appallingly low despite technological innovations such as improved seeds and fertilisers. Average cereal yields in smallholder agriculture have stagnated in Africa since the 1960s, whilst they have nearly doubled in the rest of the world (Huang et al., 2002). Large-scale commercial farming on the African continent also performs considerably better than the smallholder sector. For instance, in Zimbabwe in the period 1970–2000, maize yield averaged 0.8 t ha^{-1} (std. dev. 0.4 t ha^{-1}) for the smallholder sector and 3.9 t ha^{-1} (std. dev. 1.0 t ha^{-1}) for the commercial farming sector (Andersson, 2007). Differences in agricultural potential go a long way in explaining this disparity, as the best agricultural lands were expropriated for white settlers during the colonial era. However, even in similar agro-ecological circumstances, huge differences in yields are observed between the majority of smallholder farmers and the best performing ones (Zingore et al., 2007), suggesting that while a potential for higher land productivity exists, it is not realised because of social and economic factors (Djurfeldt et al., 2005). By inferring from an analysis of the labour, cash and price constraints, as well as risk mitigation strategies of smallholder farmers in northern Zimbabwe, it is shown why many smallholder farmers

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[7] Conservation Farming packages as promoted by ICRISAT perhaps constitute an exception as they specifically target food insecure farmers with no cattle and plough, acknowledging these farmers' need to reduce labour peaks (see Twomlow et al., 2008b).

in southern Africa do not – or are not able to – intensify their production, but instead, are disposed towards agricultural extensification. Appreciating the rationale of existing farming practices of smallholder farmers, it is suggested that many farm practices promoted under the banner of CA are likely to befall a similar fate as Alvord's recommendations for agricultural intensification.

This article is divided in two parts. Part 5.2. compares the Alvord model and CA, looking at the ideas and assumptions underpinning the technologies promoted, the extension approaches deployed, and the fate of the Alvord model some 80 years after it was introduced. Part 5.3. shifts the attention to smallholder farming practices and their embedding in a wider socio-economic environment. It builds on extensive fieldwork in Dande Communal Area in the Zambezi Valley, a sparsely-populated agricultural frontier in northern Zimbabwe, characterised by increased competition over land between nature conservation and agriculture (Chapter 2). As elsewhere in southern Africa, the extension of CA in this area is seen as a way to enable a sustainable increase in yields with minimum negative consequences for the environment.

5.2. MODELS OF AGRICULTURAL INTENSIFICATION

5.2.1. Theoretical models of agricultural production growth

Two ideal-typical models to increase agricultural production may be distinguished. First, increased farm output may be achieved through 'extensification'; extending the area under cultivation, while maintaining or reducing inputs per unit area (Figure 1a). Yields remain stable or decrease whilst water and nutrient losses per unit area often remain unaltered (Erenstein, 2006). Second, production increases may be achieved by means of intensification. Yield is increased through greater capital and/or labour input per unit area. The 'Green Revolution', which drove massive production increases in Asia (World Bank, 2008), is a typical example of capital-driven intensification (that is use of hybrid seeds, chemical inputs and mechanization; Figure 1b). 'Ecological intensification' increases resource use efficiency - for example light, water and nutrient use (Figure 1c; Giller et al., 2002; 2006). It revolves around the idea of sustainable production, seeking to increase land productivity while conserving natural resources, that is soil, water, and surrounding wild nature. However, ecological intensification often requires more labour per unit area.

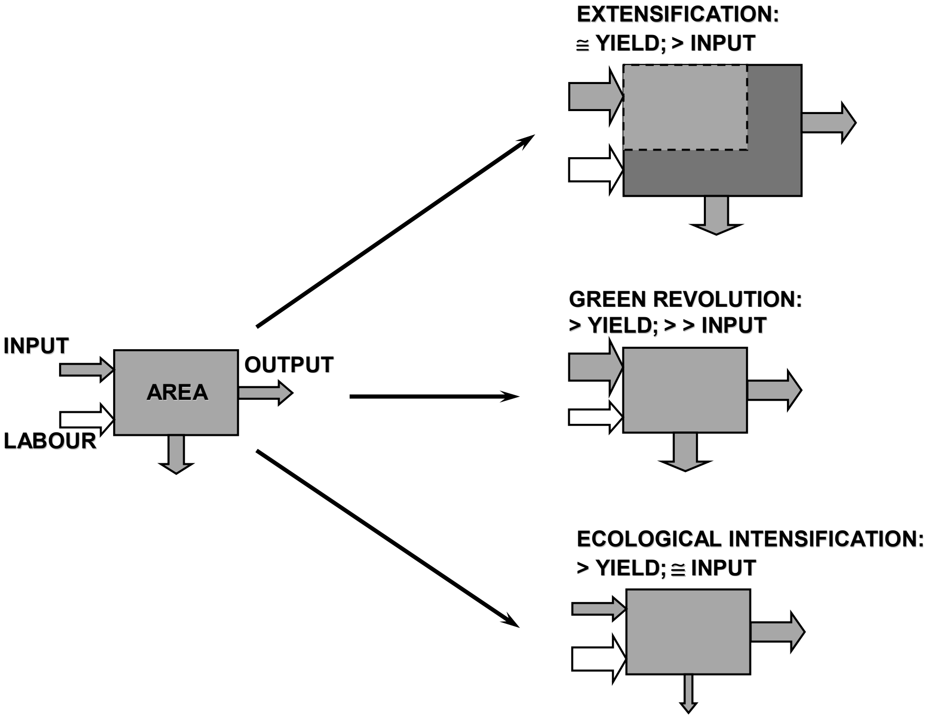

Figure 1. Three pathways to increase production: Extensification, Green Revolution (increased use of external inputs) and Ecological intensification (improved resource-use efficiency). Downward arrows represent water and nutrient losses. Sizes of the various arrows are proportional to the corresponding fluxes. Impact of the three pathways on yield (i.e. harvest per surface area) and quantity of input used per surface area is described by '≅', meaning the value remains roughly constant; '>', meaning the value increases; and '>>', meaning the value increases greatly.

Farming technologies are often classified as either land-saving or labour-saving, that is, as resulting in agricultural intensification and extensification respectively (Erenstein, 2006). In practice, however, technologies may be used differently, rendering a clear-cut classification problematic. Intensification and extensification are seldom mutually exclusive. For instance, whereas chemical fertilisers are generally seen as a land-saving technology, their massive adoption by Zimbabwean smallholder maize growers in the mid 1980s went hand in hand with an expansion of land cropped with maize (Andersson, 2007).

Besides farming technologies, socio-economic circumstances may also direct farm development towards intensification or extensification. First, whilst agricultural intensification is often triggered by land scarcity, extensification is a common strategy when sufficient land is available (Boserup, 1965; Erenstein, 2006). Second, proximity to urban markets increases the incentives for intensification, reducing costs for input procurement and marketing (Woodhouse, 2002; Erenstein, 2006). Similarly, unfavourable market access in remote areas may hamper intensification (Woodhouse, 2002; Bamire and Manyong, 2003).

Below we discuss the Alvord and CA models for the intensification of African smallholder agriculture. Although developed in different historical contexts and based on different technologies – most notably, opposing views regarding use of the plough – the paragraphs below reveal a striking historical continuity in their disregard for the rationale of existing farm practices, and in their extension approach.

5.2.2. Segregation, modernization and erosion control: the 'Alvord model' of agricultural intensification

Emery Alvord's appointment as "Agriculturalist for the Instruction of Natives" in 1926 was the result of a proposal for the industrial development of Africans, formulated by the Chief Native Commissioner, Mr. Keigwin (Bolding, 2003:37). Agricultural intensification in the lands set aside for African occupation – the Native Reserves (now called Communal Areas) – was Alvord's key task. He was to,

"*… develop Native Reserves so as to enable them to carry a larger population, and so avoid, as far as possible, the necessity for acquisition of more land for native occupation.*" (Chief Native Commissioner, 1932)

Alvord's efforts were thus part and parcel of the colonial governments' racial segregation policies. Concentrating more people in the Native Reserves meant that permanent cultivation had to replace the common practice of shifting cultivation. While working as a missionary at Mount Selinda on the country's eastern border, Alvord developed a set of agricultural practices that could increase yields and modernise African agriculture (Page and Page, 1991; Davis, 1992). Laid down as 'commandments' for permanent agriculture (Bolding, 2004: 53), the 'Alvord model' of modern agriculture became an integral part of the civilizing enterprise colonial officials and missionaries such as Keigwin and Alvord had set themselves.

Emblematically represented by the plough, a set of blanket recommendations consisting of five key practices – ploughing, manuring, crop rotation, sole cropping[8] and planting in lines – sought to sustain the permanent cultivation of the generally poor soils of the Native Reserves (Table 1a, Page and Page, 1991; Davis, 1992). In agronomic terms, this farming model aimed to increase both input supply to the crop (for example manure application) and resource use efficiency through improved crop management (for example planting in lines).

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[8] Agronomists generally use "sole cropping" to refer to the practice of planting one crop in one field.. In Alvord's days this practice was known as mono-cropping, which is now often taken to mean one crop in a field continually year after year.

Table 1. Components of a) the Alvord model and b) Conservation Agriculture and their impact on yield and labour needs (+/0/- indicate positive, neutral and negative impacts, respectively; arrows indicate implications)

a)

Components	Yield	Labour needs
Ploughing	+ (1)	-
Manuring	+	+ (2)
Crop rotation (with legumes)	+ (4)	0
Sole-cropping/tree removal (3)	+ (5)	- (6)
Planting in lines/cultivating(7)	+ (8)	- (8)

(1) reduces weed population, increases mineralization of organic matter, increases water infiltration
(2) extra-labour required for manure collection, composting and transport to the field
(3) the dashed arrow indicates that ploughing implies tree removal, but not necessarily sole-cropping
(4) controls pest, increases nitrogen supply in the case of legumes
(5) reduces competition between crop species and between crop and trees
(6) efficient operations (one crop per field means uniform fertilizer requirements, harvesting dates, etc.)
(7) cultivating indicates weeding using an animal-drawn cultivator or plough between the crop rows
(8) makes efficient weeding possible

b)

Components	Yield	Labour needs	
		Land Prep and Planting	Weeding
Minimum tillage	+/- (1)	+	- (2)
Mulch retention	+/- (3)	- (4)	+/- (5)
Crop rotation (with legumes)	+ (6)	0	0
Cover crops	+	-	+/-

(1) preserves soil organic matter and soil structure, but may also lead to soil compaction and crusting
(2) generally increases the number and intensity of weeding operations
(3) may reduce soil crusting, may increase water infiltration and reduce evaporation, but may also increase waterlogging, leaching and immobilization of nitrogen
(4) generally makes planting more difficult
(5) may control weeds by shading but mulch may contain seeds of weeds and mulch makes weeding by hand or cultivator more difficult
(6) controls pests, increases nitrogen supply in the case of legumes

5.2.2.1. From ‘demonstration’ to compulsion

Underpinned by an ideology of racial segregation and paternalistic development, Alvord’s package for ‘modern agriculture’ was promoted in a number of ways. At agricultural training centres in Domboshawa, north of Harare, and in Tsholotsho, in the south, mission-educated Africans were trained to become ‘agricultural demonstrators’ (extension workers). They were placed in the Native Reserves to demonstrate the standardised set of modern husbandry practices in the fields of those willing to adopt ‘modern agriculture’. Alvord emphasised that demonstrators were to work the plots together with the plot owners, building on ‘learning by doing’ and ‘seeing is believing’ (Bolding, 2003: 44, 46). A second policy was the Master Farmer programme, a training programme for farmers that has survived well into the post-colonial era (see Bolding, 2004).

As Alvord rolled out his demonstration and Master Farmer programmes, land degradation in the Native Reserves seemed only to worsen in the eyes of colonial government officials, including Alvord himself. Fuelled by a visit to the USA during the Great Dust Bowl in 1935, colonial interventions in African smallholder agriculture became increasingly informed by conservationist concerns (McGregor, 1995; Wolmer and Scoones, 2000). Although blamed on African smallholders’ misuse of the land, land degradation in the Reserves was partly of the colonial governments’ own making. More and more people were pushed onto these degradation-prone lands (Andersson, 2007: 683). In addition, the alarming rates of soil erosion were often based on landscape-level aggregations of plot-level estimates, thus ignoring the complex patterns of deposition across landscapes (Campbell et al., 1997)[9].

However ill-informed, erosion rates were used to justify more stringent soil conservation policies such as the Natural Resources Act of 1941, which empowered Native Commissioners to issue orders on – ‘Alvordian’ – farming methods to be used, and compel African farmers to construct soil conservation works such as contour ridges (Phimister, 1986; Machingaidze, 1991). Alvord’s mixed farming model which integrated crop and livestock production was also the basis of the Native Land Husbandry Act of 1951, which sought to enforce agricultural intensification by individualizing and limiting African farmers’ land and livestock holdings (Machingaidze, 1991; Phimister 1993; Andersson 1999).

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[9] The strategic use of soil erosion figures to argue for urgent action is exemplified by Whitlow (1987), who mentioned soil losses of 40 tons ha^{-1} $year^{-1}$ in Zimbabwean Communal Areas. Disregarding the accuracy of the figure, this apparently massive figure translates to top soil loss of 2.7 mm per year (assuming a bulk density of top soil of 1.5 g cm^{-3}). Such strategic use of soil erosion figures re-surfaces in contemporary CA promotion messages (Field Observations, Foundations for Farming Open day, River of Life Church, Harare, 1 February 2011).

5.2.2.2. Alvord's gospel, technology adoption and the plough

Demonstrated and enforced, Alvord's standardised model for 'modern farming' has left its legacy. Zimbabwean smallholders have adopted and adapted some or all five key practices –ploughing, manuring, crop rotation, sole cropping and planting in lines – despite criticism on their agronomic merits, applicability, and sustainability (for an overview, see Bolding, 2003). For instance, already during his time in office (1926-1950), Alvord had to acknowledge that his manure recommendations to maintain soil fertility in permanently cultivated lands were ill-suited. Most smallholder farmers simply did not have enough cattle (12-16 head per arable hectare) needed to supply the required rate of manure (Bolding, 2003: 51).[10] In 1965, it was estimated that less than half of the Native Reserve farmers owned any cattle at all (Machingaidze, 1991). Alvord's crop rotations were equally unsuited to the conditions of smallholder farmers as they did not take into account the different labour requirements, dietary needs and preferences or marketability of different crops (see below). Ploughing, sole-cropping and planting in lines have, however, become widely practised and regarded as proper farming practice by smallholder farmers. But did these 'Alvordian' technologies result in agricultural intensification? These three components of the package do have land-saving properties – that is that may lead to intensification – but they also have labour-saving properties – that is that may lead to extensification (Table 1a). In many areas where population was sparse, they enabled farmers to manage larger lands, and if close to markets, this gave rise to a category of so called 'plough entrepreneurs', who opened up extensive land areas to increase production (Ranger 1985: 36; Phimister 1988: 72-79,143). Colonial administrators noted:

> "*…the native is rapidly taking to the plough and the use of the plough is becoming almost general throughout the country… the average yield in bags per acre is deplorably low and has decreased with the advent of the plough.*"[11]

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[10] Alvord recommended 10-15 tons kraal manure per acre (37 tons per ha) every four years (Grant, 1976: 252). Manure use was also limited as it increased weed infestation (Bolding, 2003: 52), and its effectiveness depended on soil type and rainfall conditions (McGregor, 1995)

[11] Colony of Southern Rhodesia Statistical Bureau (1932) *Official Yearbook of the Colony of Southern Rhodesia no.3*, Salisbury, Government Printer. p.670. In this yearbook, average grain yield was estimated to be 700 kg ha^{-1} in 1902, and decreased to an estimated 500 kg ha^{-1} in 1930. The number of ploughs in the Native Reserves increased exponentially, 'and by 1940 nearly every family owned one' (Scoones, 1997; Palmer, 1977). In that year there were about hundred agricultural demonstrators based in the Native Reserves (Davis, 1992: 53).

In those areas where population had become dense - as a result of the colonial state's segregationist land policies - such an extensification-based development path was less feasible. It was in these areas that Alvord's demonstrators 'tended to secure the greatest degree of cooperation from cultivators' (Phimister 1988: 275), adopting labour demanding components such as manuring. But even in these densely populated areas, demonstrators were generally welcomed by only a few farmers, most notably the entrepreneurial ones, as they reduced their labour burden. In some cases demonstrators even assumed the role of farm managers for entrepreneurial farmers (Ranger 1985:62; Phimister 1988:143-145). The adoption of the plough for agricultural extensification thus has to be understood in the context of smallholder's production constraints and market opportunities. Both were at least partially structured by colonial land and marketing policies.

It is perhaps somewhat ironic that in his autobiography, 'The Gospel of the Plow', Alvord took the plough as the symbol of his life-time efforts to intensify African land use. In 1926, when Alvord was appointed, it was estimated there were already over 27,000 ploughs in use in the Native Reserves. In the following five years this number almost doubled to over 53,000, when a mere 37 demonstrators were working in the Native Reserves (Government of Southern Rhodesia, 1952). Alvord and his demonstrators were thus not responsible for the rapid uptake of the plough by African farmers. Alvord referred to the rise of the plough as a mixed blessing, lamenting its 'misguided' use; extensive ploughing could increase soil erosion and farmers who opened up large tracks of land with the plough, could often not manage the additional hand-weeding (Bolding, 2003: 55-56). Nevertheless, the success of African smallholders' extensive market production of maize brought them in direct competition with white settler farmers. The latter turned against colonial officials like Alvord for stimulating Africans to produce. The settler state yielded to pressures of the white farmers, and introduced discriminatory marketing legislation such as the Maize Control Act (1931), which reduced market prices for African producers. Such state intervention in markets did not always cause reduced market production: 'The percentage of African sales to total African production and to total sales increased significantly' in the 1930s, as farmers tried to sustain their income by producing more (Phimister 1988:186). State-induced falling market prices could thus contribute to agricultural extensification as farmers tried to reduce costs. For Alvord, however, it was the lack of grain markets for African producers that was to blame for the failure of intensification (Stocking, 1978; Page and Page, 1991; Davis, 1992). Rather than Alvord's recommendations and extension programmes, the growing population concentrated in the Native Reserves that eventually forced smallholder farmers to cultivate the same land permanently. Alvord's recommendation to use manure followed as an – insufficient – response to declining yields, as did the use of mineral fertilisers. Having had no regard for the production constraints of smallholder farming systems, it can be concluded that in his time (1926-1950), Alvord's package for agricultural intensification was largely a failure, as it was diverted for extensification. Yet the legacy of his 'Gospel of the Plough' is immense, as the next sections will reveal.

5.2.3. From plough adoption to abandonment: what has changed?

5.2.3.1. Stemming land degradation through Conservation Agriculture

Conservationist concerns continue to inform agricultural intervention in the post-colonial period. Now framed in terms of an eroding natural resource base and biodiversity loss, underpinning contemporary policies is the persistent idea that African farming practices are both unproductive and destructive. Not surprisingly, Zimbabwe has been fertile ground for the introduction of Conservation Agriculture (CA). Based on the simultaneous application of three principles – minimal soil disturbance, permanent soil cover, and crop rotations (www.fao.org/ag/ca; Table 1b) – this model of ecological intensification (Figure 1c) has recently gained momentum in southern Africa following its successful adoption on large-scale mechanised farms in South America, North America and Australia (Kassam et al., 2009). In the latter, CA depended on use of labour-saving herbicides (unlike the hand-hoe basin-based packages promoted to Zimbabwean smallholders). It may be seen as a new gospel, this time to abandon the plough[12]. The CA principles of minimum soil disturbance, achieved through minimum-tillage, and permanent soil cover through retention of a mulch of crop residues are interdependent practices (as tillage would bury the mulch). Other components of the technological package can be viewed as

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[12] http://www.foundationsforfarming.org/Groups/104827/Foundations_for_Farming/The_Foundation/The_Foundation.aspx (Visited 23 November 2010)

consequences (Figure 2). For example, crop rotation becomes necessary as crop residues retained on the soil as mulch may carry pests and diseases.

Recent projects and training manuals promoting CA evidence a tendency to include more and more technological components. For instance, the Foundations for Farming[13] promotes composting as part of the CA package, ICRISAT includes fertiliser micro-dosing (Twomlow et al., 2008a), while ICRAF promotes 'Conservation Agriculture with trees'[14]. Although such additions evidence the popularity and strategic value of the CA concept for donor-dependent research and development organizations, these additions are also responses to the ambiguous impact of some CA components on land and labour productivity (Table 1b). In order to increase the suitability of CA to smallholder farming systems, new technical components are constantly added in an attempt to increase benefits, or to overcome the negative effects on crop production. Adopting CA thus results in a cascade of technologies to be adopted, and possibly, in a complete overhaul of existing practices (Figure 2). Hence, more than Alvord's technologies which have been adopted rather independently from one another, CA is a 'technology package' – a set of interrelated components that require wholescale adoption to result in increased production (Table 1b; Figure 2).

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[13] http://www.foundationsforfarming.org/Groups/104832/Foundations_for_Farming/Resources/Resources.aspx (Visited 23 November 2010)

[14] http://www.worldagroforestry.org/regions/eastern-africa/our-projects/conservation_agriculture_with_trees (Visited 23 November 2010)

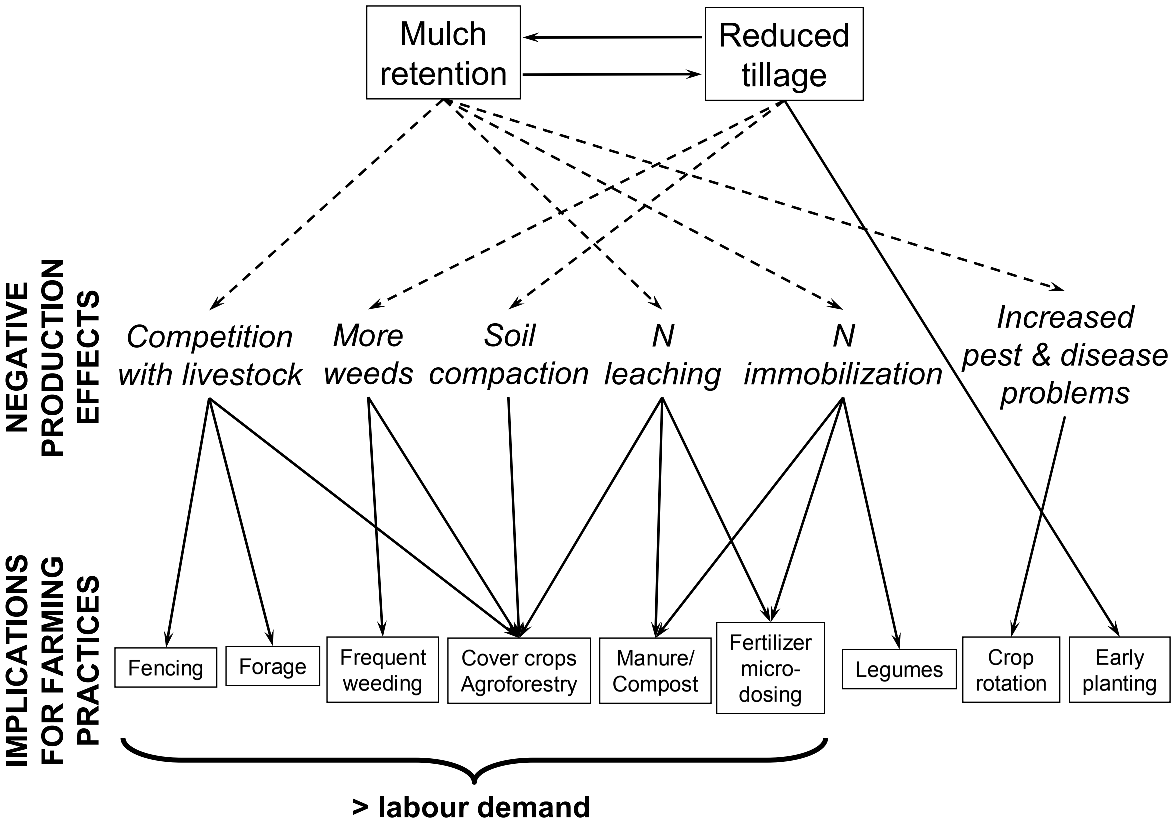

Figure 2. Two main principles of CA and their consequences: possible negative effects on production and implications for farming practices.

5.2.3.2. Conversion justified with science… and extended with faith

The similarities between the Alvord and CA models for agricultural intensification extend beyond a shared ideology of resource conservation and land degrading farm practices of African smallholders. First, protagonists of CA deploy similar extension strategies. For instance, in manuals, documentaries and slide-shows [15], the land degrading and inefficient nature of African smallholder agriculture is often illustrated by pictures of gully erosion and farmers in fields with stunted, yellowish crops. The superiority of the particular CA package promoted is then demonstrated scientifically, through detailed plot-based comparisons of yields, soil erosion, and runoff rates between CA and conventional farming (see for example Thierfelder and Wall, 2009)[16]. As in Alvord's days, quantifications of land degradation are used strategically to communicate urgency, and the need for revelation of 'farmer mindsets' (Zimbabwe Conservation Agriculture Taskforce, 2008: 5; Hobbs et al., 2008).

Invoking God and the gospel constitutes a second congruence between Alvord and CA protagonists. Just as Alvord, who built on mission-educated demonstrators and Christianised 'modern' farmers that were presumably freed of superstitious beliefs like witchcraft (Page and Page, 1991), CA is often financed and extended through churches and faith-based organisations[17]. For instance, Brian Oldreive's River of Life Church has been at the forefront of its promotion in Zimbabwe. Viewing CA as a way to farm 'faithfully', he equated it with 'Farming God's Way' (Oldreive, 2005). Soil cover with mulch is referred to as 'God's blanket'. The promotion of CA thus becomes an evangelizing enterprise.

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[15] An example is the promotional video on www.fao.org/ag/ca (visited 23 November 2010).

[16] Conventional' farming without fertilisers is often compared with CA with – donor supported – fertiliser (see CBDC, 2009). Thus, in these comparisons, the effect of CA *per se* is confounded with the effect of fertilisers. Moreover, CA adoption may be driven by NGO supported inputs more than by the merits of CA itself (Mazvimavi and Dimes (2009). Note the similarity with the valued labour input provided by Alvord's demonstrators.

[17] Faith-based donor organizations such as Catholic Relief Services and Care International, invest substantially in CA promotion, while FAO funds CA trainings at the River of Life church.

<u>*5.2.3.3. A technology-driven approach, disregarding farm practice: ‘one size fits all’*</u>

Arguably, the most striking similarity between Alvord’s model for agricultural intensification and CA is the disregard for the rationale of existing farm practices and for the diversity of socio-economic environments within which they take place. In Alvord’s days, local practices such as shifting cultivation were perceived as wasteful and destructive, to be replaced by ‘modern’ integrated crop-livestock farming, modelled on northern European and American family farms (Wolmer and Scoones, 2000). Similarly, the extension of CA to smallholder farmers in southern Africa is modelled on its success in large-scale, mechanised farms in the Americas and Australia (Giller et al., 2009).

Labelling existing farm practices as wasteful and destructive is, of course, a convenient way to ignore them altogether and justify the blanket recommendation of a new set of practices. Although Alvord’s understanding of African agriculture was considerable (see Alvord, 1929), he operated within the confines of the segregationist colonial state that sought to concentrate Africans in reserves, intensify agriculture there, while simultaneously suppressing smallholder farmers’ market production. Regardless Alvord’s awareness of these contradictory goals of colonial policy, his package was primarily a technological one, ignoring the embeddedness of farming practices in a wider socio-economic environment – its labour constrained production in particular.

Protagonists of CA appear to have learned little from Alvord’s experiences. Again an intensification package is promoted as a ‘one size fits all’ set of technologies, without much attention for existing farming practices and the suitability of the promoted technologies within the socio-economic context in which they are to be adopted.

Below, in Part 5.3., the focus shifts to understanding smallholder farming practices within their specific socio-economic environment. Understanding such practices, it is suggested, casts doubts on the suitability of CA.

5.3. FARMER PRACTICE VS. INTENSIFICATION MODELS

The material presented below builds on fieldwork among smallholder farmers in Dande Communal Area in the Zambezi Valley, a relatively thinly populated area (17 pers. km^{-2} in 2002) in northern Zimbabwe. Here, agricultural intensification is seen as a way to spare land for wildlife conservation beyond the borders of nearby protected areas. The analysis aims to understand better the rationale of African smallholder farming, and particularly, trajectories of farm development. It is shown why Zambezi valley farmers are predisposed towards agricultural extensification.

A survey (n = 176) was used to construct a typology of farmer diversity in the study area, based on their practices and endowment. Four farmer types were delineated: hand-hoe farmers not growing cotton (Type 1); hand-hoe farmers growing cotton (Type 2); ploughing farmers growing cotton and having less than four draught animals (Type 3); and ploughing farmers growing cotton and having four draught animals or more (Type 4)[18]. A sub-sample of 38 farmers representative of farmer diversity was selected for a detailed analysis of decision-making processes governing resource allocation to farming. First, farm labour and cash calendars were constructed. A second round of interviews focused on farmers' perspectives on 'good farming' and his/her preferences for farm development if specific inputs were increased. To facilitate dialogue on these development pathways, a role-playing game was used: the "Dande Game". The Dande Game was made of a board representing the major soil types farmers distinguish: upland loamy sand ("*shapa*") and upland sandy clay loam ("*mutapo*"), and sandy loam near rivers ("*bandate*"). Bottle tops were used to represent one acre plots of the five major crops cultivated in the area – cotton, maize, sorghum, cowpea and groundnut. Production assets such as labour and spans of animal draught power were represented by cards. The game was played by first asking the interviewee to represent the crop-soil type combinations of his/her farm as it was during the previous cropping season. Farmers were then asked how they would change their cropping pattern under various scenarios, such as access to all major soil types, more draught animals, or increased

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[18] The distinction between "hand-hoe" and "ploughing" is based on the mode of land preparation for the main dryland crops. Type 1 and 2 farmers never use animal draught power, while Type 3 and 4 farmers may occasionally use hand-hoes in riverbank fields or in gardens.

labour availability. During the discussions, farmers were asked to reflect on specific technologies associated with CA, that is minimum-tillage, crop residue mulching, crop rotation and intercropping with legumes. Issues discussed during these interviews were also raised in group interviews in three wards along a west-east gradient of increased population density and less tsetse infestation (see Chapter 2): from Angwa Bridge to Mazambara and Mushumbi Pools. This gradient is significant for the understanding of farm diversity as tsetse infestation prevents the use of animal drawn ploughs, while higher population densities may limit farm expansion.

5.3.1. Organizing production: smallholders' disposition towards agricultural extensification

5.3.1.1. Labour constrained production

In southern Africa, farming is often limited by labour rather than land. In Zimbabwe's Zambezi Valley, available animal draught power and manpower are good predictors of farm size (Chapter 2). Hand-hoe farmers (Types 1 and 2) on average cultivate 2.1 ha, while ploughing farmers with one (Type 3) and two animal spans (Type 4) on average cultivate 3.6 and 6.0 ha, respectively.

Southern Africa is characterised by a narrow optimum planting window (Phillips et al., 1998; Raes et al., 2004), while timely first weeding is crucial to avoid problems of crop establishment (Vogel, 1994). As labour calendars evidence, smallholder farming in the Zambezi Valley is characterised by two labour peaks; one at land preparation and planting in November-December, and one at the first weeding in January (Figure 3). For hand-hoe farmers (Type 1 and 2), who generally lack resources to hire labour, the labour peak at first weeding is particularly pronounced. Weeds grow fast and vigorously because of the relatively fertile soils and high temperatures that characterise the Zambezi Valley. For Type 1 and 2 farmers, land preparation and planting are spread over a longer time period, as field clearing and the opening of planting stations can already commence before the onset of the rains. However, weed growth is not controlled by ploughing nor are weeding efforts alleviated by the use of ox-drawn cultivators. In contrast, ploughing farmers (Type 3 and 4) face two labour peaks. These farmers can only start land preparation and planting after the onset of the rains, as ploughing requires moisture to soften the soil. Although ploughing and the use of labour-saving cultivators control weed growth, these farmers still face a labour peak at weeding; a cultivator does not eliminate the need for manual weeding between plants in the same row (Figure 3).

In the Zambezi Valley, the labour peak at the time of first weeding is a major determinant of the land area harvested, even for ploughing farmers. Farmers who cannot mobilise enough labour at first weeding, are forced to abandon parts of their planted field as exemplified by data from the EU-PARSEL project in the area. During the 2008-2009 season 28% of sorghum fields (n = 164) and 17% of cotton fields (n = 149) decreased by almost a third in size between planting and harvesting time.

The primacy of the labour peak at first weeding explains Zambezi Valley farmers' preference for technologies such as ploughing and residue burning that save labour at this time of the season (see below). Ploughing generally reduces weed infestation at planting time and is more effective in controlling perennial weeds than minimum-tillage (Vogel, 1994), whilst manual weeding is easier on a bare soil than on a mulched soil (see below). In opposition, technologies that increase labour demand during weeding are ill-suited to smallholders of the Zambezi Valley, particularly the resource poor. From discussions with farmers, this appears to be the case for minimum-tillage and mulching, the main components of CA (Table 1b).

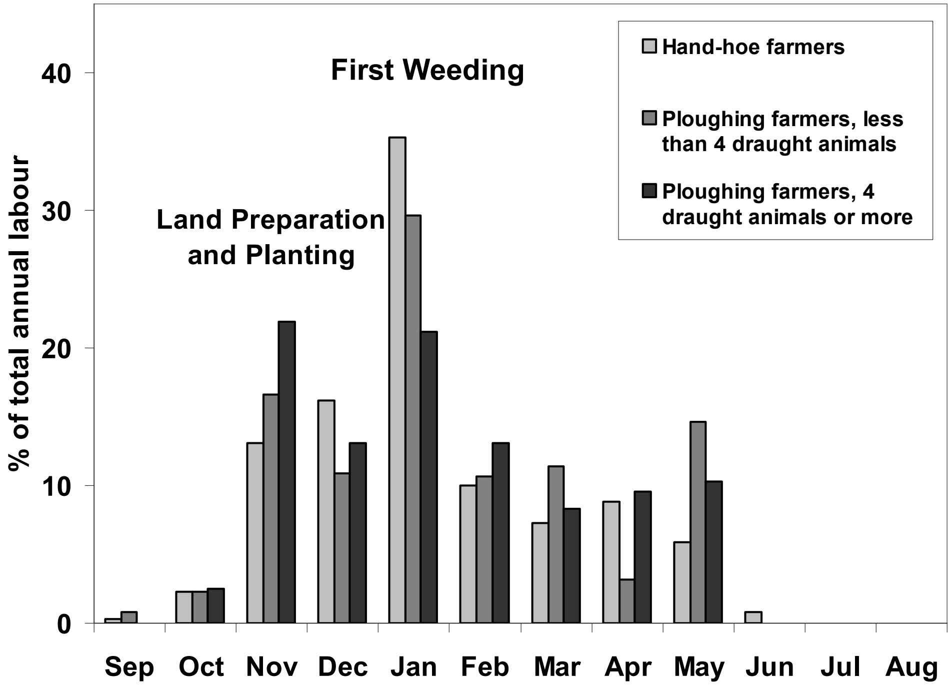

Figure 3. Mean monthly labour allocation for three types of farmers during the 2007-08 season in Dande Communal Land, Zimbabwe *(n = 38)*.

5.3.1.2. Mobilizing cash for farming

To overcome labour constraints, farmers may purchase herbicides or hire additional labour during peak periods. In the Zambezi Valley cotton farmers receive most of their farm inputs – seeds, fertilisers and pesticides – on credit from cotton companies that recover their investments in cotton. There is relatively little direct purchase of agricultural inputs. The wealthiest farmers (Type 4) spend on average only 4% of their total cash income directly on agricultural inputs, while for other farmer types this is 1% or less. Problems of availability, high prices and a hyper-inflationary economic environment have reduced the possibility of direct purchases of inputs in recent years. Zambezi Valley farmers who do access mineral fertilisers on credit tend to use small quantities on their cotton, as credit recovery rates are high[19]. Therefore, fertile land is generally secured by investing labour in clearing an additional piece of land

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[19] Data from the EU-PARSEL project show that during the 2008-2009 season, farmers were using, on average, only 12 kg N ha^{-1}, 34 kg P ha^{-1} and 6 kg ha^{-1} on their cotton fields.

before the rains start (that is before labour peaks), rather than by purchasing fertiliser to maintain the fertility of already cultivated lands. This investment strategy was revealed by the Dande Game: when offered hypothetical increases in assets all farmers expanded the area of land they cultivated, instead of concentrating resources on the land already cultivated.

Farmers' peak expenditure, at planting and first weeding between November and January, reflects the investment pattern of labour hiring[20]. Especially farmers growing cotton on large land areas (Type 3+4) hire additional labour for weeding (Figure 4). However, during labour peaks labour availability is reduced and labour costs increase (White et al., 2005). By contrast, labour is cheap before the rainy season, as poorer hand-hoe farmers (Type 1 and 2) are keen to earn cash to purchase food. This cheap labour allows wealthier farmers to clear large tracts of fertile land for agriculture. Thus, agricultural extensification is not only driven by the high cost of fertilisers compared with the farm gate prices of agricultural commodities, making its use unprofitable, but also by the availability of cheap labour outside peak periods.

Agricultural intensification strategies that require hiring labour, particularly – as in the case of CA – during peak periods when labour is scarce and expensive, require substantially more cash investment. Strategies that increase cash requirements for inputs and/or for hiring labour are unlikely to be adopted when the profitability of small-scale farming remains stable or declines, as has recently been the case for cotton profitability in Zimbabwe.

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[20] The expenditure peak partly corresponds with the beginning of the school year, when school fees, uniforms and stationary need to be purchased.

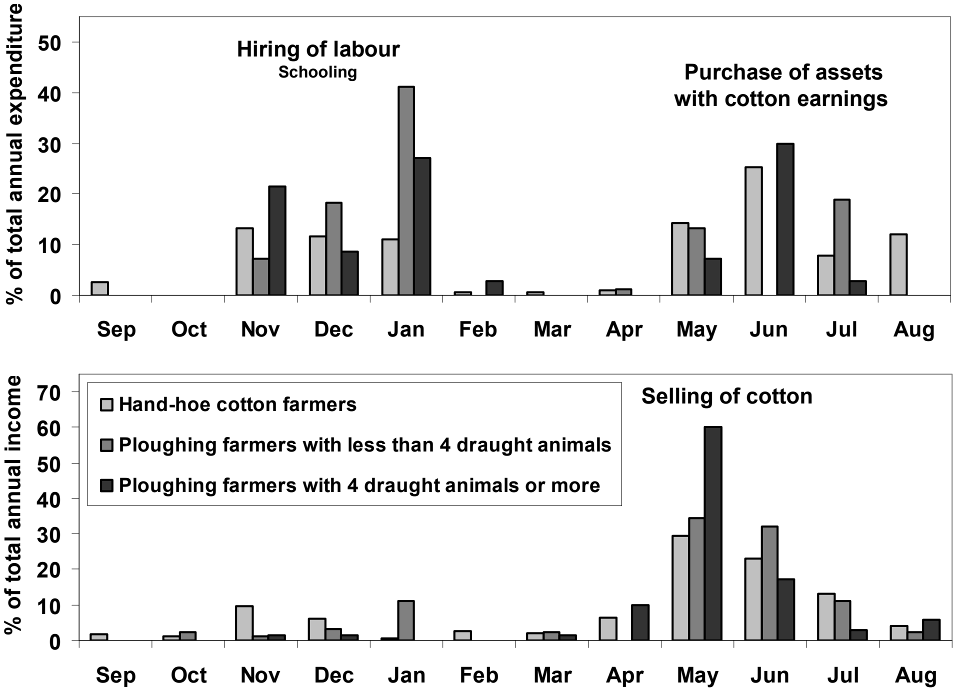

Figure 4. Mean monthly cash allocation for three types of farmers during the season 2007-08 in Dande Communal Land, Zimbabwe (n = 38). Cash expenditure during the period November-January represent labour hiring and, to a lesser extent, expenses related to schooling. Cash expenditures in the period May-July represent the purchase of clothes, productive assets such as livestock and other household needs using cotton income.

5.3.1.3. Agricultural intensification vs. mitigating risk

Both strategies for farmers to increase production – agricultural intensification and agricultural extensification – require more labour and/or cash inputs. But clearing new fertile lands during off-peak periods does not only require less cash than investing in fertilisers, extending one's field has other advantages as well. Farmers generally prefer to spread their labour and cash inputs to reduce the risk of crop failure.

First, in the Zambezi Valley, having a number of fields, with different soils, planted with different crops, and managed differently, is a strategy to mitigate risks of drought, pest attacks and destruction by wildlife. For instance, farmers indicated that soils richer in clay ("*mutapo*") are best suited for cotton. However, when exploring different cropping patterns through the Dande Game – 'what would you grow if you had access to all soil types?' – farmers indicated that in years of drought, cotton performs better on sandy loam ("*bandate*")[21]. Thus they explained their preference to spread cotton cultivation over fields with contrasting soil types given the unpredictable rainfall, rather than concentrating on one field.

Second, agricultural extensification can also serve to mitigate the effects of drought on cereal production. Farmers indicated that in dry years, those who planted a large field always harvested something: as weeds do not develop as strongly in dry years, farmers can manage large fields with less labour than during higher rainfall years. Half of the interviewed farmers indicated that during a drought year, two acres of maize weeded once would yield more than one acre of maize weeded twice.

5.3.1.4. Crop demands, markets, livelihoods and in/extensification pathways

As already alluded to, market prices influence farm development pathways. For instance, land scarcity and higher producer prices near urban markets may drive agricultural intensification (Bamire and Manyong, 2003; Erenstein, 2006). Equally, relative land abundance and high input prices in remote areas such as the Zambezi Valley, may predispose farmers to extensification. Woodhouse (2002) noted that these socio-economic factors may be even more important than agro-ecological conditions in explaining population growth and the orientation of farm production towards intensification or extensification.

The cash and labour demands of specific crops as well as their different uses also shape such farm development pathways. Different crops have specific meanings for people. A comparison of cotton and cereal production in the Zambezi Valley can illuminate this. Poor market prices for cereals mean that these crops are primarily grown for food although surplus production may be sold. Being independent from the market for one's food appears to be a strong social force. Even well-endowed farming households specialised in cotton production do not cease to produce cereals altogether.

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[21] Sandy clay loam has a high water retention capacity, but also a high permanent wilting point. These soils require substantial rainfall before water becomes available for the crop. Sandy loam has less capacity to retain moisture and a lower permanent wilting point.

Second, different crops have different labour demands. During the ‘Dande Game’, when asked to compare the cropped area of a farming household only growing cotton with the cropped area the same household could manage when only growing cereals, farmers highlighted the extra labour demand of cotton production for weeding and pesticide application. They estimated that a household could manage 25-60% less land area under cotton than under cereals. Accordingly, the farmers saw larger farming households – more helping hands – as more suitable for cotton cultivation, while farms with more draught animals and ploughs were considered best for cereal farming. Hence, the relative market prices for cereals and cotton may drive farm development along an intensification or an extensification pathway. In the Zambezi Valley extensification is probable, as the profitability of labour-demanding cotton has followed a declining trend in the past decade[22] (until 2010 when the price of cotton doubled, see Appendix 1), whilst cereal marketing in Zimbabwe was liberalised in 2009.

5.3.2. Farmer practice and Conservation Agriculture: an unlikely marriage

The above exploration of farm practices reveals how limited cash, labour peaks, low output and high input prices, and risk aversion, predispose smallholder farmers in southern Africa to agricultural extensification. The availability of – relatively fertile – land enables such an expansive farm development pathway in the Zambezi valley, but such a development is perhaps unlikely in areas characterised by high land pressure and poor soils. Nevertheless, the Zambezi Valley case illuminates why the technologies for agricultural intensification as promoted in CA are problematic in many smallholder farming contexts.

5.3.2.1. Ploughing: the hallmark of a good farmer

Although diverse in terms of their farming practices and their endowment, interviewed farmers’ responses to the questions: ‘What makes a good farmer? What does (s)he have or do differently than others?’ were strikingly similar: having animal draught power, a plough and a cultivator, were seen as the main attributes of a good farmer

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[22] A farmer explained ‘250 kg could buy one head of cattle in the 1990s; nowadays, twice this amount is required’ (Interview with Mr R. Matongora, Madzeverete, 9 November 2009)

(Table 2). As for Alvord in the 1920s, the plough remains the hallmark of good farming.

Table 2. "*What makes a good farmer (murimi akanaka)? What does (s)he have or do differently than others?*" (n=36)

What makes a good farmer?	Number of respondents	Proportion of respondents
Having animal draught power, plough(s) and cultivator(s)	35	97%
Producing surpluses	17	47%
Having seeds (quantity and quality)	13	36%
Having manpower (family and/or hired labour)	12	33%
Having a large field	9	25%
Practicing proper weeding	5	14%
Using chemicals (fertilizers, pesticides, etc)	5	14%

As already shown above, Zambezi Valley farmers value the plough foremost for weed control (67%). Secondly, in the hot and dry climate of the Zambezi Valley where yields are foremost limited by water availability, ploughing is perceived as a means to increase moisture retention (52%) and water infiltration (45%) (Table 3). Finally, smallholders value the plough for the rapid land preparation it permits (24%). In low rainfall areas, the optimum planting window is narrow and the plough enables large areas of land to be cultivated quickly (Nyamudeza, 1999).

Farmer's appreciation of plough use as a way to maximise the utilization of rainwater, diametrically contradicts the view of CA protagonists, who argue that plough use should be minimised to increase water use efficiency (Gowing and Palmer, 2008; Rockström et al., 2009). Agronomists agree that on (clay-poor) loamy soils, such as those found in the Zambezi Valley, soil crusting occurs, leading to run-off and poor water infiltration. The crust can be broken by ploughing or, alternatively, its formation can be avoided by mulching as is proposed with CA (Awadhwal and Thierstein, 1985). Why then do farmers not mulch?

Table 3 – “*What are the benefits of ploughing?*” *(n=33)*

Reasons for ploughing	Number of respondents	Proportion of respondents
Weed control	22	67%
Increased moisture retention	17	52%
Improved water infiltration	15	45%
Fast and easy plant growth due to loosened soil	17	52%
Fast land preparation / big land	8	24%

5.3.2.2. Mulching vs. burning crop residues

Removing crop residues (for cattle feed) or burning them is a widespread practice among smallholder farmers in the Zambezi Valley – three quarters of the farmers interviewed did so. Hand-hoe farmers do so because retained crop residues – mulch – increase the labour burden during planting and weeding in the beginning of the season (Table 4). It may increase labour costs, as a labour hiring hand-hoe farmer explained:

> “*Casual workers charge you more to open planting stations in fields where you did not burn.*”[23]

Such considerations are not relevant to those who plough, since ploughing incorporates most of the residues. However residue burning may also be practiced to reduce pests and weeds or to release nutrients for the crop to be planted (Table 4). During group interviews, other reasons included: facilitating mice hunting, avoiding trampling of one’s field by free grazing cattle, and not attracting dangerous wildlife like elephants and buffaloes that feed on crop residues. While some reasons are specific to the Zambezi Valley, to abandon burning involves an additional labour input; for planting and weeding, as well as for constructing fire breaks as fires often spread from neighbouring fields[24].

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[23] Interview with Courage Nhamoyemari (2 February 2010).

[24] Fires may spread from neighbouring farms or natural vegetation, that are annually burnt for a number of reasons, for example to facilitate hunting of antelopes.

Table 4 – "*Why do you burn residues?*" (n=25)

Reasons for burning	Number of respondents	Proportion of respondents
Easier land preparation and weeding	18	72%
Reduction in termite and millipede populations	6	24%
Weed control	5	20%
Increased fertility	4	16%

5.3.2.3. The impossibility of frequent crop rotation

Both the Alvord and CA packages for agricultural intensification emphasise the importance of crop rotation, albeit for different reasons. For Alvord, making best use of available soil nutrients was a prime concern, and he promoted a four-year rotation with two consecutive years of maize, followed by a legume crop and a small grain crop. Consequently, half of the farm should be occupied by maize and the other half by legume and small grain crops. In CA, annual crop rotation is required as pests and diseases may be carried over to the following crop in the mulch. This means that the farm should be occupied by at least two crops on equal areas. Both types of crop rotations are highly problematic for smallholders. Firstly, not all farmers grow a wide variety of crops, or cultivate similar land areas to different crops.[25]

Secondly, as already mentioned above many farmers have access to different types of soils that differ in their suitability for particular crops. Farmers' preferred combinations of crops and soil types were brought out by the 'Dande Game': 1) maize on "*bandate*" soils close to the rivers, 2) sorghum and cowpea on "*bandate*" soils, but further away from the rivers; 3) groundnuts on lighter "*shapa*" soils, and; 4) cotton on "*mutapo*" (the heavier soils). Although limited access to specific soil types, food security and risk spreading considerations complicate such ideal-typical combinations in practice, these preferences make crop rotation impractical.

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[25] For instance, in the Zambezi Valley in 2006, hand-hoe farmers were growing an average of 1.1 ha of cereals and an average of 0.7 ha of cotton (*n* = 78), whilst ploughing farmers were growing an average of 1.3 ha of cereals and an average of 2.6 ha of cotton (*n* = 98).

5.3.2.4. 'Intercropping with legumes is for poor farmers'

Intercropping with cover crops, especially legumes, is often promoted in CA. However, in the Zambezi Valley only 20% of the interviewed farmers were practicing legume intercropping – mainly groundnuts and cowpea with a cereal. The main reason given for not intercropping was crop competition, resulting in a decline in yield of the legume crop. Farmers may also associate legume intercropping with poverty:

"*A good farmer is not supposed to practise intercropping; intercropping is mainly done by old people who are trying to make the most out of a small piece of land.*"[26]

Thus, although the benefits of legume intercropping are well documented in the scientific literature (for example Craufurd, 2000), farmers in the Zambezi Valley appear committed to sole cropping as promoted in the Alvord model (Table 1a).

5.4. CONCLUSIONS: FAILING TO YIELD, OR FAILING TO INNOVATE?

Whereas interventions in African agriculture have been aimed at agricultural intensification, the analyses presented in this article show how the socio-economic constraints faced by many smallholder farmers – that is limited cash, labour peaks, low output and high input prices, and high risks – predispose them towards extensification. Technical packages which may exacerbate such constraints are ill-suited to the circumstances of smallholder farmers. In the Zambezi Valley, where labour availability for weeding is a major limiting factor, the increased weed pressure in CA is a major – but probably not the only – reason preventing farmers from embracing it. Without more attractive prices for farm produce, or other sources of income, farmers will not be able to hire additional labour, or to purchase the labour-saving herbicides required to overcome the increased weed problems that may result from CA adoption.

Agricultural technologies do not, however, have strict intensifying or extensifying properties: often they have both. It is the interaction between the technology and the agro-ecological and socio-economic environments which directs farming on an

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[26] Interview with Rambros Matongora (9 November 2009)

intensification or extensification pathway. The example of the plough in Alvord's time is illustrative: although its use was promoted to intensify land use, its adoption often meant a 'diversion' towards extensification. Similarly, depending on the circumstances in which it is introduced, CA may not contribute much to agricultural intensification, but may result in agricultural expansion and extensification. For instance, the widespread adoption of CA and herbicides in the Brazilian Cerrados went hand in hand with a massive expansion of agricultural land (Landers, 2001; Klink and Macado, 2005).

As has been highlighted above, smallholder farming in the Zambezi Valley cannot be taken as representative for the southern African region as a whole, as its hot climate and relatively fertile soils render weeding rather than planting the major labour peak in production. Land abundance – enabling agricultural extensification – is, however, less specific to the Zambezi Valley than may be assumed. In areas with denser populations than the Zambezi Valley (17 pers. km^{-2} in 2002), such as Malawi's southern province (>200 pers. km^{-2}, Benson et al. 2002), acute land shortage may indeed preclude agricultural extensification. Yet, in most parts of southern Africa population densities are relatively low: 18 pers. km^{-2} in Zambia, 29 in Mozambique and 32 in Zimbabwe[27]. Agricultural extensification is not merely a predisposition of smallholder farmers, but often a realistic possibility for farm development as is apparent from high deforestation rates in the region (for example 1% per annum in Zambia, 1.7% per annum in Zimbabwe[28]). Farm expansion into grazing lands, and the hiring of unused land are also common options (Chimhowu and Woodhouse, 2008).

We may therefore conclude that despite sustained efforts to intensify smallholder agriculture, farmers in the region have been 'failing to yield'. The repeated failure of intervention models to learn from the rationale of smallholder production systems

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[27] Population figures of 2008, United Nations Population Division (http://www.un.org/esa/population/publications/wpp2008/wpp2008_highlights.pdf, visited 23 November 2010)

[28] Deforestation rates for the period 2000-2005, data from the Global Forest Resource Assessment of 2005 (http://foris.fao.org/static/data/fra2005/global_tables/FRA_2005_Global_Tables_EN.xls, visited 23 November 2010)

goes a long way in explaining their adoption failure. From Alvord to CA, local practices have been disregarded by interventionists, and the persistent conviction that the problem of low productivity and land degradation in African agriculture is purely technical has led interventions to be limited to attempts to change farmer 'mindsets', through demonstration and trainings. This approach has changed little in almost a century of agricultural research and extension. More worrying than smallholders failure to increase yields, seems to have been the failure of researchers, policy makers, donors and development agencies to innovate.

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General discussion and conclusions: Agricultural intensification – saving space for wildlife?

Let us return to the main research question of this study: does CA have the potential to intensify agricultural production with minimum negative environmental effects, and save space for wildlife? Chapter 2 and Chapter 3 demonstrated the importance to develop innovative cotton cropping systems for the conservation of wildlife habitat in the Mid Zambezi Valley, outside of protected areas. Indeed, by enabling the accumulation of cattle and the expansion of plough-based agriculture, cotton farming has been the major driver of extensive and rapid land use changes that started after the national independence in 1980 (Chapter 2). The 'environmental footprint' per farm was increasing significantly with the area under cotton and with the number of draught animals owned (Chapter 3). Cotton production may have negative effects on the Mid Zambezi Valley ecosystem, but it also offers opportunities for conservation. Cotton farming is more labour-intensive than other crop production (i.e. cereals), and thus requires less space in agricultural frontiers such as the study area, where agricultural production is limited by labour more than by land (Chapter 3). Therefore, maintaining or increasing the relative profitability of cotton vs. other crops may 'spare land' for nature. Chapter 4 explored the potential of CA to increase the productivity and efficiency of cotton-based smallholder systems. It concluded that with the current level of mulch achieved in typical smallholder conditions and the current fertilisation rates, CA offered little potential to intensify cotton and cereal production in the Mid Zambezi Valley. Chapter 5 further demonstrated that, although necessary to save space for wildlife, the adoption of yield increasing technologies is unlikely in agricultural frontiers, where extensification is the rule. Thus, additional measures have to be taken in order to save space for wildlife in the unprotected land of the Mid-Zambezi Valley.

Below, I explore implications of these findings for field-based stakeholders dealing with agricultural production and biodiversity conservation (farmers' organisations, cotton companies, governmental departments, non-governmental organisation, conservation agencies, safari operators, CAMPFIRE committees, etc). The first three chapters explore implications emerging from the results of this study at each level of the analysis: plot-level, farm-level and landscape-level. The fourth and final part explores three popular myths that shape the way conservation landscapes are constructed. I use the term conservation landscape to describe unprotected areas of high biological value occupied by people.

6.1. THE CONTRIBUTION OF CA TO THE INTENSIFICATION OF SMALLHOLDER PRODUCTION

This section explores implications of the results of this study at plot-level. First, the different components of CA may only be suitable to particular circumstances. Second, maximizing biomass production may enable the retention of larger quantities of mulch than those achieved in this study and may increase the short-term performance of CA. Third, CA is only one approach amongst many aiming to increase resource use efficiency: it may be suitable in a limited set of circumstances, whilst other approaches may be more appropriate in other circumstances.

6.1.1. The need for a flexible and pragmatic approach

Findings from Chapter 4 and Chapter 5 demonstrate that CA may be better suited to particular situations than others: fine-textured soils less prone to surface crusting than coarse-textured soils and circumstances where large quantities of biomass can be retained as mulch. In cotton systems, this latter point implies the necessity of crop rotation (as cotton stalks have to be destroyed for phytosanitary reasons in Zimbabwe, and therefore cannot be used as mulch). It also requires low grazing pressure, as in sub-Saharan Africa, crop residues become a public good available for communal grazing after harvest. I use these findings, in additions to field observations and discussions with farmers in other cotton production areas of Zimbabwe and West Africa, to develop the decision-making tree for rainfed cotton in sub-Saharan Africa presented in Figure 1. The aim of this tree is to help select the cotton cropping systems that are as close as possible to CA *sensu stricto* and that are the most suitable for smallholder farming circumstances. It is based on the direct benefits (economic yield) these cropping systems are likely to generate on the short-term, which represent the main concern of smallholders. Indirect benefits for the environment (e.g. erosion control, C sequestration) and long-term benefits of maintenance/improvement of soil physical, chemical and biological properties were not taken into account. Moreover, this tree is constructed considering opportunities and constraints relating solely to biophysical aspects, assuming for example that herbicides are available and labour is not limited for cultivating.

The decision making tree of Figure 1 is based on four criteria: (1) the importance of water as a limiting factor and the occurrence of delayed land preparation, (2) soil texture, (3) the possibility of crop rotation, and (4) the intensity of the grazing pressure from communal livestock. The rationale behind the construction of this decision-making tree is developed below. Cropping systems themselves are described in Table 1.

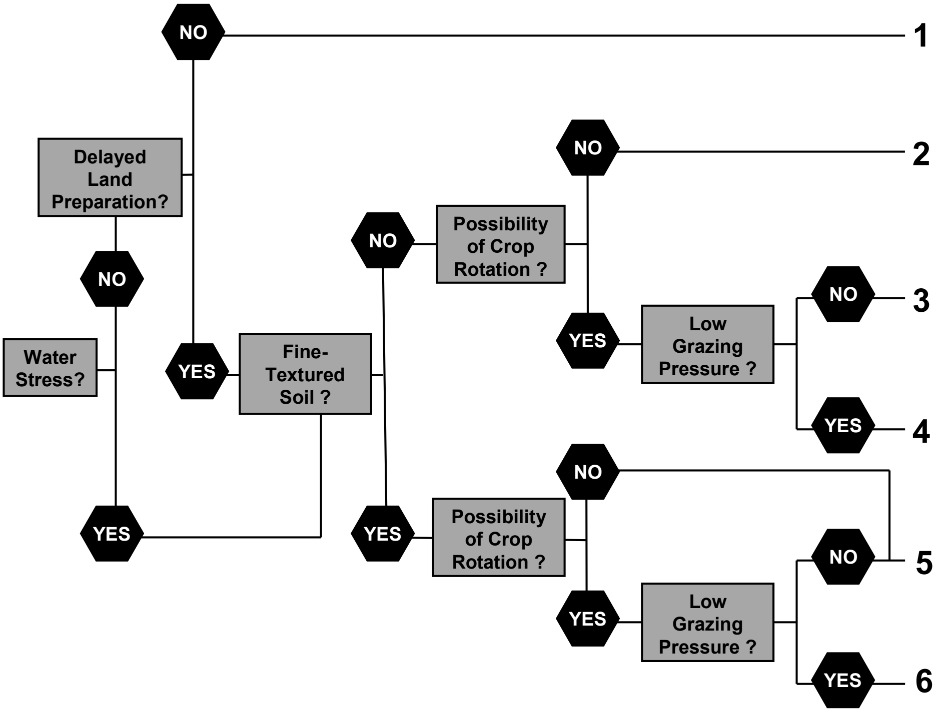

Figure 1. Decision-making tree for the selection of cropping systems based on CA principles that are the most suitable for smallholder rainfed cotton in sub-Saharan Africa.

The only two direct short-term benefits that may be expected from CA are increased water-used efficiency (Erenstein, 2002; Findeling et al., 2003; Scopel et al., 2004) and early planting, as land preparation is simplified and often carried out before the first efficient rains (Haggblade and Tembo, 2003). In areas where neither water stress nor delayed land preparation (due to limited animal draught power) limit crop productivity, resources available to agricultural research and development should be directed towards technologies other than CA (e.g. integrated soil fertility management, yield protection, post harvest measures).

Moreover, CA may have neutral – or even slightly negative – effects on coarse-textured soils prone to surface crusting i.e. the majority of the soils in the study area (Chapter 4). On such soils, crusting may only be avoided if large quantities of residues are retained as mulch. In areas where cattle numbers are high and where residues are grazed communally after harvest, only small quantities of residues will be retained as mulch, which will be insufficient to prevent soil crusting. In this context, a ‘mechanical opening’ of the soil will be needed, through ploughing or the use of a cultivator. Winter-ploughing may be attractive to maximize the annual input of organic materials to the soil, burying residues out of reach of communal livestock. Maximizing the annual input of organic materials is particularly important in the long-term management of coarse-textured soils, as organic input more than tillage determines the amount of soil organic matter stored in the soil at the long-term equilibrium (Chivenge et al. 2006). In contrast, results from participatory evaluation suggest that minimum-tillage would be beneficial on soils rich in expanding 2:1 clays (e.g. Vertisols), even if the quantities of material retained as mulch are limited (Chapter 4). Infiltration is maintained by the cracks forming during shrink and swell cycles in these soils (Murray and Quirk, 1980). A farmer in the District of Gokwe North coined them ‘self-ploughing soils’. Minimum-tillage is also justified on these heavy soils, as mechanical operations limited to the use of animal draught power (ploughing, cultivating) are very difficult when they are wet. Finally, minimum-tillage has more effect on clay soils to stabilize soil organic matter content, as the aggregates that form and occlude organic matter are disturbed by mechanical operations (Six et al., 2002).

Furthermore, the benefits of intercropping a long-cycled legume to a cereal (Chapter 4) may not be captured in areas with intense communal grazing, as fields would have to be guarded against roaming herds after the harvest of the cereal. In this situation, short- rather than long-duration legumes should also be used (e.g. cowpea) for their grain to be harvested before or at the same time as the cereal.

Finally, strict no-tillage (i.e. direct-seeding) requires the retention of a thick mulch of crop residues on the soil surface, through which the seed is planted. In the case of cotton production, it makes rotation with another crop necessary, most likely with a cereal, as the destruction of cotton residues is compulsory for sanitary reasons. Strict no-tillage is thus not feasible if such a rotation is itself not feasible. Strict no-tillage also necessitates the use of herbicides for weed control, as the use of a cultivator requires a bare soil (residues interfere with mechanical operations, Chapter 5).

Table 1. Description of the cropping systems in Figure 1

Cropping system	Tillage method	Weed control method	Cropping sequence
1	Ploughing	Cultivating or Herbicide spraying	Indifferent
2	Ploughing	Cultivating	Indifferent
3	Winter-ploughing followed by Ploughing or Ripping	Cultivating	Cotton – Cereal + Short-cycled legume
4	Ripping or Direct Seeding	Herbicide spraying	Cotton – Cereal + Long-cycled legume
5	Ripping	Herbicide spraying	Indifferent
6	Ripping or Direct seeding	Herbicide spraying	Cotton – Cereal + Long-cycled legume

According to the decision-making tree, individual technological components of CA - minimum-tillage, crop residue mulching, and crop rotation and association – are not suitable to all circumstances of smallholder cotton production in sub-Saharan Africa (Table 1). The promotion of minimum tillage is only advisable in half of the cropping systems (4, 5, 6). Crop residue mulching is only possible in a third of the cropping systems (4, 6), residues being either grazed during the dry season or destroyed in the case of cotton. Similarly, crop rotation with the inclusion of N_2-fixing legumes is only possible in half of the cropping systems (3, 4, 6). This tree goes beyond the identification of 'niches' in which CA fits or not, as proposed by Giller et al. (2009). It calls for a flexible and pragmatic approach with certain components of the technology fitting and others not, depending on local circumstances. This approach departs from the FAO definition, which presents CA as a package of interrelated components that can only be adopted all together. Such definition appears more ideological than practical for African smallholder farming. Presenting CA as a set of technologies aiming at increasing the basket of technologies currently available to smallholders may ultimately serve them better than an ideology. In addition to the biophysical dimension used in this tree, the socio-economic dimension needs to be taken into account to understand the likelihood of the different components of CA to be adopted in a given area (Chapter 5). It was suggested that the benefits of CA, and the likelihood for it to be adopted, could also be increased by increasing biomass production (Chapter 5).

6.1.2. Increasing biomass production

Chapter 4 concludes that larger quantities of mulch than those achieved under this study may increase the short-term benefits of CA, by preventing soil crusting and by controlling water runoff. The quantity of residues left in the field after the dry season may be increased by increasing biomass production. The amount of residue produced by a cereal crop is a function of its yield and its harvest index. The latter is largely genetically determined, whilst the former is strongly influenced by management. Increasing cereal yield may be achieved by modifying defining factors (e.g. by using a higher yielding variety), limiting factors (e.g. increased nutrient inputs, rainwater harvesting), and/or reducing factors (e.g. weed, pest and disease control) (van Ittersum and Rabbinge, 1997). Under circumstances where the modification of these factors is not feasible, due to capital and/ or labour constraints, other strategies have to be used to increase biomass production. These may include the use of cereal landraces with a lower harvest index, intercropping, agroforestry, and the use of weedy biomass.

Using a local landrace may result in greater quantities of residues being produced, as local landraces generally have a lower harvest index than improved varieties. Although they generally have a lower grain yield compared with improved varieties, local landraces may be economically competitive due to other benefits (e.g. better resistance to pests, access to specialized market). In the study area for example, several local landraces of sorghum were cultivated (Appendix 2). Although these landraces achieved smaller grain yields than improved varieties, they suffered less from bird attacks (due to the high tannin content of their grains) and were less prone to destruction by roaming livestock, elephants and buffaloes (the stem of these landraces was drier and contained less sugar, and was therefore less palatable). Reduced sensitivity to wildlife destruction represents a major advantage in the study area, particularly in its western side where crop destruction by wildlife is frequent (Chapter 1). In addition, reduced palatability to both domestic and wild herbivores means that a greater fraction of the residues produced is retained at the end of the dry season. Finally, the grain of the majority of these landraces fetched high market prices as they possessed qualities of interest to industrial breweries (Appendix 2).

When the use of local landraces does not represent an economic advantage compared with the use of improved varieties, other biomass-increasing technologies may be selected. Intercropping a legume crop with sorghum increased the amount of biomass being retained as mulch at the end of the dry season by an average of 40% compared with sorghum sole-cropping, with no yield penalty for sorghum (Chapter 4). Legume intercropping may generate other benefits, such as improving nitrogen balance (Chapter 4), weed control from the closed canopy formed (Olsen et al., 2005) or narrower C:N ratio of the produced mulch, thus avoiding potential problems of temporary N immobilization (Palm et al., 2001). Perennial plants may have a greater primary productivity than annual plants. Therefore, intercropping agroforestry species may increase the quantity of biomass being produced, and yield other benefits such as nutrient cycling and micro-climatic regulation. The adoption of exotic agroforestry species is generally low (Mercer, 2004), regardless of the amount of resources invested in the promotion of the technology. However, keeping trees in the fields was a traditional practice in much of southern Africa before the colonial era (Wilson, 1989) and remained a common practice in the western side of the study area (Appendix 3). A number of trees regarded as belonging to spiritual entities protecting the land were being retained when opening new fields. The role of some of these species in improving the soil status in terms of its concentration in C, N, P and K is well known (see e.g. Dunham, 1991 for the case of *Faidherbia albida* and *Kigelia africana* in the Mid-Zambezi Valley). Use of these species may lead to far greater adoption of agroforestry. In deeper soils, *Faidherbia albida* is of particular interest, due to its unusual reverse phenology that makes competition between the tree and annual crops minimal (Vandenbeldt, 1992). It has recently been re-discovered by ICRAF and is now heavily promoted across Africa as a "*fertiliser tree*" (Garrity et al., 2010).

More complex associations combining various plant functional groups may increase benefits. For instance, several studies have demonstrated increasing rates of ecosystem processes (e.g. net primary productivity, nutrient retention) with increasing species diversity (Naeem et al., 1994; Tilman et al., 1996). However, differences in species (i.e. in traits) would appear to have a larger effect on ecosystem processes than species diversity alone (Hooper and Vitousek, 1997). Trait-based ecology could offer a useful approach to the design of cropping systems composed of several species combining complementary traits (e.g. N_2-fixation by legumes, nutrient cycling by agroforestry species) and delivering a set of ecosystem processes of interest to farmers (Brussaard et al., 2010). For a particular situation, the pool of possible cropping systems hence obtained should further be filtered by an economic filter (comparative cost with alternative cropping systems using chemical and mechanical interventions in terms of capital, labour, etc) and a socio-cultural filter (see the socio-ecological niche conceptual framework developed by Ojiem et al., 2006). Redundancy (i.e. niche overlap) may also be an important objective in the design of multi-species cropping systems to ensure the reliability of ecosystem processes in stochastic environments (e.g. net primary productivity in a context of inter-annual climatic variability; Naeem, 1998).

Increasing planned plant diversity may be beneficial for the maintenance of ecosystem processes. However, even in a cropping system with low planned plant diversity, total plant diversity may be high if fields have not been cultivated for extensive periods of time and/or if the intensity of cultivation is low. For instance, average plant diversity in cotton, maize and sorghum fields in the study area were 12.2 (± 3.0), 16.2 (± 4.1) and 13.0 (± 3.2) species ha^{-1} respectively. These so-called 'weeds' can participate in ecosystem processes valuable to farmers, such as N retention. For instance, the N concentration of the above-ground biomass of the 11 weed species most frequently found in the study area were greater than the N concentration in maize residues (Figure 1 of Appendix 4). Weeding operations are often inadequate in the study area (in terms of timeliness and frequency) due to labour constraints, and weed growth is often vigorous due to hot temperatures and the prevalence of relatively fertile soils (Chapter 5). Thus, weeds generally provide a substantial amount of the biomass being produced and remaining in the field at the end of the dry season (Figure 2a of Appendix 4). The retention of this weedy biomass as mulch can improve significantly the N balance (Figure 2b of Appendix 4). This is consistent with the findings of Promsakha Na Sakonnakhon et al. (2006). Evidently, trade-offs exist between crop and weed biomass and between crop and weed total N. Thus, I am not proposing here to reduce weeding frequency and intensity to increase purposely weed biomass, but simply stating the fact that the contribution of weeds to biomass production is often ignored by agronomists whilst it may be substantial in labour-limited farming systems and/or on relatively fertile soils.

6.1.3. One of several ways to increase resource use efficiency

In this study, fertiliser use and crop protection were found to be more important than tillage and soil mulching in obtaining a good yield (Chapter 4). These results agree with Gowing and Palmer (2008) who stated that "*CA does not overcome constraints on low-external-input systems*". The benefits of CA may only be expressed under good agronomic management. In other words, CA may only be beneficial in relatively intensive systems, as a means to use external inputs more efficiently, controlling horizontal and vertical losses (Figure 1 of Chapter 1.). Thus, I see CA as only one option within a larger body of approaches aiming at increasing water and nutrient use efficiency, including use of improved germplasm, timely planting and weeding, splitting of fertiliser application, spot application of fertilisers, and agroforestry. The simultaneous application of two or more of these approaches generally leads to synergetic effects and to a stepwise improvement of water and nutrient use efficiency (Vanlauwe et al., 2010).

Increasing crop water and nutrient use efficiency has the dual benefit of increasing productivity and reducing the fraction of the resources susceptible to be lost and to become an environmental problem off-site (for example, increased N use efficiency reduces the amount of N susceptible to leaching). For a particular resource (e.g.

water, N, P, K), resource use efficiency can be defined as the product of capture efficiency (capture by the crop of a certain portion of the total available resource) and conversion efficiency (conversion of the amount of the resource captured into plant biomass; Giller et al. 2006). Conversion efficiency is mainly genetically determined, and thus can be improved by e.g. improved crop varieties. Capture efficiency of a given biophysical resource is in part regulated by the availability of other limiting resources (Janssen et al., 1990) and the fulfilment of other plant requirements in terms of e.g. aeration and physical support (Vanlauwe et al., 2010). For example, rainfall use efficiency of Sahelian pastures can be increased several fold by nutrient application (Penning de Vries and Ditèye, 1991). In addition, soils with a small soil organic carbon content are generally poorly responsive to mineral fertilisers (Lal, 2010; Vanlauwe et al., 2010). Capture efficiency can be increased through good agronomic practices aiming at maximizing crop demand: timely planting and control of yield-reducing factors such as weeds, pests and diseases. It can also be increased by splitting fertiliser application in several small doses, responding to rainfall and crop demand as the season develops, for nutrient supply to match as much as possible crop nutrient demand (Piha, 1993). Capture efficiency can also be increased by spot application of small doses of fertilisers ('micro-doses') close to crop plants (Twomlow et al., 2010). Finally, it can be increased by controlling losses and therefore increasing retention of a given resource *in situ* (this is the aim of CA, which in theory controls horizontal losses through soil mulching and vertical losses through recycling of nutrients by deep rooted cover crop; Figure 3 of Chapter 1).

This broad basket of technologies could be defined as 'Integrated Soil Fertility Management' ("*a set of soil fertility management practices that necessary include the use of fertiliser, organic inputs and improved germplasms, combined with the knowledge on how to adapt these practices to local conditions, aimed at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity*"; Vanlauwe et al., 2010). It could also be defined as 'eco-efficient agriculture' ("*achieving more agricultural outputs, in terms of quantity and quality, for less input of land, water nutrients, energy, labor, or capital*"; Keating et al., 2010) or 'ecological intensification' ("*achieving consistent production at high levels without causing environmental damage*"; Cassman, 1999). Ultimately, all these concepts (including

CA) revolve around the principles of increased productivity and efficiency. The multitude of concepts and definitions, in my view, creates confusion amongst farmers, donors and researchers themselves and is detrimental to the overall agenda of supplying the world with adequate agricultural commodities with minimum environmental degradation. Under given circumstances, the most suitable technologies should be supported, regardless of the school of thought it belongs to.

6.2. FARMING SYSTEMS IN AGRICULTURAL FRONTIERS

This section explores implications of the results of this study at farm-level. Many conservation landscapes, such as the study area, have become 'agricultural frontiers' due to new market opportunities or land constraints in neighbouring areas. This section argues that farming systems in theses areas are often misconceived, leading to inadequate interventions. First, farmers in these areas reason in terms of labour productivity and not in terms of land productivity/yield (Chapter 5). Second, conservation landscapes are often perceived as marginal (geographically, economically, or agroecologically) whilst they are in real fact areas of opportunities for local smallholders: farming systems there are driven by markets more than by the mere fulfilment of food needs.

6.2.1 Systems limited by labour rather than by land

In the past decades, production ecology has gained ground as the theoretical basis for the design of technologies to reduce the gap between attainable yields and actual yields (van Ittersum and Rabbinge, 1997). Successes of the Green Revolution have led researchers, development agencies and their donors to place emphasis on yield/land productivity rather than on production itself. Whereas this is congruent with the reasoning of smallholders in most farming areas, I argue that it diverges from the reasoning of smallholders in agricultural frontiers, where land does not limit production. Below, I consider two ideal-typical models of smallholder farming: one representing farming systems where land is more limiting (in relative terms) than labour, and one where labour is more limiting (in relative terms) than land. This distinction is analytical and simplifies reality greatly, as most real life farming systems are neither strictly land- nor strictly labour-limited. Nevertheless, it is useful to conceptualise the specificities of farming systems in agricultural frontiers.

In areas where land is more limiting than labour, the surface area available to a given farm generally does not change from one season to the next and can be assumed to be a constant. In this context, production may only be increased by increasing yield/land productivity. Land available per farm is constrained by high population density, and the variability of the surface area cultivated per farm is small compared with the variability of yield per farm (function of the availability and management of biophysical resources; Woodhouse, 2002; Erenstein, 2006). The situation is different in areas where labour is more limiting than land, as is the case in the study area (Chapter 5). There, the surface area cultivated per farm depends on the labour and animal draught power available for land preparation and weeding (Chapter 3). For a given farm and except during years of drought, yield does not change much from one season to the next as fertile land can be obtained by clearing natural vegetation (vegetation clearance is done outside of labour peaks, Chapter 5). In this context, production is mainly increased by increasing labour productivity. Land availability being non-limiting, every farm can access relatively fertile soils and yield variability per farm is small compared with the variability of the surface area cultivated per farm (function of the availability and management of manpower and draught power, Chapter 3).

The functioning of these two conceptual models is represented by Figure 3: systems primarily limited by land are driven by the availability and management of biophysical resources, whilst systems primarily limited by labour are driven by the availability and management of manpower and animal draught power. Technologies aiming at increasing land productivity/yield are poorly suited to farming systems limited primarily by labour, such as those found in the study area (Chapter 5). The promotion of these technologies in such a context will not, on its own, lead to agricultural intensification and land sparing for nature. For an effective land sparing to occur, the promotion of yield increasing technologies must be accompanied by other measures such as the one described below in Section 6.3.

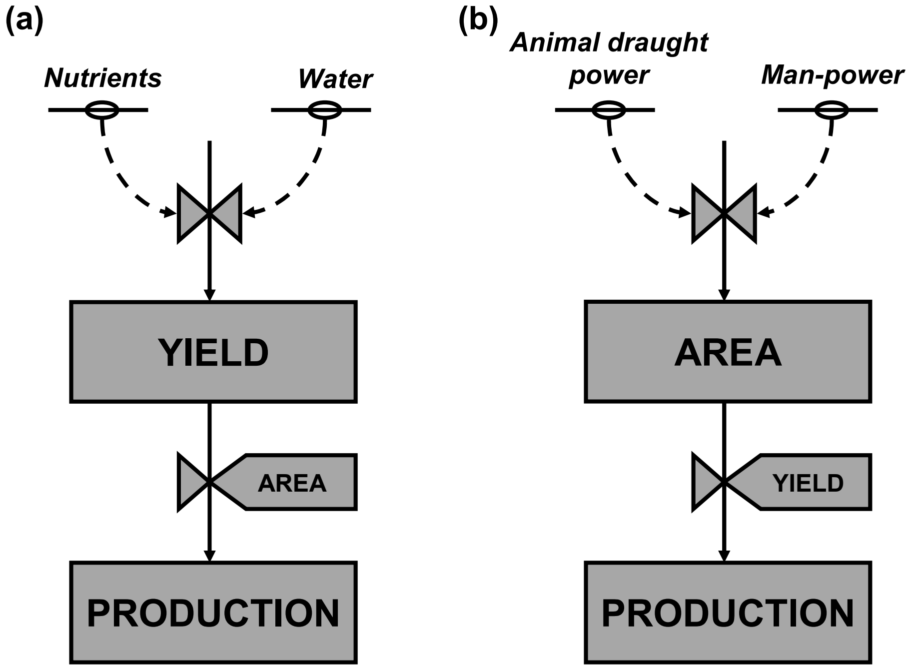

Figure 3. Representation of (a) a land limited system and (b) a labour-limited system. In a land-limited system, the cropped area per farm can be considered a constant (small variability between farms) whilst yield is determined by the combination of available nutrients and available water. In a labour-limited system, yield can be considered a constant (small variability between farms) whilst the cropped area per farm depends on the combination of available animal draught power and available manpower.

6.2.2. Remote, but still shaped by markets

Some authors have suggested that semi-arid areas were marginal areas for farming where access to remittance income represented a key factor of wealth differentiation (e.g. Frost et al., 2007). By contrast, the study area was found to be an area of economic opportunity, where the capacity to mobilize production resources, and in particular labour during times of peak demand, differentiated wealth groups (Chapter 2; Chapter 3; Chapter 5). Through the combination of cash cropping and availability of fertile land, agricultural frontiers offer economic opportunities to new migrants. Conservation landscapes are too often considered to become agricultural frontiers as a result of an increased population of farmers mainly concerned by food security, whereas market opportunities are often an important driver, as exemplified by the influence of cotton farming on land use change in the study area (Chapter 2) (Chapter 2). These areas may be remote, but they are often connected to national and even global markets (Giller et al., 2008). Nowadays, most farming systems are shaped by markets and farming for subsistence only rarely exists in reality. Failure of conservation agencies to recognize the connection of farmers to markets in conservation landscapes that are scantly populated explains, I argue, their failure to anticipate land use change detrimental to the environment. For example, Madhusudan (2005) describes how the increase in coffee price created a market for cattle manure in a distant village bordering an Indian protected area. This in turn resulted in an increase in the number of cattle owned by the so-called 'subsistence farmers' of this village, and a greater grazing pressure on the protected area itself. Similarly, WWF, a leading international conservation agency, still 'naïvely' perceives the residents of the Miombo Ecoregion (a large area of south-central Africa that encompasses the study area) as largely subsistence farmers: in the report framing the organization's conservation priorities in the Ecoregion, it is stated that "*70 to 80% of the Miombo Ecoregion is used by rural cultivators and pastoralists for subsistence purposes*" (Byers, 2001).

Understanding the influence of agricultural commodity market on farming systems in conservation landscapes can open new opportunities for biodiversity conservation. In Chapter 3 for example, it was suggested that the replacement of cotton as the main cash crop by cereal would have negative consequence on the Mid Zambezi Valley ecosystem. The influence of cotton and cereal markets on the surface area appropriated by agriculture is further explored below with a very simple simulation model. Based on the understanding of the functioning of farming systems in the study area (Chapter 3. and Chapter 5.), the model presented in Figure 3b was further developed (Figure 4; Appendix 5):

- ✓ To take into account the fact that labour demand is not spread evenly across the season but marked by peak(s); it is therefore labour available during the (most pronounced) peak that constrains production (Chapter 5.);
- ✓ To differentiate cotton production and cereal production; cereal production covered the food needs of the household whilst cotton production - and potentially part of the cereal production - was sold to generate income;

- ✓ And to explore dynamics through the inclusion of a positive feed back between production/income and labour productivity (via the purchase of additional draught animals).

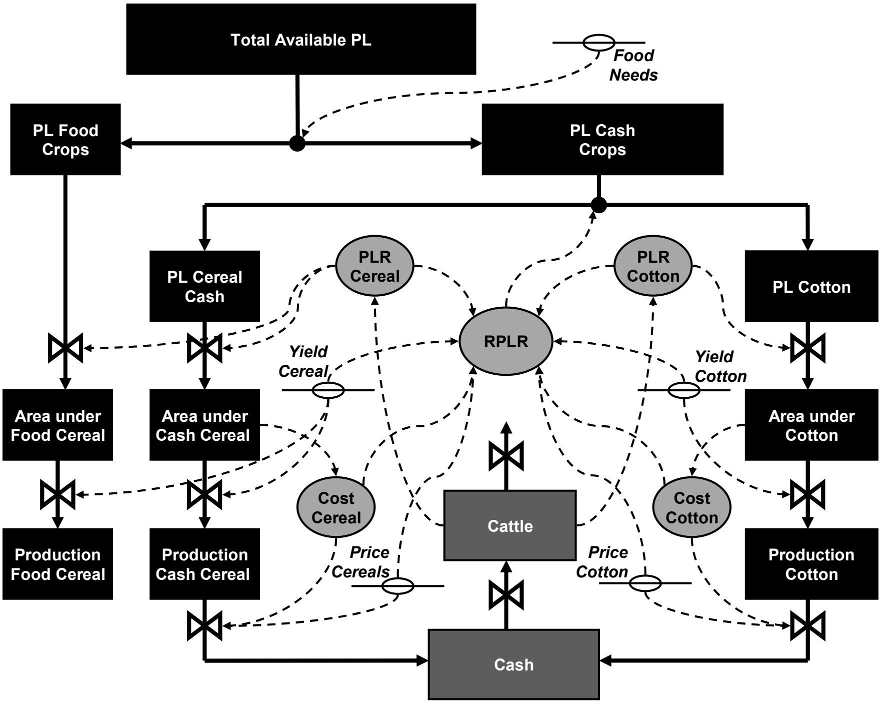

Figure 4. Schematic representation of a dynamic model of farm development in the study area, linking labour available at peak (in man-days), cultivated area (in ha), production (in kg), cash (in US$) and cattle number. Cattle are used to pull cultivators and facilitate weeding: their number therefore impacts the amount of peak labour required per area (in man-day ha $^{-1}$). Cotton and cereals are sold for cash. Once cash available exceed a certain threshold (200 US$), a new head of cattle is purchased (PL: peak labour; PL Food Crops: peak labour available for food cropping; PL Cash Crops: peak labour available for cash cropping; PLR: peak labour requirement (man-day ha $^{-1}$); RPLR: return to peak labour ratio).

In this model, when the cash of a farm unit exceeds the value of a head of cattle, a new head is purchased. A relative cattle death rate higher than the relative cattle birth rate was used (0.4 and 0.3, respectively): therefore regular purchases of cattle were necessary to increase or maintain the number of cattle owned by a farm unit. I defined for both cotton and cereals the ‘peak labour requirement’ (PLR) as the labour required per crop area (in man-days per ha). For cotton and cereals, three values were given to PLR depending on the number of pairs (spans) of cattle owned: a high value when no pair of cattle was owned, a medium value when one pair of cattle was owned and a low value when two or more pairs of cattle were owned. According to the findings of Chapter 4, PLR was also set to be higher for cotton than for cereals, for a given number of cattle owned (Figure 5a).

Economic yields (kg ha^{-1}), output prices (US$ kg^{-1}) and production costs (US$ ha^{-1}) for cotton and cereals were the main inputs of the model. These variables were combined with PLR for cotton and cereals to calculate the 'return to labour peak ratio' (RLPR), defined as the ratio between the economic return of a unit of peak labour invested in cotton (US$ man-day^{-1}) and the economic return of a unit of peak labour invested in cereals (US$ man-day^{-1}). The value of RPLR was used to calculate the proportion of peak labour available for cotton production, the remainder being dedicated to cereal production (Figure 5b).

Figure 6 shows the results of six runs of the model presented above, for a farm of five people (each estimated to contribute 50 man-days of labour during peak periods and each consuming 150 kg cereal grain year^{-1}), receiving 400 kg cereal grain year^{-1} as food aid, receiving a cotton price of 0.3 US$ kg^{-1} and sustaining a cost of cotton production of 80 US$ ha^{-1}. A set of three runs used a cotton yield of 800 kg ha^{-1}, and another set of three runs a cotton yield of 1200 kg ha^{-1}. For each cotton yield, three runs were used with a market price for cereals of 0, 0.15 and 0.30 US$ kg^{-1}. The comparison of the outputs of these runs shows that commodity market is as important as yield in explaining the surface area occupied by a farm in an agricultural frontier (Figure 6). In particular, it shows that when the profitability of cereals increases and when cotton yields decline, the surface area required by a farm unit increases. In such a context, it also shows that supporting cotton productivity (i.e. increasing cotton yield) would be 'sparing land' (Chapter 3).

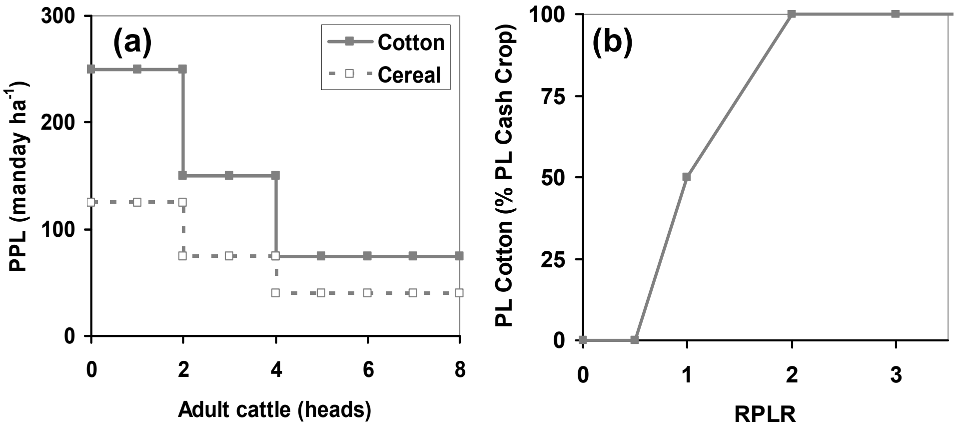

Figure 5. (a) Values of PLR (productivity of peak labour) for cotton and cereal production used in the model represented in Figure 4, as a function of the number of cattle; and (b) proportion of the peak labour available for cash cropping dedicated to cotton as a function of the value of RPLR (return to peak labour ratio)

This model could probably be adapted to most agricultural frontiers and the basic conclusion from this simulations would probably still stand i.e. that supporting the profitability of cash crops having large requirement in labour may ‘spare land’ for nature without compromising the livelihood of farming households. However, yield increase, may not be sufficient for an effective land sparing of natural vegetation to occur in agricultural frontiers (see below). The value of keeping forests may have to be increased for it to exceed the opportunity cost of clearing them for agriculture. This model and its outputs also show that the choice to be made between ‘wildlife-friendly farming’ and ‘land sparing’ is not only governed by the ability or not of the species of interest to survive in farmland under increasing farming intensity (Green et al., 2005), but also by the socio-economic characteristics of the farming systems considered. Well-meaning but poorly designed interventions - such as the promotion of cereal farming in the study area to divert farmers from the production of ‘polluting’ cotton – may lead to net negative effects on the environment (expansion of the surface area used for farming in our example). This illustrates the need for an interdisciplinary understanding – associating ecologist, agronomists and social scientists – to conserve biodiversity and ecosystem functions outside of protected areas.

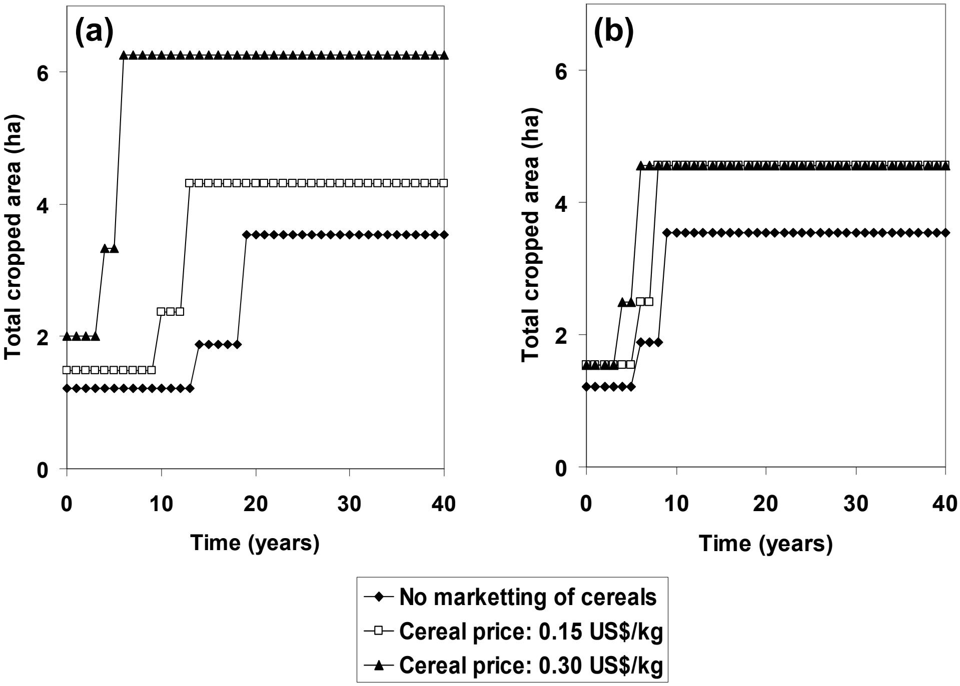

Figure 6. Results of a simulation using the model represented in Figure 4 with (a) a cotton yield of 800 kg ha^{-1} and (b) a cotton yield of 1200 kg ha^{-1}.

6.3. INTENSIFICATION AND PAYMENT FOR ENVIRONMENTAL SERVICES: POSSIBLE SYNERGIES

Agricultural intensification is required to save space for wildlife outside of protected area. However, extensification is often the rule in conservation landscape where land is not limited. As a result, yield-increasing technologies would be rejected in these areas as their implementation costs, in terms of capital and/or labour, are higher than the opportunity cost of clearing natural vegetation for agriculture (Chapter 5). In this section, I examine the possibility of payment for environmental services (PES) to save land for wildlife, first by raising the opportunity cost of clearing forests, and second by covering part of the cost of intensification. The PES approach recognizes the legitimate right of people to live in conservation landscapes and strives to compensate them for the foregone uses judged incompatible with the provision of environmental services, and to reward them for actively enhancing or maintaining environmental services (Grieg-gran et al., 2005; Swallow et al., 2009).

The PES approach states that environmental services have to be economically valued and that their increasing scarcity makes them potentially tradable (Wunder, 2007). The PES approach is not new (particularly in Latin America; Grieg-gran et al., 2005), but the globalization of these payments has only emerged in the 21st century. Carbon has become the most 'popular' global PES due to the prominence of climate change issues on the global agenda. Under the Clean Development Mechanism (CDM), industrialized countries are able since 2001 to meet a part of their emission reduction commitments by carrying out specific forestry activities to sequester carbon in developing countries (UNFCCC, 2001). However, only afforestation and reforestation are eligible for carbon credits under the CDM. Averted deforestation projects are not currently eligible under the first commitment period of the CDM and will only be considered post-2012. To fulfil this gap, the much debated 'Reduced Emission from Deforestation and forest Degradation' (REDD) was first introduced by the Coalition of Rainforest Nations at the 13th conference of the UNFCCC. REDD may be considered under the Voluntary Carbon Market. Although designed to limit harmful climate change, REDD could provide additional benefits, such as the conservation of biodiversity and the improvement of the livelihoods of the people living in conservation landscapes (Miles and Kapos, 2008; Venter et al., 2009).

Adapting the methodology used by Butler et al. (2009) to compare the potential value of tropical forest managed through REDD with the value of oil palm plantations, I compared the profitability of a natural dry forest in the study area if it were included in a REDD scheme to the profitability of the same area if it were cleared for cotton production. I used the values of carbon provided by Butler et al. (2009) for voluntary carbon markets and compliance markets. Results are provided by Table 2. They show that retaining forest areas and managing them through REDD is not economically competitive compared with cotton production if REDD credits are traded in voluntary markets: even the poorest yielding cotton plots economically outperforms the forest with the highest standing biomass. Outcomes might be different if REDD credits were traded in compliance markets (Table 2).

Table 2. Comparison of the minimum and maximum profitability (in US$) of one hectare of cotton and one hectare of standing forest generating 'Reduced Emission from Deforestation and forest Degradation' (REDD) credits traded through voluntary carbon markets or through compliance markets based on certified emission reductions (CER). The profitability from cotton fields was calculated from a production period of 30 years, a production cost of 244 US$ ha^{-1} year^{-1} (cost during the 2008-09 cropping season; source: Alliance ginneries LTD), a seed cotton price of 0.15 US$ kg^{-1} (average price for 2009 in the study area). Minimum and maximum profitability of cotton fields were based on cotton yields of 600 kg ha^{-1} and 1200 kg ha^{-1}, respectively. The profitability of the standing forest when REDD credits were traded through voluntary carbon markets and compliance CER markets was calculated with a value of CO_2 equivalent of 4.4 US$ t^{-1} and 37.57 US$ t^{-1} respectively (Butler et al., 2009). Minimum and maximum profitability of the standing forest were based on a quantity of above-ground carbon of 42 t ha^{-1}, and 96 t ha^{-1} respectively (Tambara et al., unpublished).

Value	Cotton field	Standing forest	
		Voluntary carbon market	Compliance CER
Minimum	1 602	650	5 554
Maximum	4 302	1 511	12 900

Moreover, monitoring, transaction and protection costs were not deducted from the profitability of the standing forest managed through REDD in the calculation used. They may be extremely variable, and may reduce the profitability of standing forests substantially. It has been argued that REDD would only benefit areas where forest protection is the most cost effective. For example, Venter et al. (2009) estimated that with a target of a 20% reduction in deforestation, funding for cost-effective REDD would be expected almost exclusively in South America, where agricultural opportunity costs are relatively low. Some authors have concluded that REDD is unlikely to benefit biodiversity in areas where carbon benefits are small, unless additional resources can be sourced – such as a biodiversity premium paid by willing purchasers of REDD credits (Miles and Kapos, 2008; Venter et al., 2009). Similarly, in the absence of a 'pro-poor premium', other authors have argued that REDD was unlikely to benefit poor communities in the developing world, but rather better-off, more efficient suppliers (Grieg-gran et al., 2005; Laurance, 2008; Smith et al., 2009). Transaction costs and monitoring costs are indeed expected to be higher when many landholders are involved and when land uses are diverse.

Despite of these draw-backs, REDD and other PES could play a pivotal role in catalysing land use changes that are compatible with both agricultural production and biodiversity conservation. In particular, PES could finance (part of) the cost of the inputs required for intensification and (part of) the cost of promoting technologies ensuring that these inputs are used as efficiently as possible. This opportunity has not been explored fully. Avoiding 'leakages' - i.e. displacement of agriculture and other pressures - is a fundamental component of any PES project, as such leakages are otherwise deducted from PES benefits. However, this often translates into the promotion of low-input farming methods assumed to increase yield, but not of high-yield (input intensive) farming methods. I see a large opportunity in creating a functional tandem between PES and (ecological) intensification: PES may contribute towards triggering a process of intensification, whilst intensification could spare the land needed to generate PES. Figure 7 represents schematically this vision for the study area. In this area, a PES scheme already exists since 1989: the Communal Area Management Program for Indigenous Resources (CAMPFIRE). Through this scheme, the Rural District Council (i.e. local Government) markets on behalf of local communities trophy hunting quotas – mainly elephants and buffaloes – to an international safari hunting clientele (Taylor, 2009). Income from CAMPFIRE can be considered a compensation to rural households for the opportunity cost of retaining patches of wildlife habitat and for the cost – in terms of crop and livestock damage and threat to human lives - of living with wildlife (Frost and Bond, 2008). Revenues generated by CAMPFIRE may be substantial (Taylor, 2009), but were not sufficient to deter residents from cotton production and to attract them towards wildlife conservation (Chapter 2). A similar outcome is likely with REDD in the study area (Table 2). The combination of the two PES, however, may generate enough revenues to change land management, especially so, I argue, if the bulk of these revenues is used for the purchase of yield-increasing external inputs (fertilisers in particular). Additionally, premium prices could encourage the production of cotton through technologies maximizing the efficiency of use of external inputs (see above).

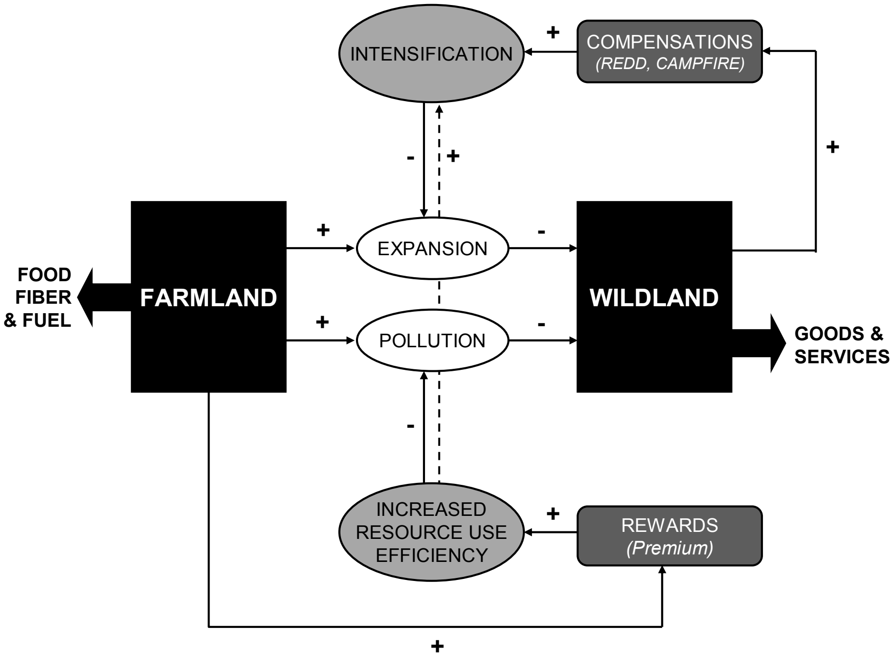

Figure 7. Potential role of payment for environmental services (compensations and rewards) in encouraging intensive and efficient cropping systems that are both productive and benign for the environment.

For the implementation of this vision to be effective, it should be acknowledged that strong regulations should be in place and enforced. For instance, avoiding free riding of community members is key (Pretty, 2003). Controlling immigration is also of prime importance to preserve a certain stability between resource users and the resource itself (Scholte, 2003; Balmford and Whitten, 2008). A prerequisite is, of course, the existence of strong local institutions (Pretty, 2003) and of mechanisms of local governance. However, PES programmes tend to jump from technical issues to politico-legal issues without ensuring that appropriate local institutions and governance are in place (Rands et al. 2010). Last but not least, knowledge at landscape level is required on the relationship between the amount of services of interest being delivered and different land use patterns (Kremen et al., 2004; Polasky et al., 2005).

6.4. THREE PERSISTENT MYTHS ABOUT AGRICULTURE AND CONSERVATION IN AFRICA

The myths presented below, I argue, are widely spread in the Western world and influence the donor-community and policy makers. They do not help mitigating the conflicts between agricultural production and biodiversity conservation, but in fact enhance these conflicts. These myths, I argue, are a barrier to any form of pragmatic innovation that could improve the interaction between agricultural production and biodiversity conservation in conservation landscapes of the developing world, Africa in particular.

6.4.1. The 'wilderness myth'

Africa is often presented by Western conservationists as a wild continent unspoilt by Western civilization. This 'wilderness myth' is a resurgence of old romantic discourses inherited from colonial contacts with Africa (Wolmer, 2007). It is being widely marketed by the industry of safari tourism, documentaries and even cartoons (Norton, 1996; Vivanco, 2004; Murray and Heumann, 2007). It also influences deeply policy-makers and donors in believing that conservation landscapes of Africa are pristine and have emerged independently of the action of people (Pretty, 2003). This is of course a deeply erroneous perception: most of the population of sub-Saharan Africa lives in the most biodiversity-rich areas (Balmford et al., 2001). 'Wildlands' without evidence of human occupation or human use represent in fact only 22% of Earth's ice-free land, most of which being located in the least productive regions, in barren region with sparse tree cover (Ellis and Ramankutty, 2008).

'Wilderness' is a misrepresentation of reality, a product of the Western culture and, as Cronon (1996) puts it, a "f*antasy of people who have never themselves had to work the land to make a living*". The wilderness myth is off course a threat to people living in conservation landscapes of the developing world, and it has been used widely to expropriate people from their land (e.g. Brook, 2005). But this myth is also a threat to biodiversity. By separating people and nature, it denies any possibility of biodiversity conservation outside of protected areas. The current network of protected areas in the developing world is already underfunded (James et al., 2001, estimate that only a third of its financial needs are covered). The gap between current funding and funding needs is also likely to increase as the cost of enforcement will rise with increased population (Balmford and Whitten, 2003). Therefore, the development of alternative approaches to the wilderness approach ('fences-and-fines') is urgently needed, not only to preserve the source of livelihood of people living in conservation landscapes, but also to conserve biodiversity itself. The myth of wilderness, finally, encourages Westerners to believe they are separate from nature. As pointed out by Cronon (1996), this is likely to reinforce environmentally irresponsible behaviour. It is also likely to create distance between Westerners and non-Westerners living in conservation landscapes.

6.4.2. The myth of the 'ecologically noble savage'

The resurrection in the past decades of the image of 'wild Africa' by Western conservationists has been paralleled by the resurrection of the image of the 'non-Western primitive' (Neumann, 1996). The 'primitivist discourse' has long been used by Western ideologies to justify land use interventions in Africa. During the colonial era, the 'primitive' methods of 'backward' African farming were condemned as 'inefficient' and 'destructive', and massive state intervention for soil conservation was called for (Chapter 5). The 'primitivist discourse' resurfaced around the time of the Earth Summit in Rio de Janeiro in 1992. This time, however, 'the non-Western Other' is not being demonized, but romanticized in a similar way as European sentimentalist literature did in the 18th century, with the 'noble savage'. The discourse of what is sometimes referred to as the 'ecologically noble savage' (Hames, 2007), argues that 'local people' have been living in harmony with nature for generations, thanks to their traditions and cultural values (Neumann, 1997). Unsustainable practices are seen as resulting from the incursion of immigrants and/or the breakdown of traditional societies. The ecologically noble savage myth is widely propagated by cultural products such as the magazine *National Geographic* (Lutz and Collins, 1993; Neumann, 2004).

The ecologically noble savage discourse has been used by few indigenous groups, mainly in Amazonia, as a political tool to secure land rights (Hames, 2007). More generally, however, this stereotype has threatened rather than secured the livelihood of the communities living in conservation landscapes. First, if these communities fail to demonstrate to Western conservationists the benign nature of their practices on biodiversity, they may be evicted (Neumann, 1997; Chapin, 2004). Secondly, the need to preserve 'ecological nobility' dictates for 'local', 'traditional' practices to be preserved from the threat of 'outside' 'modern' practices. It leaves these communities isolated and unable to innovate technically and institutionally, despite their often rapidly changing environment. The use of external inputs is forbidden, following the myth that organic farming is the only mode of farming compatible with nature conservation (see below). Institutional innovation is forbidden, following the assumption that 'traditional' societies need to be preserved. This naïvely ignores their heterogeneity and their internal conflicts, which may weaken them against the influence of new powerful stakeholders (e.g. logging companies, mining companies; Giller et al., 2008).

6.4.3. The 'organic myth'

During Alvord's days, agricultural intensification of smallholder farming was expected from heavy manure application and N_2-fixation by legumes (Chapter 5). However, Alvord himself acknowledged that the manure rates he was recommended were simply not realistic for Zimbabwean smallholders who did not have enough cattle or, for the majority, did not have any cattle at all (Machingaidze, 1991; Bolding, 2004). Similarly, frequent rotation of grain crops with legume crops has remained impracticable, as legume have remained a minor crop, due mainly to lack of market. Thus, maintaining smallholder production on permanently cultivated fields using solely organic nutrient sources was simply a myth. I argue that this myth has persisted through CA. Indeed, the key role of mineral fertilisers in obtaining high yields in small CA plots meticulously managed is often downplayed or ignored (Haggblade and Tembo, 2003). Whereas this study has shown that CA may only have a positive effect on crop yield in smallholder systems when adequate fertilisation is in place (Chapter 4), the belief that CA can increase productivity without further need for mineral fertiliser (or with less mineral fertiliser) is spread by popularised and widely diffused reports such as "*Scaling up Conservation Agriculture in Africa: strategy and approaches*" published by FAO (2009b). In this report, mineral fertilisers are only mentioned in a table constructed with supposedly empirical data from a Kenyan farm and showing a yield in CA double of the yield with "*conventional* *farming*" with half the amount of mineral fertiliser. In the same report, CA is said to promote "*the management of the finite soil resource with great care to safeguard the organic matter and natural inherent fertility*" and to be "*based upon soil life and health*". This support the construction of CA projects that use at best small quantities of mineral fertilisers (see for example the promotion of 'micro-dosing' in parallel with CA, Twomlow et al., 2010).

This undue stress on minimal reliance on mineral fertilisers comes from the fact that the donor community appears to favour farming technologies based on organic rather than mineral inputs, to avoid environmental problems similar to those that have developed in Europe and North America (Giller et al., 2002). Excessive use of mineral fertilisers may be an environmental threat in Western countries, but their increased use is probably an environmental opportunity for conservation in the study area (and in most of Africa) given the net quantities of nutrient being removed annually due to farming (Chapter 3).

An 'organic myth' is targeting Africa, the last area where the Green Revolution did not take place. Increased production in an environmentally-friendly way is expected to occur without external inputs, but rather using legumes, farmyard manure, agroforestry species and mulches. This is a (dangerous) myth for a number of reasons. First, organic amendments can only sustain crop production on their own in rare cases, due to limitations in their quality and their availability (Vanlauwe and Giller, 2006). In the study area, residue retention and use of available manure would only marginally improve partial nutrient balances, which would remain negative (Chapter 3). Second, it is unclear if the slow release of nutrients from organic composts and green manures can adequately match crop demand (Palm et al., 2001). Third, organic farming achieves yields inferior to those achieved by intensive farming, and thus consumes more space to meet any production target (Green et al., 2005). The production of manures and plant materials for the maintenance of fertility in organic farming also requires extra land (e.g. grazing area, field dedicated to the production of biomass), what Guzman Casado and Gonzales de Molina (2009) describe as "*the land cost of sustainability*".

Farming systems based on organic nutrient sources appeal to donors and development agencies, because they require a diversified system, with livestock to produce manure, legumes fixing N_2, agroforestry species to recycle nutrients, catch crops to attract pests, etc. Diversification is perceived as an aim to pursue for smallholder farming systems. However, Frost et al. (2007) view a diversified livelihood strategy more as a reflection of the lack of opportunity to specialize in high-income activities and/or of a risky environment. Indeed, when a number of factors are right, smallholders can develop through specialized production systems, as has been the case in Zimbabwe with the so called ‘maize-based green revolution’. Thanks to a combination of political stability, the promotion of short-season hybrid varieties, high guaranteed producer prices, subsidies from the Grain Marketing Board and increased access to credits for the purchase of seeds and fertilisers, the national smallholder maize production doubled in six years, between 1980 and 1986 (Eicher, 1995). Also more than half a century earlier, Zimbabwean smallholders had taken advantage of the maize market during the ‘decade of peasant prosperity’ (1915-1925; McGregor, 1995).

Therefore, the ‘organic myth’ resonates strongly with the myth of the ‘ecologically noble savage’. By making sure African farmers do not commit the same ‘mistakes’ as Western farmers when engaging in intensification, African farmers are denied what makes Western farming successful: external inputs and specialization.

6.5. CONCLUDING REMARKS

Over the past ten 10 years that I have visited the Mid-Zambezi Valley regularly, I have observed a rapid conversion of natural vegetation for agriculture and a rarefaction of large mammal sightings. The Mid-Zambezi Valley has been an agricultural frontier since the late 1980s and has continued to receive migrants. With political instability and economic collapse in the recent years, the flow of migrants in search of a source of livelihood – mainly former employees in urban centres and commercial farms - has increased. If the conservation of African wildlife outside of the few protected ‘islands’ scattered across the continent is a desirable goal, it is obvious from the example of the Mid-Zambezi Valley that alternatives are needed, in order to alleviate pressure on wildlife without degrading local livelihoods. CAMPFIRE offers a great base on which to construct a ‘CAMPFIRE+’ that would integrate payment for environmental services and agricultural intensification, under the control of strong local institutions. Implementing such an approach, I argue, is not insurmountable if existing interventions are coordinated and if resources are pooled together. In fact, only a modest fraction of the existing cash flow of the Mid-Zambezi Valley (from donor-funded projects, the cotton industry, the safari industry, CAMPFIRE, ecotourism, etc) might be sufficient. The greatest challenge is probably for our perceptions of conservation landscapes in Africa, and what they should be, to be freed from myth.

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Appendix 1 – Trend in cotton profitability in Mbire District

Appendix 2 - Local sorghum varieties in Mbire District

Appendix 3 - Sacred trees in Mbire District

Appendix 4 – Contribution of weeds to biomass production and N retention in the fields of Mbire District

Appendix 5 – Construction of the dynamic model for the farming systems of Mbire District

Appendix 1 – Trend in cotton profitability in Mbire District

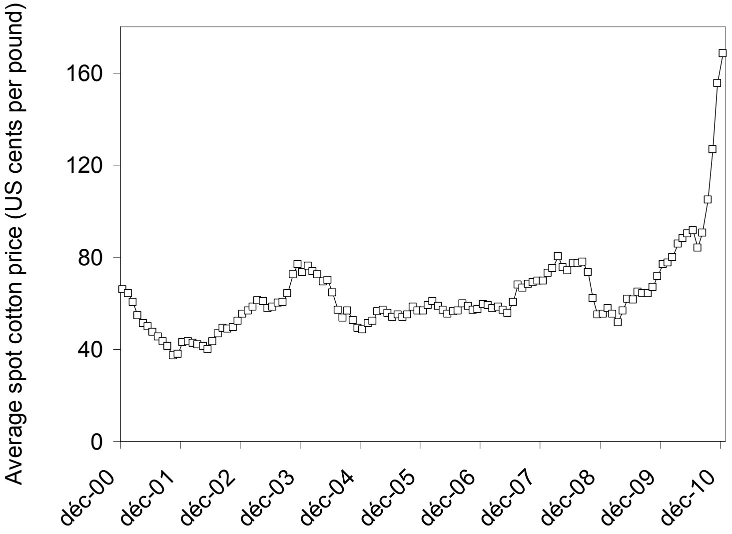

Figure 1. Trend in the world prince of cotton lint (in US$ cent per pound), from December 2000 to December 2010 (Source: USDA Market News).

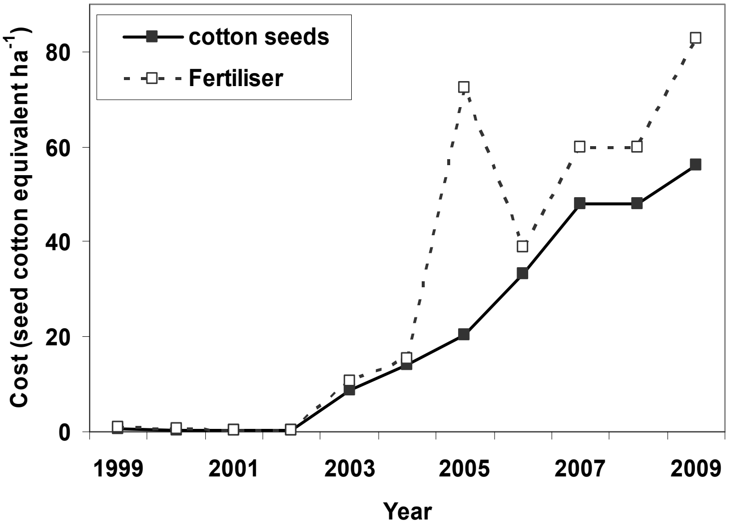

Figure 2. Cost of cotton seeds and fertiliser needed for one hectare, in seed cotton equivalent (‘recovery rates’) from 1999 to 2009 (Source: the Cotton Company of Zimbabwe).

Appendix 2 - Local sorghum varieties in Mbire District

Table 1. Local sorghum varieties in Mbire District and their main characteristics (data collected during Community Seed Fairs, Participatory Rural Appraisal in three locations - Mushumbi Pools, Mazambara and Angwa bridge – and interviews)

Vernacular name	High-yielding (*)	Possibility to eat green grains	High biomass production (*)	Short- to Medium-season	Adapted to moderate rainfalls and droughts	Unpalatable to birds	Unpalatable to wildlife	Characteristics
Kandheva	X			X	X	X		Grains white outside, red inside
Kanzvovzo			X	X	X	X	X	Red sorghum; very well suited to beer production; not suited for sadza[1] (causes constipation)
Kanzamba / Kapudzi Duri		X	X	X	X		X	Multipurpose variety (sadza, beer); sweet grains (well suited for maheu[2])
Nyanjena / Nyanjeya		X	X				X	Open heads
Chisiri / Nyamukomba			X			X	X	Very big heads; heads that bends when matured (avoiding bird attacks and germination before harvest if late rains are received); produces a good sticky sadza
Kanjeya		X	X				X	Small heads
Matipa		X	X				X	Ovoid grains; water demanding; has to be planted early (dry planting)
Rongwe			X				X	Tallest and longest season variety (harvested in June), water demanding; has to be planted early (dry planting)
Chinyande			X				X	Similar to *Rongwe* but maturing faster and having smaller and whiter grains

* compared with an improved commercial variety

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[1] Thick porridge

[2] Non-alcohol beer

Appendix 3 - Sacred trees in Mbire District

Table 1. Main sacred trees traditionally kept in the fields of Mbire District (data collected through Participatory Rural Appraisal in three locations - Mushumbi Pools, Mazambara and Angwa bridge – and individual interviews)

Scientific name	Vernacular name	English name
Andasonia digitata	Mahuyu	Baobab
Brachystegia manga	Mukamba	Blue-leaves Brachystegia
Cordylia africana	Mutondo	Wild mango
Diospyros mespiliformis	Mushuma	Jackal-berry/Africa Ebony
Faidherbia albida	Musangu	Winter Thorn
Ficus bussei	Mutowe	Zambezi Fig
Ficus capreifolia	Muchichiri	River Sandpaper Fig
Khaya anthotheca	Mururu	Red Mahogany
Kigelia africana	Mumvee	Sausage Tree
Kirkia acuminata	Mutwa/Mubvumira	White Seringa
Piliostigma thonningii	Mutukutu	Camels-foot
Sterculia africana (*)	Murere	Tick tree
Tamarindus indicus	Musiga	Tamarind

* the only specimens of this species that are sacred are those that are too big to be encircled by an adult person

Appendix 4 – Contribution of weeds to biomass production and N retention in the fields of Mbire District.

During the 2008-09, nine farms were selected in the study area: three in West Angwa, three in East Angwa and three in Mushumbi Pools (see Figure 1 of Chapter 3 for a description of these three geographic zones). In each geographic zone, the three farmers were selected on the basis of resource-endowment: poor, medium and rich. For the cotton, maize and sorghum fields of these farmers (generally one field per crop per farm), above-ground biomass of weeds and crop was estimated twice in the season: at harvest time, and at the end of the dry season (immediately before the beginning the succeeding rainy season). In each field, 5 m × 5 m quadrants were placed randomly. The number of quadrats set in each field depended on the size of the field, with the aim of sampling roughly 1% of the total field area. Above-ground biomass was clipped in each quadrant and divided in crop biomass and weed biomass. Crop and weed biomass were weighed separately, and a sample was oven-dried for 48 hours at 60°C to convert to kg dry matter (DM) ha^{-1}. During the sampling at harvest time, the various weed species present in the quadrants were also recorded. The most frequent ones were sampled and the samples were oven-dried for 48 hours at 60°C and their N concentration was determined colorimetrically after a Kjeldahl digestion.

Figure 1 compares the N concentration in the biomass of the most frequent weed species and the major crops. Figure 2 compares the contribution of crop and crop + weed to above-ground biomass and N in the above-ground biomass at harvest time and at the end of the dry season.

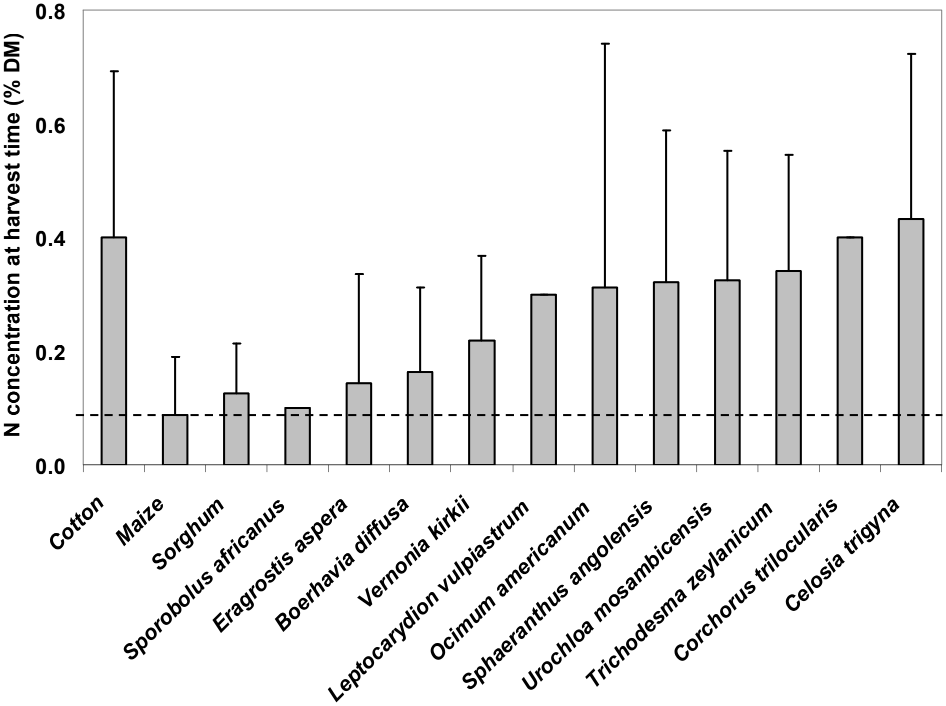

Figure 1. Mean concentration in N of the residues of the main crops (cotton, maize and sorghum) and of the 11 most frequent weed species (i.e. encountered in at least 30% of the plots surveyed), at the time of harvest (between end of April and beginning of June). The dotted line represents the mean concentration in maize residues (0.09%).

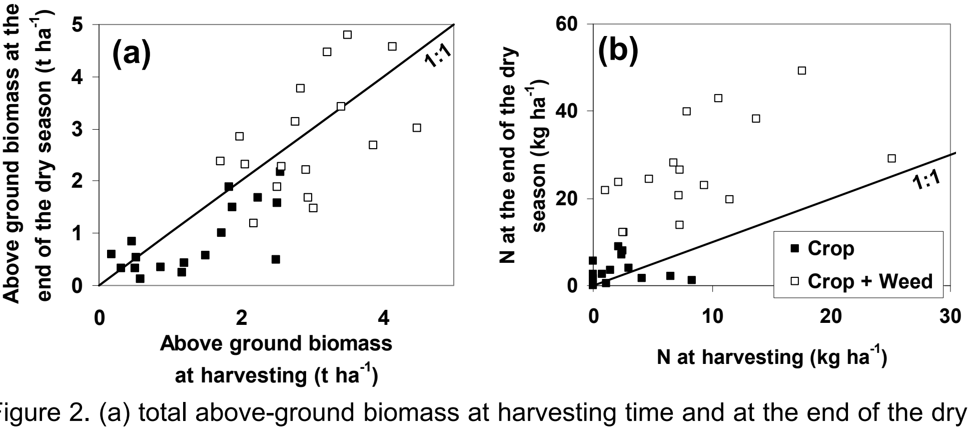

Figure 2. (a) total above-ground biomass at harvesting time and at the end of the dry season when considering crop only or crop and weeds; and (b) total above-ground N at the time of harvesting and at the end of the dry season when considering crop only or crop and weeds.

Appendix 5 – Construction of a dynamic model for the farming systems of Mbire District.

VARIABLES:

TOT_AREA(t) : Total cropped area at time t (ha)

AREA_COT(t) : Area cropped in cotton at time t (ha)

AREA_CRL_FD(t) : Area cropped in cereal for food production at time t (ha)

AREA_CRL_CSH(t) : Area cropped in cereal for cash at time t (ha)

PROD_CRL_FD(t) : Cereal production for food at time t (kg)

CATTLE(t) : Number of cattle at time t (head)

CASH(t) : Cash savings at time t (US$)

INC(t) : Income at time t (US$)

EXP(t) : Expense at time t (US$)

TOT_PL : Total labour available at peak (man-day)

PL_CSH(t) : Peak labour invested in cash cropping at time t (man-day)

PL_COT(t) : Peak labour invested in cotton production at time t (man-day)

PL_CRL_FD(t) : Peak labour invested in cereal production for food at time t (man-day)

PL_CRL_CSH(t) : Peak labour invested in cereal production for cash at time t (man-day)

PROP(t) : Proportion of the peak labour for cash cropping invested in cereal production

RPLR(t) : Return to peak labour ratio at time t

PLR_COT(t) : Peak labour requirements of cotton production at time t (man-day ha^{-1})

PLR_CRL(t) : Peak labour requirements of cereal production at time t (man-day ha^{-1})

PARAMETERS:

HH : Size of the household (people)

F_AID : Cereal received as food aid (kg)

YLD_COT : Cotton yield (kg ha^{-1})

YLD_CRL : Cereal yield (kg ha^{-1})

P_COT : Cotton price (US\$ kg^{-1})

P_CRL : Cereal price (US\$ kg^{-1})

CST_COT : Cost of cotton production (US\$ ha^{-1})

RBR : Relative birth rate of cattle

RDR : Relative death rate of cattle

EQUATIONS:

$$\text{TOT\_AREA}(t) = \text{AREA\_COT}(t) + \text{AREA\_CRL\_FD}(t) + \text{AREA\_CRL\_CSH}(t)$$

$$\text{AREA\_COT}(t) = \text{PL\_COT}(t) / \text{PLR\_COT}(t)$$

$$\text{AREA\_CRL\_FD}(t) = \text{PROD\_CRL}(t) / \text{YLD\_CRL}$$

$$\text{AREA\_CRL\_CSH}(t) = \text{PL\_CRL\_CSH}(t) / \text{PLR\_CRL}(t)$$

$$\text{PROD\_CRL\_FD}(t) = (\text{HH} \times 150) - \text{F\_AID}$$

$$\text{CATTLE}(t) = (\text{CATTLE}(t-1) \times (1 + \text{RBR} - \text{RDR})) + \text{PUR}(t)$$

$$\text{CASH}(t) = \text{CASH}(t-1) + \text{INC}(t) - \text{EXP}(t) - (\text{PUR}(t) \times 200)$$

$$\text{INC}(t) = (\text{AREA\_COT}(t) \times \text{YLD\_COT} \times \text{P\_COT}) - (\text{AREA\_COT}(t) \times \text{CST\_COT}) + (\text{AREA\_CRL\_CSH}(t) \times \text{YLD\_CRL} \times \text{P\_CRL})$$

$$\text{EXP}(t) = \text{HH} \times 15$$

$$\text{TOT\_PL} = \text{HH} \times 50$$

$$\text{PL\_CSH}(t) = \text{TOT\_PL} - \text{PL\_CRL\_FD}(t)$$

$$\text{PL\_COT}(t) = \text{PROP}(t) \times \text{PL\_CSH}(t)$$

$$\text{PL\_CRL\_FD}(t) = \text{AREA\_CRL\_FD}(t) \times \text{PLR\_CRL}(t)$$

$$\text{PL\_CRL\_CSH}(t) = \text{PL\_CSH}(t) - \text{PL\_COT}(t)$$

$$\mathrm{RPLR}(t) = (((\mathrm{AREA\_COT}(t) \times \mathrm{YLD\_COT} \times \mathrm{P\_COT}) - (\mathrm{SF\_COT}(t) \times \mathrm{CST\_COT})) / \mathrm{PLR\_COT}(t)) / ((\mathrm{AREA\_CRL\_CSH}(t) \times \mathrm{YLF\_CRL} \times \mathrm{P\_CRL}) / \mathrm{PLR\_CRL}(t))$$

$$\mathrm{PROP}(t) = \begin{cases} 0 & \text{if } \mathrm{RPLR}(t) < 0.5 \\ \mathrm{RPLR}(t) - 0.5 & \text{if } 0.5 =< \mathrm{RPLR}(t) < 0.5 \\ 0.5 + 0.5\,(\mathrm{RPLR}(t) - 1) & \text{if } 1 =< \mathrm{RPLR}(t) < 2 \\ 1 & \text{if } \mathrm{RPLR}(t) >= 2 \end{cases}$$

$$\mathrm{PLR\_COT}(t) = \begin{cases} 250 & \text{if } \mathrm{CATTLE}(t) < 2 \\ 150 & \text{if } 2 =< \mathrm{CATTLE}(t) < 4 \\ 75 & \text{if } \mathrm{CATTLE}(t) >= 4 \end{cases}$$

$$\mathrm{PLR\_CRL}(t) = \begin{cases} 125 & \text{if } \mathrm{CATTLE}(t) < 2 \\ 75 & \text{if } 2 =< \mathrm{CATTLE}(t) < 4 \\ 40 & \text{if } \mathrm{CATTLE}(t) >= 4 \end{cases}$$

INITIAL CONDITIONS:

$\mathrm{CATTLE}(0) = 0$

$\mathrm{CASH}(0) = 0$

Summary

Competing claims for land are acute in the developing world. An increase in agricultural production is required to feed its growing population whilst there is desire to prevent biodiversity loss, not least to maintain ecosystem processes. Agriculture affects local biodiversity through direct change in land use, and regional and global biodiversity through indirect effects such as fragmentation and alteration of hydrological and biogeochemical cycles. Innovative farming technologies using the principles of 'conservation agriculture' (CA) have emerged in various parts of the world, with the aim of combining profitable agriculture with minimum negative consequences for the environment. In particular, CA is currently been vigorously promoted by a wide range of international research and development organisations. In some of Zimbabwe's agricultural frontiers shared with wildlife, CA has been proposed as a means to increase agricultural productivity and reduce wildlife decline. Mbire District can be considered agricultural frontier. It lies in the Mid-Zambezi Valley, in the northern fringe of Zimbabwe, and hosts a well-preserved biodiversity, including the emblematic African megafauna (e.g. elephant, buffalo, hippopotamus, lion, leopard, kudu, sable, impala). Wildlife abundance in Mbire District results from the fact that until recently, the area was considered marginal for agriculture. After Zimbabwe's independence in 1980 the area witnessed a 'cotton boom' as a result of large-scale tsetse fly eradication campaigns, smallholder resettlement schemes and the promotion of cotton farming. As a result, wildlife habitat has shrunk and wildlife numbers have been reported to decline. Integrating insights from various disciplines and spatial dimensions, the main objective of this study was to describe and analyse current tensions between agricultural production and environmental conservation; and then to explore the potential of CA to intensify agricultural production with minimum negative environmental effects, and therefore save space for wildlife.

To quantify land use changes that occurred since independence in a pilot zone of Mbire District and to analyse the contribution of a number of drivers to these changes, existing data were analysed and a land use data base was developed for two wards (administrative sub-divisions of district) within Mbire District (Chapter 2). In

these two wards, participatory rural appraisal and individual farm interviews (*n* = 176) were also carried out to analyse the contribution of three major potential drivers: (1) increase in human population; (2) increase in cattle population (and the expansion of associated plough-based agriculture), and; (3) expansion of cotton farming. The population of Mbire District almost doubled between 1992 and 2002, while the livestock densities increased at rates above 15% in the early 1990s and the late 2000s. In both wards, an exponential relationship described the expansion of farmland over the years, from 1980 to 2007. Although direct effects of land use change on wildlife densities could not be proven, our study suggests that the consequences for elephant and buffalo numbers are negative. All three of the above drivers have contributed to the observed land use change. However, farmland was found to expand faster than human population, and to have followed a similar rate of expansion in cattle sparse, tsetse infested areas as in tsetse free areas where cattle-drawn plough agriculture dominates. This implies the existence of a paramount driver, which is demonstrated to be cotton farming. Contrary to common belief, tsetse control was not the major trigger behind the dramatic land use change observed in Mbire District, but merely alleviated a constraint to cattle accumulation. Without the presence of a cash crop (cotton), land use change would have been neither as extensive nor as rapid as has been observed. The way people farm, therefore, is as great a concern as population increase.

To compare the impact on the environment of food crop farming (cereals) versus cash crop farming (cotton) in Mbire District, we developed a measure of the ‘environmental footprint’ of farming based on ten locally-relevant indicators: cropped area, fallow area, pesticide use, plant diversity loss, soil C loss, N, P and K removal values, calorific deficit and forage deficit (Chapter 3). The analysis was done on 37 farm households of varying resource endowment in three locations along a gradient of increasing farming intensity: West Ward 2, East Ward 2 and Ward 3 and 9. The environmental footprints of farming in West Ward 2 and East Ward 2 (low population density and farming intensity) were very small compared with that of Ward 3 and 9 (higher population density and farming intensity). Four farm types were delineated along the cereal-based/cotton-based continuum of farms. West Ward 2 had more farms growing mainly cereals than Ward 3 and 9, which had more farm growing large areas of cotton. East Ward 2 represented an intermediate distribution of farms. The environmental footprint per farm was increasing significantly when 'moving up' along the cereal-based/cotton-based continuum. A kilogram of seed cotton required 60% more land, removed twice as much N, 50% more K and 20% more P than a kilogram of cereal. However, except for pesticide use and N removal, one man-day invested in cotton production had a smaller environmental footprint than a man-day invested in cereal production. This might lead to important differences in environmental footprints if farmers were to specialise in one crop or another, as farming in Mbire District is limited by labour more than by land. Specialising in cereal production would increase the total cropped area by more than 20% and the total fallow area by more than 35% in East Ward 2 and in Ward 3 and 9. By contrast, specialising in cotton production would decrease the total cropped area by more than 30% and the fallow area by more than 20% in East Ward 2 and in Ward 3 and 9. Therefore, maintaining or increasing the relative profitability of cotton vs. cereal may 'spare land' for nature.

Impact of farming on biodiversity does not only depend on the type of crop grown or on the area being cultivated, but also on the way in which the land is farmed. To explore the potential of CA to increase crop productivity in the short-term under the semi arid conditions of Mbire District, unfertilised on-farm trials were conducted during three consecutive seasons and farmers' cotton fields receiving various fertilisation rates were monitored during two seasons (Chapter 4). The performance of CA was compared against current farmers' cropping practices (CP), for the production of cotton and sorghum. In addition to biophysical measurements, farmers' perceptions of the technology were also assessed. CA did not affect cotton productivity during the first two years of experiment, which received average or above average rainfall. During the drier 2009-10 season, rather than stabilising yield, CA had a slightly negative effect both in on-farm trials (average yield of 730 and 820 kg ha^{-1} under CA and CP, respectively) and in farmers' cotton fields (average yield of 1220 and 1440 kg ha^{-1} under CA and CP, respectively). There was no difference in runoff between CA and CP on a relatively fine-textured soil, but significantly more runoff with CA on a coarser-textured soil (14 mm during the wetter 2008-09 season), due to surface crusting. Most soils in the study area fall into this latter category. For these reasons, farmers perceived ploughing as necessary during drier years to maximize water infiltration, but saw CA as beneficial during wetter years as a means to 'shed water' and avoid waterlogging. This challenges the common description of CA as a water-harvesting technology. Crusting may be avoided by the production of greater quantities of mulch than what was achieved in this study (average of 770 kg ha^{-1} in on-farm trials). The retention of sorghum residues and the inclusion of N_2-fixing legumes, however, resulted in less N being exported by cropping from the CA fields compared with the CP fields.

To understand how CA would fit in the farming systems of Mbire District, this model was compared to another model of agricultural intensification, the Alvord model, which was introduced in colonial Zimbabwe 80 years ago (Chapter 5). More specifically, smallholder farming practices in Mbire District and their embedding in a wider socio-economic environment were also analysed. From Alvord to CA, it appears that the approach used in agricultural research and extension for smallholders has changed little in almost a century. In particular, local practices have been persistently disregarded, and the problem of low productivity and land degradation in African agriculture has remained perceived as purely technical. The analysis of smallholder farming practices in Mbire District showed how the socio-economic constraints they faced (and that smallholders in most parts of southern Africa probably face) – e.g. limited cash, labour peaks, low output and high input prices, and high risks – predisposed them towards extensification. Technical packages which may exacerbate such constraints are ill-suited to the circumstances of smallholder farmers. Agricultural technologies do not, however, have strict intensifying or extensifying properties: often they have both. It is the interaction between the technology and the agro-ecological and socio-economic environments which directs farming on an intensification or extensification pathway. In Mbire District, where labour availability for weeding is a major limiting factor, the increased weed pressure in CA is a major – but probably not the only – reason preventing farmers from embracing it.

As a conclusion (Chapter 6), mitigating conflicts between the increase of agricultural production and biodiversity conservation requires major innovations, far beyond CA. CA should be seen as part of a larger basket of technologies aiming at 'ecological intensification'. In the limited circumstances where CA is the most appropriate one, it will have to be adapted to local circumstances to fit farming systems. A pragmatic, more flexible approach than presently used is required for the design, evaluation and extension of technologies based on CA principles. Intensification itself is unlikely in agricultural frontiers, where extensification is often the rule. In these areas, when designing and evaluating cropping systems, researchers have to let go of the traditional emphasis on land productivity (yield) and rather focus on labour productivity. Payment for environmental services, associated with (ecological) intensification, offers great potential to secure profitable agricultural production and effective biodiversity conservation in these landscapes. For such an approach to be implemented, local communities would have to be empowered through the right interventions, and not, as often the case, through interventions targeting mythical wilderness areas as home of a mythical noble savage.

'Competing Claims' op land zijn vaak acuut in de ontwikkelingslanden. Een verhoging van de landbouwproductie is nodig om de groeiende bevolking te voeden, maar tegelijkertijd zou dit niet ten koste moeten gaan van de biodiversiteit en het ecosysteem. Landbouw beïnvloedt de lokale biodiversiteit middels directe verandering in het landgebruik, en de regionale en mondiale biodiversiteit door indirecte effecten, zoals de versnippering en verandering van hydrologische en biogeochemische cycli. Innovatieve landbouwmethoden gebaseerd op de principes van '*Conservation Agriculture'* (CA) pogen winstgevende landbouw te combineren met minimale negatieve gevolgen voor natuur en milieu. CA is ontwikkeld en geïmplementeerd in verschillende delen van de wereld en in de afgelopen jaren is het ook grootschalig gepromoot onder kleinschalige boeren in Afrika door een breed scala van internationale onderzoeks- en ontwikkelingsorganisaties.

Zimbabwe heeft een aantal gebieden waar landbouw en beschermde natuurgebieden aan elkaar grenzen (*agricultural frontiers*), en waar wild zowel binnen als buiten beschermde gebieden voorkomt. In deze gebieden is CA geïntroduceerd om de landbouwproductiviteit te verhogen, en tegelijkertijd een daling in wild-populaties tegen te gaan. Mbire district in de *Mid Zambezi Valley*, in het noorden van Zimbabwe, is zo'n gebied. Het staat bekend om zijn goed bewaarde biodiversiteit, inclusief de karakteristieke Afrikaanse megafauna (bijv. olifanten, buffels, nijlpaarden, leeuwen, luipaarden, kudu, sable, impala). Deze overvloed aan wild in Mbire district komt doordat het gebied tot voor kort als marginaal voor landbouw werd beschouwd. Na de onafhankelijkheid van Zimbabwe in 1980, vond er in het gebied een enorme expansie van kleinschalige katoenproductie plaats (de zogenaamde *cotton-boom*). Deze expansie was het gevolg van een grootschalige bestrijding van de tseetseevlieg, hervestigingsprogramma's voor kleine boeren, en de promotie van de katoenproductie door de Zimbabwaanse overheid. Als gevolg van dit overheidsingrijpen zijn de leefgebieden voor het wild gekrompen, en wild-populaties afgenomen. Het belangrijkste doel van deze studie is het beschrijven en analyseren van de huidige spanningen tussen landbouwproductie en natuurbehoud in dit gebied, door inzichten van verschillende academische disciplines en ruimtelijke dimensies te integreren. De studie exploreert het potentieel van CA om landbouwproductie te intensiveren met minimale negatieve gevolgen voor het milieu, en hoe dit ruimte voor wild kan creëren of behouden.

Hoofdstuk 2 kwantificeert veranderingen in landgebruik en analyseert de factoren die hiertoe bijgedragen hebben. Gebruikmakend van bestaande data is een database voor landgebruik ontwikkeld voor twee *wards* (administratieve subdivisies in een district) in Mbire district. In deze *wards* werden participatieve rurale assessments uitgevoerd en een vragenlijst afgenomen onder boeren (n = 176) om de bijdrage van drie belangrijke factoren te analyseren: (1) de bevolkingstoename; (2) de toename van de vee populatie (en de gerelateerde uitbreiding van landbewerking middels dierlijke tractie), en; (3) de uitbreiding van de katoenproductie.

Tussen 1992 en 2002 is de bevolking van Mbire district bijna verdubbeld. De vee populatie is in een periode van circa 15 jaar met 15% toegenomen, en het landbouwareaal is exponentieel gegroeid tussen 1980 en 2007. Alhoewel directe effecten van veranderingen in landgebruik op wildpopulaties niet konden worden aangetoond, suggereert de studie dat de gevolgen voor de olifant en buffel populaties in het gebied negatief zijn. Alle bovengenoemde factoren hebben bijgedragen aan veranderingen in landgebruik. Echter, het landbouwareaal groeide sneller dan de bevolking, en de uitbreiding in tseetsee gebieden (waar weinig vee aanwezig is), en tseetsee-vrije gebieden (waar de vee-getrokken ploeg de landbouw domineert) is vergelijkbaar. Dit impliceert het belang van de derde factor: de katoenproductie. In tegenstelling tot het dominante discours, zijn de drastische veranderingen in landgebruik in Mbire district niet primair het gevolg van de bestrijding van de tseetseevlieg, die landbewerking met de vee-getrokken ploeg mogelijk maakte. Deze factor verklaart slechts de beperkte expansie van de vee populatie. Zonder de factor ‘katoen’ zouden de veranderingen in landgebruik niet zo omvangrijk zijn geweest en niet zo snel hebben plaatsgevonden als werd waargenomen. Veranderingen in landgebruik zijn derhalve niet te reduceren tot een gevolg bevolkingstoename. Zij zijn vooral ook een gevolg van de manier waarop mensen landbouw bedrijven .

In hoofdstuk 3 wordt een instrument ontwikkeld waarmee de ‘ecologische voetafdruk’ van de landbouw in Mbire district kan worden gemeten. Een vergelijking tussen de milieu- en omgevingseffecten van het verbouwen van voedselgewassen (granen) en het verbouwen van katoen staat hierbij centraal. De analyse maakt gebruik van tien indicatoren: bebouwde landbouwgrond, braakliggende landbouwgrond, pesticide gebruik, afname van plant diversiteit, afname van C in de bodem, onttrokken N, P en K, calorische tekorten en voedergewassen tekorten. De analyse is gebaseerd op de gegevens van 37 agrarische huishoudens van verschillende welstand, op drie locaties langs een gradiënt van toenemende landbouw intensiteit: west-*ward* 2, oost-*ward* 2 en *wards* 3 en 9. De ‘ecologische voetafdruk’ van de landbouw in west- en oost-ward 2 (beide met een lage bevolkingsdichtheid en lage landbouw intensiteit) is zeer klein vergeleken met die in *ward* 3 en 9 (met een hogere bevolkingsdichtheid en hogere landbouw intensiteit). Vier verschillende typen van boeren werden geïdentificeerd op basis van de grootte van hun veestapel en hun oriëntatie op graan- of katoenproductie. West-*ward* 2 bevat meer boeren die vooral granen verbouwen in vergelijking met *ward* 3 en 9, waar katoenboeren domineren. Oost-*ward* 2 laat een gelijke verdeling van graan- en katoenboeren zien. De ‘ecologische voetafdruk’ per boer wordt groter wanneer we langs het continuüm van graan richting katoen oriëntatie bewegen. Het produceren van een kilogram katoen vereist 60% meer land, onttrekt twee keer zoveel N, 50% meer K, en 20% meer P dan het produceren van een kilogram graan. Echter, één dag arbeid geïnvesteerd in de productie van katoen heeft een kleinere ‘ecologische voetafdruk’ dan één dag arbeid geïnvesteerd in graanproductie (alleen de indicatoren pesticide gebruik en onttrokken N vormden uitzonderingen op dit patroon). Gewasspecialisatie zou dus kunnen leiden tot belangrijke verschillen in de ‘ecologische voetafdruk’ van de landbouw, aangezien meer dan een gebrek aan land het arbeidstekorten zijn die de landbouw in Mbire district structureren. Het specialiseren in graanproductie zou het bebouwde landbouwareaal met meer dan 20% doen toenemen, en de totale oppervlakte braakliggende landbouwgrond meer dan 35% doen toenemen in oost-*ward* 2 en in *ward* 3 en 9. Specialiseren in katoenproductie zou, daarentegen, het bebouwde landbouwareaal met meer dan 30%, en de braakliggende landbouwgrond met meer dan 20% doen afnemen in oost-*ward* 2 en in *ward* 3 en 9. Daaruit kan worden opgemaakt dat het handhaven of verhogen van de relatieve winstgevendheid van katoenproductie ten opzichte van graanproductie, meer land voor natuur zou kunnen opleveren.

De impact van de landbouw op de biodiversiteit in een gebied is uiteraard niet alleen afhankelijk van het type gewas dat wordt verbouwd en het bebouwde areaal, maar ook van de manier waarop een gewas wordt verbouwd. Om de potentie van CA – het op korte termijn verhogen van productiviteit – onder de semi-aride condities van Mbire district te verkennen, werden onbemeste *on-farm* experimenten opgezet (hoofdstuk 4). Van de in de experimenten participerende boeren werden ook de katoenvelden en de toepassing van kunstmest in die katoenvelden gevolgd. De experimenten vonden plaats gedurende drie opeenvolgende seizoenen, terwijl voor de katoenvelden er data beschikbaar was voor twee seizoenen. De prestatie van CA werd vergeleken met de huidige productie praktijken (Cropping Practices or CP) van boeren voor zowel katoen als sorghum. Naast biofysische metingen werden ook de visies van de boeren op de CA productietechnieken in kaart gebracht. CA had geen invloed op de productiviteit van katoen tijdens de eerste twee jaren van het experiment waarin de regenval gemiddeld en bovengemiddeld was. In het drogere seizoen 2009-2010 resulteerde CA niet in de stabilisatie van de productiviteit, maar had zij een licht negatief effect op de productiviteit. Zowel in de *on-farm* experimenten, als in de katoenvelden van de participerende boeren daalden de opbrengsten per ha (naar respectievelijk gemiddeld 820 en 730 kg ha^{-1} onder CA en CP in de experimenten, en gemiddeld1440 en 1220 kg ha^{-1} onder CA en CP in de katoenvelden van boeren). Er was geen verschil in de afstroom *(runoff)* van regenwater tussen CA en CP op bodems met een relatieve fijne textuur, maar beduidend meer *afstroom* van regenwater met CA op een bodem met een grovere textuur (14 mm tijdens de nattere seizoen 2008-2009). Dit is een gevolg van korstvorming van het bodemoppervlak. Daar de meeste bodems in het studiegebied van grove textuur zijn, zien boeren zich genoodzaakt om te ploegen om zo de waterinfiltratie te maximaliseren in drogere jaren. In natte jaren ervaren ze niet ploegen (een onderdeel van CA) als gunstig, aangezien het een manier is om overtollig regenwater snel af te voeren en *waterlogging* te voorkomen. Deze bevindingen zetten vraagtekens bij de heersende opvatting dat CA als voordeel heeft dat zij het watervasthoudend vermogen van de bodem kan bevorderen. Korstvorming van het bodemoppervlak van grove textuur bodems kan voorkomen worden door het behouden van zoveel mogelijk organisch materiaal (*mulch*) op het bodemoppervlak. Een hogere productie van organisch materiaal (*mulch*) dan wat werd bereikt in dit onderzoek (gemiddeld 770 kg ha^{-1} in de *on-farm* experimenten), kan worden gerealiseerd door sorghum in combinatie met stikstofbindende vlinderbloemigen te verbouwen. De grote hoeveelheid organisch materiaal (in de vorm van gewasresten), die zo wordt gerealiseerd, resulteert eveneens in minder export van stikstof (N) uit CA velden in vergelijking met CP velden.

Of en hoe CA zou kunnen passen in de agrarische productiesystemen van Mbire district, staat centraal in hoofdstuk 5. In dit hoofdstuk hebben we het CA-model vergeleken met een ander model voor de intensivering van de Afrikaanse landbouw: het ‘Alvord model’. Dit beleidsmodel werd zo’n 80 jaar geleden geïntroduceerd door Emery Alvord, een Amerikaanse missionaris die leiding gaf aan het koloniale overheidsdepartement voor Afrikaanse landbouw. Naast een vergelijking van deze beleidsmodellen voor de intensivering van het landgebruik, analyseert dit hoofdstuk de organisatie van agrarische productiesystemen in Mbire district en hun inbedding in de wijdere sociaaleconomische omgeving. Wanneer we het ‘Alvord model’ vergelijken met CA, dan lijkt er in bijna een eeuw weinig veranderd in de aanpak van landbouwkundig onderzoek en voorlichting voor kleinschalige boeren. De lokale landbouwpraktijken van boeren zijn hardnekkig genegeerd, en de lage productiviteit en landdegradatie in de Afrikaanse landbouw worden nog steeds gezien als een puur technisch probleem. De analyse van landbouwpraktijken in Mbire district laat zien hoe de sociaaleconomische omgeving waarin kleinschalige boeren opereren, extensivering in de hand werken (hetgeen waarschijnlijk geldt voor de meeste kleinschalige boeren in zuidelijk Afrika). Voorbeelden zijn de beperkte toegang tot cash, arbeidspieken, lage gewasprijzen, hoge prijzen voor inputs (zaaizaad, kunstmest, herbiciden en pesticiden), en een hoog misoogst risico. Technische interventies kunnen dergelijke beperkingen verergeren als ze niet goed zijn afgestemd op de omstandigheden van kleinschalige boeren. Agrarische technologieën zijn echter niet inherent intensiverend of extensiverend van aard; meestal kunnen ze voor beide worden aangewend. Het is de interactie tussen de technologie en de agro-ecologische en sociaaleconomische omgeving, die de landbouw in de richting van intensivering of extensivering stuurt. In Mbire district, waar de beschikbaarheid van arbeid voor het wieden een belangrijke factor is die de landbouw productie beperkt, vormt de toename van onkruid door CA een belangrijke – maar niet de enige – reden waarom boeren CA niet omarmen.

Hoofdstuk 6 betoogt dat een verdere toename van de landbouwproductiviteit én het behoud van biodiversiteit innovatieve oplossingen vergt die veel verder gaan dan alleen CA. CA moet worden gezien als onderdeel van een groter pakket van technologieën die gericht zijn op ‘ecologische intensivering’. In de beperkte situaties waarin alle CA principes toepasbaar zijn, zal CA aangepast moeten worden aan de lokale omstandigheden om in agrarische productiesystemen van kleinschalige ingepast te kunnen worden. Een pragmatische en meer flexibele aanpak is vereist voor het ontwerp, de evaluatie en verspreiding van CA-technologieën. Intensivering van de landbouw is onwaarschijnlijk in gebieden waar land nog niet schaars is en waar landbouw en natuur aan elkaar grenzen; zoals het onderzoek laat zien is in deze gebieden extensivering vaak de norm. Bij het ontwerpen en evalueren van agrarische productiesystemen voor dit soort gebieden, dienen onderzoekers zich niet – zoals gangbaar – alleen toe te leggen op de productiviteit van het land (opbrengst per hectare). Zij zullen zich meer moeten richten op de arbeidsproductiviteit. Het betalen van kleine boeren voor hun bijdrage aan het behouden en beschermen van natuur, in combinatie met (ecologische) intensivering, biedt wellicht grote mogelijkheden om winstgevende agrarische productie en de effectieve bescherming van de biodiversiteit te bewerkstelligen. Om zo’n benadering effectief te implementeren, is het noodzakelijk dat lokale gemeenschappen worden ondersteund door middel van de juiste interventies, en niet, zoals vaak het geval is, interventies die gericht zijn op een mythische wildernis als de leefomgeving van een mythisch nobel volk.

Les conflits d'usage pour l'espace sont aigus dans les pays en voie de développement. Une augmentation de la production agricole est requise pour alimenter leur population croissante, tandis que ralentir les pertes en biodiversité est souhaitable, ne serait-ce que pour maintenir les processus écosystémiques. L'agriculture affecte la biodiversité locale directement par un changement d'occupation du sol, mais aussi la biodiversité régionale et globale par des effets indirects tels que la fragmentation des écosystèmes ou la perturbation des cycles hydrologiques et biogéochimiques. Des systèmes de culture innovants basés sur les principes de l'agriculture de conservation (AC) ont émergé dans plusieurs régions du monde, dans le but de combiner agriculture performante et impacts environnementaux minimaux. En particulier, l'AC est actuellement diffusée vigoureusement par un large éventail d'organismes internationaux dans le domaine de la recherche et du développement agricole. Dans certaines frontières agricoles Zimbabwéennes partagées avec la grande faune Africaine, l'AC a été proposée comme moyen d'augmentation de la productivité agricole et de réduction du déclin de la faune. C'est le cas du district de Mbire, qui se situe dans la Moyenne Vallée du Zambèze, dans le nord du Zimbabwe, et qui héberge une biodiversité remarquablement préservée, dont toute la mégafaune africaine emblématique (éléphant, buffle, hippopotame, lion, léopard, koudou, hippotrague, impala, etc). L'abondance de faune de Mbire est le résultat de sa marginalité agricole historique. A la suite de l'indépendance du Zimbabwe en 1980, le district a subi un boom cotonnier, grâce à des campagnes d'éradication des mouches tsétsé à grande échelle, un programme de distribution de terre à des migrants et la promotion de la culture du coton elle-même. En conséquence, l'habitat de la faune s'est rétréci et les densités de faune sont en déclin. En intégrant les points de vue de diverses disciplines, à des niveaux d'étude différents, l'objectif principal de cette étude est de décrire et d'analyser les tensions existantes entre la production agricole et la conservation de la faune; et d'explorer le potentiel de l'AC dans l'intensification de la production agricole avec des impacts négatifs minimaux sur l'environnement, et donc dans la possibilité d'épargner de l'espace pour la faune.

Résumé

Afin de quantifier les changements d'occupation des sols qui ont eu lieu depuis l'indépendance dans une zone pilote du district de Mbire et afin d’estimer la contribution de plusieurs facteurs potentiels, les données existantes ont été analysées et une base de données d'occupation des sols a été développée pour deux wards (subdivisions administratives du district) du district de Mbire (Chapitre 2). Dans ces deux wards, des entretiens collectifs et individuels (*n* = 176) ont également été conduits pour analyser la contribution de trois facteurs potentiels majeurs: (1) l’accroissement de population humaine ; (2) l’augmentation du cheptel bovin (et l'expansion de l'agriculture attelée qui lui est associée); (3) l’expansion de la culture du coton. La population humaine du district de Mbire a presque doublé entre 1992 et 2002, alors que les densités de bovins ont augmenté à des taux supérieurs à 15% au début des années 1990 et à la fin des années 2000. Dans les deux wards, l'expansion les superficies cultivées a augmenté de façon exponentielle au cours du temps, de 1980 à 2007. Bien qu’un impact direct des changements d’occupation des sols sur les densités de faune n’a pas été démontré, notre étude suggère des conséquences négatives sur les densités d’éléphants et de buffles. Chacun des trois facteurs étudiés a contribué aux changements d’occupation des sols observés. Cependant, les surfaces cultivées ont augmenté plus rapidement que la population humaine, avec en outre des taux de croissance semblables dans les zones infestées par les mouches tsétsé et dépourvues de bovins, et dans les zones où les mouches tsétsé ont été éradiquées et où l’agriculture attelée domine. Ceci implique l'existence d'un autre facteur primordial, en l’occurrence la culture du coton. Contrairement à la croyance populaire, l’éradication des mouches tsétsé n'a pas été le déclencheur principal des changements considérables d'occupation des sols dans le district de Mbire, mais a simplement allégé une contrainte à l'accumulation des bovins. Sans la présence d'une culture de rente (coton), les changements d'occupation des sols n'auraient été ni aussi intenses ni aussi rapides que ce qui a été observé. Ainsi, la façon dont l’agriculture est pratiquée est aussi préoccupante pour la conservation de la biodiversité que l'accroissement de la population humaine.

Afin de comparer l'impact environnemental des systèmes de culture vivriers (céréales) avec celui des systèmes de culture de rente (coton) dans le district de Mbire, nous avons développé une mesure de l'empreinte environnementale de l’agriculture basée sur dix indicateurs appropriés à la situation locale: surface cultivée, surface mise en jachère, utilisation de pesticide, perte de diversité végétale, perte de C du sol, exportation de N, P et K, déficit calorifique et déficit fourrager (Chapitre 3). L'analyse a été faite sur 37 unités de production de richesse variable dans trois sites le long d'un gradient d'intensification agricole: West Ward 2, East Ward 2 et Ward 3 et 9. Les empreintes environnementales de l'agriculture de West Ward 2 et de East Ward 2 (faibles densités de population et intensités agricoles) étaient restreintes en comparaison de celles de Ward 3 et 9 (densité de population et intensité agricole plus élevées). Quatre types de ferme ont été délimités le long du continuum système céréalier/système cotonnier. West Ward 2 avait plus d’unités de production cultivant principalement des céréales que Ward 3 et 9, qui avait plus d’unités de production cultivant de larges surface de coton. East Ward 2 représentait une distribution intermédiaire d’unités de production. L'empreinte environnementale par unité augmentait de manière significative le long du continuum système céréalier/système cotonnier. Un kilogramme de coton-graine exigeait 60% de terre cultivée en plus, exportait le double d’N, 50% plus de K et 20% plus de P qu'un kilogramme de céréale. Cependant, excepté pour l’utilisation de pesticide et l’exportation d’N, un homme-jour investi dans la production de coton avait une empreinte environnementale plus petite qu'un homme-jour investi dans la production de céréale. Ceci pourrait aboutir à des différences importantes d’empreintes environnementales si les unités de production devaient se spécialiser dans l’une ou l’autre de ces cultures, étant donné que la production agricole dans le district de Mbire est limitée par le travail plus que par le foncier. La spécialisation dans la production céréalière augmenterait les surfaces totales cultivées de plus de 20% et les surfaces totales en jachère de plus de 35% dans East Ward 2 et Ward 3 et 9. En revanche, la spécialisation dans la production de coton diminuerait les surfaces totales cultivées de plus de 30% et les surfaces totales en jachère de plus de 20% dans East Ward 2 et Ward 3 et 9. Par conséquent, maintenir ou augmenter la rentabilité du coton par rapport à celle des céréales pourrait ‘épargner de l’espace’ à la nature.

L'impact de l'agriculture sur la biodiversité dépend non seulement du type de culture et des surfaces mises en culture, mais aussi des techniques culturales employées.

Résumé

Dans le but d'explorer le potentiel de l'AC d'augmenter sur le court terme la productivité agricole dans les conditions semi-arides qui sont celles du district de Mbire, des essais en ferme non-fertilisés ont été conduits pendant trois saisons consécutives et les champs de coton d'un échantillon d'unités de production recevant des taux de fertilisation variés ont été suivis pendant deux saisons (Chapitre 4). Les performances de l'AC ont été comparées à celles des pratiques paysannes actuelles (PA), pour la production de coton et de sorgho. En plus de mesures biophysiques, les perceptions des paysans vis-à-vis de l'AC ont été évaluées. L'AC n'a pas affecté la productivité du coton pendant les deux premières années d'expérimentation, qui ont reçu des précipitations moyennes ou au-dessus de la moyenne. Pendant la saison 2009-10, plus sèche, plutôt que de stabiliser les rendements, l'AC a eu un effet légèrement négatif aussi bien dans les essais en milieu paysan (rendements moyens de 820 et 730 kg ha^{-1}, pour les traitements AC et PA respectivement) que dans les champs de coton des différentes unités de production (rendements moyens de 1440 et 1220 kg ha^{-1}, pour les traitements AC et PA respectivement). Il n'y avait pas de différence de ruissèlement entre les traitements AC et PA sur un sol à texture relativement fine, mais significativement plus de ruissèlement dans le traitement AC que dans le traitement PA sur un sol à texture plus grossière (14 millimètres pendant la saison 2008-09 relativement humide), en raison de la formation d'une croûte de battance. La plupart des sols de la zone d'étude appartiennent à cette dernière catégorie. Pour cette raison, les paysans ont déclaré que le labour était nécessaire pendant les années sèches, afin de maximiser l'infiltration, mais ont perçu l'AC comme bénéfique durant les années plus humides, afin d'éliminer les excès d'eau et éviter l'engorgement des sols. Ceci va à l'encontre de la description commune de l'AC en tant que technologie de récolte de l'eau. La formation d'une croûte de battance peut être évitée par la production de plus grandes quantités de paillis que ce qui a été réalisé dans cette étude (moyenne de 770 kg ha^{-1} dans les essais en ferme). Cependant, l'exportation nette d'N par la culture était moindre dans le traitement AC que dans le traitement PA, grâce à la conservation des résidus de sorgho et l'inclusion de légumineuses fixatrices d'N_2.

Pour comprendre comment l'AC s'insérerait dans les systèmes agraires du district de Mbire, ce modèle a été comparé à un autre modèle d'intensification agricole, le modèle d'Alvord, qui a été introduit au Zimbabwe à l'époque coloniale il y a 80 ans (Chapitre 5). Plus spécifiquement, les pratiques agricoles paysannes du district de Mbire et leur signification dans un environnement socio-économique plus large ont été également analysées. D'Alvord à l'AC, il s'avère que l'approche utilisée dans la recherche et la vulgarisation agricoles pour les petits producteurs a peu changé en presque un siècle. En particulier, les pratiques paysannes ont été constamment négligées, et le problème de faible productivité et de dégradation des sols dans l'agriculture africaine est resté perçu comme purement technique. L'analyse des pratiques agricoles des petits producteurs du district de Mbire montre que les contraintes socio-économiques auxquelles ils font face (et probablement auxquelles les exploitations familiales de la plupart des régions d'Afrique australe font face) – trésorerie limitée, pic de travail, prix des intrants élevés, prix des extrants faibles, risque élevé, etc – les prédisposent à l'extensification. Les technologies pouvant exacerber ces contraintes sont inadaptées aux conditions des exploitations familiales. Les techniques agricoles, cependant, n'ont pas de propriétés d'intensification ou d'extensification strictes: souvent ils ont les deux. C'est l'interaction entre la technologie et l'environnement agro-écologique et socio-économique qui dirige l'agriculture sur la voie de l'intensification ou de l'extensification. Dans le district de Mbire, où la disponibilité en main d'œuvre au moment du désherbage est un facteur limitant majeur, la pression accrue en adventices est une raison importante - mais probablement pas la seule – prévenant l'adoption de l'AC par les petits producteurs.

Pour conclure (Chapitre 6), l'atténuation des conflits entre augmentation de la production agricole et conservation de la biodiversité exige des innovations majeures, bien au delà de l'AC. L'AC ne devrait probablement être perçue que comme un élément d'un plus large panel de techniques visant à 'l'intensification écologique'. Dans les situations limitées où l'AC est la plus appropriée, elle devra s'adapter aux conditions locales pour s'insérer dans les systèmes agraires existants. Une approche pragmatique et plus souple que celle actuellement utilisée est nécessaire pour la conception, l'évaluation et la vulgarisation des technologies basées sur les principes de l'AC. L'intensification elle-même est peu probable dans les frontières agricoles, où l'extensification est souvent la règle. Dans ces régions, lors de la conception et de l'évaluation des systèmes de culture, les chercheurs doivent cesser de placer l'accent sur la productivité de la terre (rendement) et se concentrer sur la productivité du travail. L'association de paiements pour services environnementaux à l'intensification (écologique) présente un potentiel important pour combiner production agricole rentable et conservation efficace de la biodiversité dans ces régions. Pour la mise en application d'une telle approche, les capacités des communautés locales devront être renforcées par les bonnes interventions, et pas, comme souvent cas, par des interventions visant de mythiques régions sauvages, habitées par le mythique 'bon sauvage'.

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I started working in the Mid-Zambezi Valley in 2002, under a development project aiming at increasing the benefits people were drawing from wildlife and minimizing conflicts. I was immediately overwhelmed by the area, by its people and the love and hate relationship they nurture with the ‘big fives’ and by this indescribable, though so palpable, energy that seems to radiate from the area (Yann: I know you understand what I mean). During my two-year assignment, I learned a lot from the manager of the project, Sébastien Lebel. Seb: you taught me how knowledge can be mobilized to solve practical problems on the ground. You also equipped me with many skills necessary to carry field work in an area such as the Mid-Zambezi Valley, from repairing a Land Cruiser to skinning an impala. I also interacted a lot with Nicolas Gaidet during these two years. Nico: the confrontations we had between the point of view of an agronomist and the point of view of a conservation ecologist have definitely shaped this PhD research. It is also during this time that I met Craig Coid, a professional hunter and a guide with extensive experience and knowledge in the management of human-wildlife conflicts. Craig: I want you to know that this thesis is an extension of the numerous nights we spent sitting around a fire and talking about conservation and conflicts in areas shared by people and wildlife. It is during these two years that I met yet another person that influenced this research, Edmore Chimimba, a truly amazing character. Without his deep knowledge of the Mid-Zambezi Valley, of its social organization, of its soils, of its flora and fauna, of the optimal time for planting cotton or sorghum, and so many other things, none of the work I have been supervising there, including this PhD research, would have been possible. I was lucky to be born in a part of the world where access to education and job opportunities is relatively easy. Edmore didn’t have that luck, and I ended up supervising projects whilst he ended up being a field operation manager. I am convinced that if he had had the same advantages as me, I would have ended up being the field operation manager and Edmore the project supervisor. Edmore: thanks for everything.

I first discussed the possibility of going through the process of a PhD study in 2006 with Marc Corbeels, who later became my daily supervisor. Marc was the first person

who assisted me to organize my thoughts into a scientific format, whilst I had been mainly working as an engineer before that. Marc: you taught me what collaborative research really means. Marc was also the one who first introduced me to Ken Giller, who accepted to become my promoter. It’s difficult to thank Ken adequately in a few words, as I really feel he has been one of these life-changing encounters for me. His integrative vision of research has been a source of inspiration all along this project. His passion for farming systems in Africa and his thirst to always know more are contagious. Ken: more than just supervising me, I feel you have empowered me to conduct research and pushed my learning curve upward. It is through Ken that I met Jens Andersson, who ended up being a key supervisor of this work. Key in the sense that he added a dimension to my vision and analysis of production systems. Jens: whereas so many specialists use obscure terminologies and concepts to make their disciplines inaccessible and to remain ‘the’ experts, you have demystified social sciences for me. I always felt the gap between biophysical sciences and social sciences was narrow, but I am grateful for having worked with somebody who can cross it so easily. I just hope we will have the opportunity to fulfil our dream of a race from Mahuwe to Kanyemba one day, although I am convinced the driver of ‘The Beast’ can not be defeated. Finally, I want to thank my fourth supervisor, Pablo Tittonell. Without Pablo, the writing of the third and fourth chapters of this thesis would have no doubt been more tedious and would have delayed the whole completion of this thesis. On top of being knowledgeable in so many areas necessary for the analysis of farming systems, Pablo has this way of pushing people without making them feel pressured. Pablo, it was a privilege to be working under your guidance for six months in Montpellier.

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PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

1. **Review of literature (6 ECTS)**
    - Cotton expansion and biodiversity loss in African savannas, opportunities and challenges for conservation agriculture; published in Biodiversity and Conservation as Baudron et al., (2009)

2. **Writing of project proposal (4.5 ECTS)**
    - Integrated evaluation of conservation agriculture (CA) technologies using multipurpose grain legumes (MGL) to improve productivity and sustainability of cotton-cereal systems in the Mid Zambezi Valley (2007)

3. **Post-graduate courses (7.5 ECTS)**
    - Analysis of farming systems; WUR-UZ; Harare, Zimbabwe (2008)
    - The art of modelling; WUR (2010)
    - Spatial ecology; WUR (2011)

4. **Laboratory training and working visits (1.5 ECTS)**
    - Farming systems and trade-off analysis using models; CIALCA-NUANCES; Butare, Ruanda (2008)

5. **Deficiency, refresh, brush-up courses (1.5 ECTS)**
    - Optimization using GAMS; Montpellier, France (2007)

6. **Competence strengthening / skills courses (1.5 ECTS)**
    - Multi-agent modelling; CIRAD (2007)

7. **PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)**
    - Workshops are partly PE&RC supported INREF Programme Competing Claims on Natural Resources (CCNR)

8. **Discussion groups / local seminars / other scientific meetings (3 ECTS)**
    - CCNR Annual workshop; Massingir, Mozambique (2008)
    - CCNR-PCP Write workshop ‘Living on the edge’; Mabalauta, Zimbabwe (2009)
    - CCNR Annual workshop; Mushumbi Pools, Zimbabwe (2010)

9. **International symposia, workshops and conferences (5 ECTS)**
    - Regards croisés sur la Tapoa (panafrican workshop on community-based natural resource management); Niamey, Niger (2008)
    - Second DIVERSITAS Open Science Conference; Cape Town, South Africa (2009)

10. **Supervision of 4 MSc students; 80 days**
    - Diversity of crop productivity and resource use efficiency within smallholder farms of Mbire District, Zimbabwe; Pieter-Jan Clauwert (2007)
    - Evaluating relative contribution of changes in farming practices to habitat loss in the Mid Zambezi Valley, Zimbabwe; Mbulisi Sibanda (2008-2010)
    - L’implantation de l’agriculture de conservation dans le part national des Quirimbas; Mozambique; Irénée Velten (2009)
    - Is soil carbon the main driver of shifting and fallow cultivation in the Mid Zambezi Valley, Zimbabwe; Robin Grasnier (2010)

Frédéric was born in 1978 in rural France, in the cradle of one of the most popular breed of beef cattle in the world: the Charollais. He developed very early a marked interest for biology and for farming, and in particular for the animal kingdom and livestock farming. He spent his childhood dreaming of Africa and its wildlife. After completing his secondary education in 1996 in the local high school of Charolles, he decided to become a tropical agronomist, with the aim of working in Africa. He enrolled in a national preparatory program ('classe préparatoire') in the Lycée du Parc in Lyon, leading up to a competitive national entrance examination to state-run schools of agronomy in 1998. His poor results in mathematics and english were counterbalanced by very good results in biology and geology, and he was accepted in the 'Ecole Nationale Supérieure Agronomique de Montpellier' (now 'Sup-Agro-Montpellier'). His first experience of Africa was through an internship in a national research institute of Burkina Faso. Due to his persistent interest in animal sciences, he left Montpellier in 2000 for the 'Institut National Agronomique de Paris Grignon' (now 'Agro-Paris-Tech') to study animal nutrition and genetics and processing and marketing of animal products. He did his master thesis in the French West Indies, studying the genetic resistance of local goats to gastrointestinal parasitism. After his graduation in 2001, he was convinced that his career should be built around quantitative genetics… but the call of African wildlife was stronger. He was selected for a two-year assignment with CIRAD to work in a prime wildlife area: the Mid-Zambezi Valley. The expected outcome of this assignment was the development of farming practices based on the principles of conservation agriculture, in order to reconcile cotton production and wildlife conservation in the area. At the end of his assignment in 2004, he joined the regional office of the World Wide Fund for the Conservation of Nature (WWF) for close to a year, working mainly in Zambia and Malawi. In 2005, he was then attached for six months to the 'Fondation Internationale pour la Sauvegarde de la Faune' (IGF), working in various wildlife conservation projects in Southern Africa. From late 2005 to late 2006, he worked for Bio-Hub, a Southern African platform of expertise specialised in community-based natural resource management formed by CIRAD, WWF, IGF and the International Union for the Conservation of Nature (IUCN). When in 2007, Cirad gave him the opportunity to carry a PhD research, he wished to joined the renowned Wageningen University and was fortunate enough for Professor Ken Giller to accept to become his promotor. Frédéric then decided to go back to the conservation landscape where all the questioning around the conflicts between production and conservation started for him: the Mid-Zambezi Valley. He is based in Addis Ababa, Ethiopia, since July 2011 where he works as a Cropping System Agronomist for the International Maize and Wheat Improvement Centre (CIMMYT).

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