Biodivers Conserv
DOI 10.1007/s10531-009-9663-x

ORIGINAL PAPER

Cotton expansion and biodiversity loss in African savannahs, opportunities and challenges for conservation agriculture: a review paper based on two case studies

Frédéric Baudron · Marc Corbeels · François Monicat · Ken E. Giller

Received: 20 November 2008 / Accepted: 13 May 2009

Abstract We review agricultural impacts on biodiversity and the potential of conservation agriculture in developing productive and environment-friendly cropping systems. We then analyse experiences from two African landscapes of global importance for conservation: the Mid Zambezi Valley in Southern Africa and the periphery of the "W-Arly-Penjari" complex in West Africa. In both areas, expansion of cotton farming, considered as one of the most polluting forms of agriculture in the world, drives major land use change and loss of biodiversity. In both areas, various forms of conservation agriculture have been developed and tested. We highlight the potential benefit of conservation agriculture in controlling negative environmental effects traditionally associated with agriculture and reducing the need for land conversion through increased biophysical resource use efficiency, turning agriculture from a threat to an opportunity for conservation. Finally, we raise a number of issues that constitute challenges for the widespread adoption of these technologies by resource-poor farmers, and formulate recommendations for the development, evaluation and diffusion of conservation agriculture technologies for smallholders in semi-arid Africa.

Keywords Cotton · Smallholders · Productivity · Sustainability · Biodiversity

F. Baudron (✉) · M. Corbeels
UR Annual Cropping Systems, Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Avenue Agropolis, 34398 Montpellier, France
e-mail: frederic.baudron@cirad.fr

F. Baudron · K. E. Giller
Plant Production Systems, Wageningen University, Haarweg 333 (Building 537), Wageningen, AK 6700, The Netherlands

M. Corbeels
TSBF-CIAT, 12.5 km peg, Mazowe Road, P.O. Box MP228, Mt Pleasant, Harare, Zimbabwe

F. Monicat
UR Animal and Integrated Risk Management, CIRAD, TA E, Campus International de Baillarguet, 34398 Montpellier cedex 5, France

Published online: 05 June 2009

Introduction

Agriculture is widely perceived as the greatest threat to biodiversity, particularly in developing countries where the growing human population requires increasing quantities of food and cash crops (Main et al. 1999; Sala et al. 2000; Heywood and Watson 1995). Conventional agricultural practises of smallholder farmers lead to rapid decline of soil organic matter and fertility of the land (Zingore et al. 2005) that may fuel expansion of agriculture. Development of cash crop farming, such as cotton, may drive significant habitat conversion (Girdis 1993). Cotton has a particularly negative image, as it is considered one of the most polluting annual crops (EJF 2007; WWF 2007) and is said to have a significant impact on freshwater resources. Chapagain et al. (2006) estimated that cotton production worldwide requires 256 Gm^3 $year^{-1}$ of water, of which 42% is used for irrigation and processing, 39% is evaporated, and 19% is used to dilute pesticides to acceptable concentrations. To mitigate agricultural expansion and agricultural pollution in areas hosting important biodiversity, the most common strategy has been to increase the land surface under protected areas. More recently, attempts have also been made to offer farming communities alternative land use options that are compatible with biodiversity conservation (e.g. ecotourism, bee keeping, sustainable use of non-timber forest products), but these options are often not economically competitive with agriculture. The interest of conservation agencies in agriculture has often focused on the promotion of low external input systems, some giving encouraging results (Pretty et al. 2003). However, these systems are based on transfer of biomass (manure or plant material) and therefore require important land and labour, both of which are limited resources for smallholders (Gowing and Palmer 2008). Moreover, these systems do not reduce soil nutrient mining compared with conventional systems (de Jager et al. 2001). Conservation agriculture, by increasing water and nutrient use efficiency, appears to offer an alternative practise in which high agricultural productivity can be compatible with reduced environmental impact. Taking two case studies in sub-Saharan Africa based on cotton production, one in West Africa, and one in Southern Africa, the objective of this paper is to address potential pitfalls in the development, evaluation and diffusion of these alternative technologies based on conservation agriculture. The bulk of information used in this article was collected during a case study funded by ACT,[1] CIRAD,[2] FAO[3] and RELMA,[4] and an EU[5]-funded collaboration in the frame of the ECOPAS programme.

The impacts of agriculture on biodiversity

Agriculture is defined in its broad sense by the Merriam-Webster dictionary as "the science, art or practise of cultivating the soil, producing crops and raising livestock and in varying degrees the preparation and marketing of the resulting products" (www.merriam-webster.com). Authors from the eco-agriculture school put emphasis in their definition on

[1] African Conservation Tillage network.

[2] Centre de cooperation International en Recherche Agronomique pour le Développement.

[3] United Nations Food and Agriculture Organization.

[4] RELMA: Regional Land Management Unit of the Swedish International Development Cooperation Agency.

[5] European Union.

the "modification of natural ecosystems to provide more goods and services" (McNeely and Scherr 2003). This modification causes a drastic simplification of natural ecosystems, through direct removal of plant species and a "chain reaction" of extinction of organisms at higher trophic levels. It also modifies biomass abundance, quality and distribution and may impoverish the soil ecosystem (Giller et al. 1997). Even when fields are abandoned, important functional groups may have been lost from the soil ecosystem (e.g. loss of symbiotic mycorrhizal fungi) and regeneration of the original biodiversity may be impossible (McNeely and Scherr 2003, p. 31).

Furthermore, the impact of agriculture and biodiversity loss is not confined spatially to the newly opened agricultural fields, but extends to adjacent landscapes that may be protected areas. Indeed, protected areas interact in various ways with their peripheral lands, outside of their administrative boundaries, through ecological flows of energy, materials and organisms. Some authors use the terminology 'greater ecosystems' to designate such functional units made up of protected areas connected to their non-protected surroundings (DeFries et al. 2007). For instance, habitat conversion of non-protected areas included in greater ecosystems leads to progressive fragmentation and isolation of remaining fragments, and increases the probability of extinction of certain species, mainly due to small population sizes (Cowlishaw 1999). Unprotected areas may also play a fundamental role in biodiversity maintenance, for example through providing food and water sources or breeding grounds during part of the year for animal species.

Loss of particular species that have key functions may also produce far-reaching negative environmental effects on distant ecosystems and biodiversity (Fig. 1). Primary production is one of the major ecosystem functions usually, but not always affected by agriculture (e.g. conversion to pasture in Amazonia: Koutika et al. 1997; Desjardins et al. 2004). It generally translates into altered, sparse ground cover within cultivated ecosystems (Vitousek et al. 1997), which usually generates important water losses compared with their corresponding natural ecosystems: surface run-off, deep percolation and evaporation typically consume 70–85% of rainfall under rainfed agriculture in semi-arid sub-Saharan

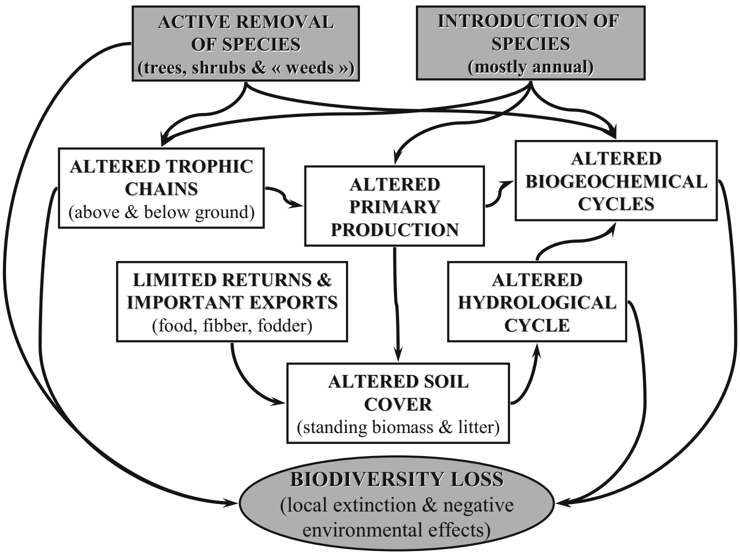

Fig. 1 Direct and indirect impacts of agriculture on biodiversity

Africa (Rockström et al. 2002). Runoff transports sediments, nutrients and possibly erosion-related pollutants to streams, lakes, estuaries and coral reefs (Farella et al. 2001). Moreover, the conversion from a large to a small standing-biomass ecosystem leads to a release of organic carbon to the atmosphere, particularly under tropical conditions (Corbeels et al. 2006). This release can be an important contribution to global climate change (Vitousek et al. 1997; Corbeels et al. 2006). Thus, agriculture may alter regional and even global hydrological and biogeochemical cycles and affect distant biodiversity.

Pollution and siltation of water bodies from field runoff is probably the most common negative environmental effect associated with agriculture worldwide (Arias-Estévez et al. 2008), whilst water is a limiting factor in many crop production systems, particularly in dryland agriculture (Rockström et al. 2002). In semi-arid areas, increasing water infiltration would have the dual benefit of increasing production and reducing unwanted losses of sediments, nutrients and agrochemicals. The same applies to mobile nutrients, such as nitrogen, that are essential and often limiting elements for crop growth, whilst they represent a potential source of off-site pollution. For instance, excessive addition of animal manures and fertilisers may cause contamination of groundwater in Western countries (Giller et al. 2001), necessitating legislation to prevent their overuse.

For a particular biophysical resource (e.g. light, water, nutrients), resource use efficiency can be defined as the product of capture efficiency (capture by the plant of a certain portion of the total available resource) and conversion efficiency (conversion of the resource into organic products, biomass in particular; Giller et al. 2006). Increasing water and nutrient use efficiency by the crop increases production with the collateral benefit of reducing unwanted losses of these elements. Depending on the quantity of residues returned to the soil and the rate of fertilisation, greater nutrient use efficiency may imply a greater retention of nutrients in the system. To illustrate this point, a comparison under similar soil and climate of smallholder practises (i.e. limited amounts of fertiliser or no fertiliser used and extraction of virtually all residues) with commercial farmers' practises (i.e. large amounts of fertiliser used and residues returned to the soil) in Zimbabwe revealed a much sharper decline of organic carbon and nitrogen in the first case, with on average 15 t C ha^{-1} and 1.7 t N ha^{-1} less at soil organic matter equilibrium (Zingore et al. 2005). Negative environmental effects (e.g. erosion, leaching), and reduced productivity and sustainability may all be consequences of processes dependent on the efficiency with which biophysical resources are used (Fig. 2).

Therefore, increasing water and nutrient use efficiency is expected to contribute directly to the mitigation of biodiversity loss, through reduced negative environmental effects, and indirectly through reduced need for land conversion, due to higher productivity and sustainability of cropping systems.

Conservation agriculture as an example to improve water and nutrient use efficiency

The fundamental principle of conservation agriculture is the retention of a mulch of crop residues on the soil surface. Research has shown that runoff decreases exponentially with the proportion of soil surface effectively covered by residues, a 30% cover of soil surface usually implying a reduction of runoff by more than 50% (Findeling et al. 2003; Scopel et al. 2004). Surface residues also limit the energy reaching the soil surface, decreasing evaporation of soil water (Scopel et al. 2004). Reduced runoff and evaporation mean that more water is available to the crop (giving increased water use efficiency). Residue retention also results in better maintenance of land productive capacity in situ (e.g. topsoil,

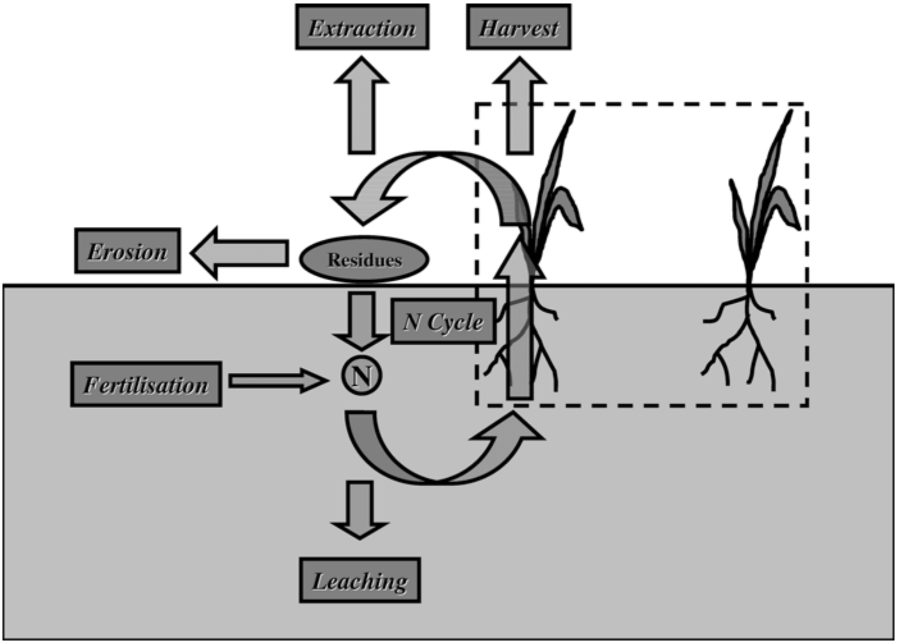

Fig. 2 Relationship between productivity (production per land and/or labour unit), sustainability (nutrient cycle sustained) and environmental externalities (erosion and leaching) in the case of nitrogen (N)

water, nutrients) and a reduction of adverse off-site impacts such as eroded sediments and erosion-related pollutants. Erosion is controlled through increased surface resistance against overland flow and enhanced surface aggregate stability and permeability (Erenstein 2002). Less erosion means that more nutrients are available to the crop. On the other hand, increased infiltration may translate into increased deep drainage and increased leaching of mobile nutrients, which may counterbalance advantages of retaining them in situ (Erenstein 2003; Scopel et al. 2004), though "by-pass flow" may occur so that most supplied nitrogen is retained in the topsoil and nitrogen leaching is limited (e.g. south-western Kenya, Smaling and Bouma 1992).

Crop residue retention contributes to soil fertility by maintaining fertile topsoil in situ, and by acting as a soil amendment. Residue retention can increase the stock of soil organic matter (Corbeels et al. 2006), particularly in fine-textured soils offering protection through aggregation ('structural protection'). Sandy soils, however, have limited capacity to protect soil organic matter and their soil organic matter content is generally small, even under native vegetation (Zingore et al. 2005; Chivenge et al. 2006). In such soils, significant carbon sequestration through conservation agriculture or other biomass-enhancing technologies might not be possible. A soil can hold organic matter only up to a saturation point mainly determined by its texture (Six et al. 2002).

Residue retention requires reduced or no-tillage, since land preparation directly affects the quantity of biomass remaining on the soil surface. Reduced soil disturbance also stabilises soil organic matter, particularly in fine-textured soils where it may be protected in microaggregates (Chivenge et al. 2006). Residue retention also requires control of grazing, and suppression of fire before planting. Communal grazing is often important in the tropics and sub-tropics and is often perceived to be a factor that limits widespread adoption of conservation agriculture (Giller et al. submitted). On the other hand, even small amounts of surface residues (<1.5 t ha^{-1}) can be effective in reducing water loss, soil erosion and increasing yield (Scopel et al. 2004, 2005). Maintaining a mulch of crop residues through the growing season also makes rotation necessary as residues may carry diseases or pests from the previous crop. In the case of cotton production, rotation with another crop, a cereal crop for instance, is critical, as destruction/burning of cotton residues is compulsory in many countries for phytosanitary reasons. In this case, the cereal production phase is required for mulch production, cotton being subsequently planted directly through this mulch.

Association of a main crop with a deep-rooted, secondary crop may prevent nutrient losses through leaching (Fig. 3). Moreover, such secondary crops may increase significantly primary production and carbon input to the soil (Corbeels et al. 2006). A suitable mulch is required to achieve both soil protection and soil fertility enhancement. Slowly decomposable crop residues, such as cereal residues, have a wide C:N ratio and may exacerbate nitrogen-stress by causing temporary nitrogen immobilisation. Thus, intercropping of cereals with legumes, which have residues with a narrow C:N ratio, may improve nitrogen availability, and thus improve the composition of the residue biomass produced. Most crop associations used in conservation agriculture include two crops: a main crop (often a cereal) and a secondary crop (often a legume with deep root system). However, more complex associations combining various plant functional groups can be beneficial, especially when the climate is erratic. For instance, resistance and resilience of grasslands to drought have been found to be enhanced by plant diversity (Tilman and Downing 1994).

The simultaneous adoption of the above principles i.e. a soil covered permanently or at least during critical stages, reduced soil disturbance, and crop associations and rotations (in

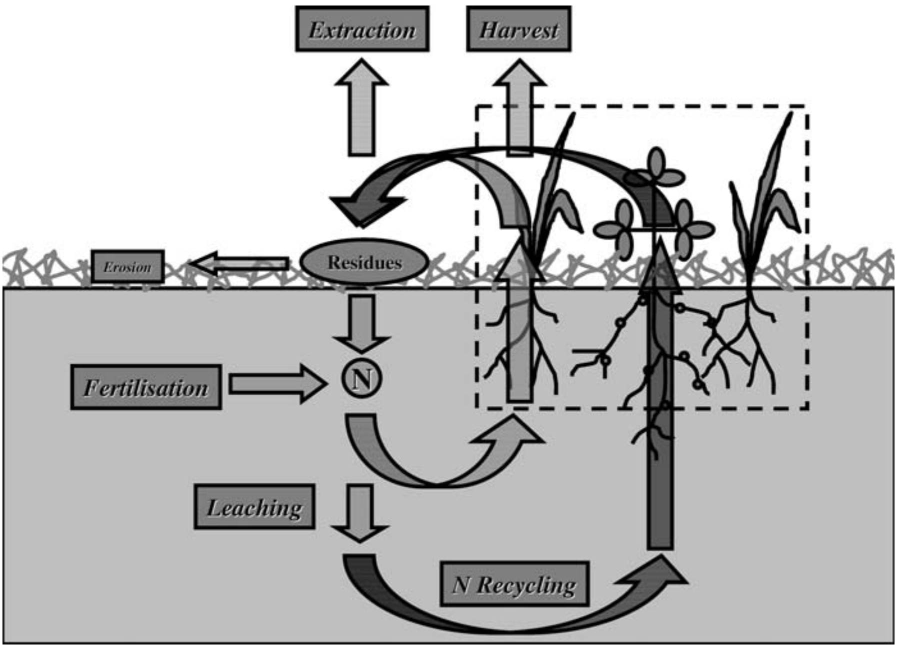

Fig. 3 Association of a deep-rooted crop ("cover crop") to the main crop in a conservation agriculture system, to recycle nutrients and increase biomass production

particular with legumes) forms what the FAO defines as conservation agriculture (www.fao.org/ag/ca). Conservation agriculture is expected to increase productivity and to mitigate negative environmental impacts traditionally associated to agriculture, through increased water and nutrient use efficiency. For this reason, conservation agriculture is sometimes described as a win–win strategy for agriculture and the environment (Lal et al. 1998).

Two case studies in sub-Saharan Africa: the Mid Zambezi Valley and the periphery of the "W-Arly-Penjary" complex

The Mid Zambezi Valley is a low-land area along the Zambezi River, encompassing the Zimbabwe-Zambia border and part of north-western Mozambique (Fig. 4). The W Park is a transfrontier Park including western Burkina Faso, northern Benin and eastern Niger, connected to Arly and Penjari Parks to form the "WAP complex" (Fig. 5). These two areas are characterised by a semi-arid climate with savannah as the dominant vegetation. Both these areas have long been deprived of infrastructure and any significant investment in rural development, are considered "marginal" and host a well-preserved biodiversity. In the Mid Zambezi Valley, there are probably 1500–2000 plant species, which reflects its wide range of habitats, the mammal fauna is relatively intact and diverse, including predators, major populations of elephant, hippopotamus and buffalo, as well as a small concentration of black rhinoceros, and over 400 bird species (Gumbo et al. 2003). The biodiversity of the WAP complex is equally rich as it hosts at least 670 plant species and a significant representation of large mammal fauna, with more than 3,800 elephants, the largest population in West Africa, abundant dwarf buffalo, kob, roan antelope, giraffe, hippopotamus, lion and several species of monkeys (Clerici et al. 2007). It represents the biggest continuum of terrestrial and aquatic ecosystems in the West African savannah belt.

Both areas are emblematic in the world of conservation. Two Zimbabwean Rural Districts of the Mid Zambezi Valley, Nyaminyami District and Mbire District (formally part of Guruve District) were the first districts of the country to receive decentralised authority to manage and benefit from their wildlife under the renowned CAMPFIRE[6], one of the first formal internationally recognised CBNRM[7] programmes. The WAP complex, became in 2002 the first biosphere reserve in Africa within the "Man And the Biosphere" programme of UNESCO.

After independence in Zimbabwe (1980), the land surface under crops and fallow increased fourfold in less than 16 years in Mbire District (Poilecot 2002; Fig. 6), expansion of cotton fields being a major contributor to this increase (Baudron et al. submitted). Agricultural development in the Mid Zambezi Valley was driven by a strong political will from the Zimbabwean Government and donors, and was assisted through tsetse eradication campaigns and opening of cotton depots. Similarly, cotton production increased dramatically at the periphery of the WAP complex, especially in the Diapaga Province in eastern Burkina Faso (Fig. 7). In the commune of Tansargua alone, the area of land under cotton increased by 70% between 2001 and 2005 (Doussa 2004). These land use changes not only cause biodiversity directly, but lead to increased isolation of remaining habitat fragments. For example, using species richness capacity (SRC), an indicator based on the empirical species-area relationship, Clerici et al. (2007) estimated the impact of increased isolation of

[6] Communal Area Management Program For Indigenous Resources.

[7] Community-Based Natural Resource Management.

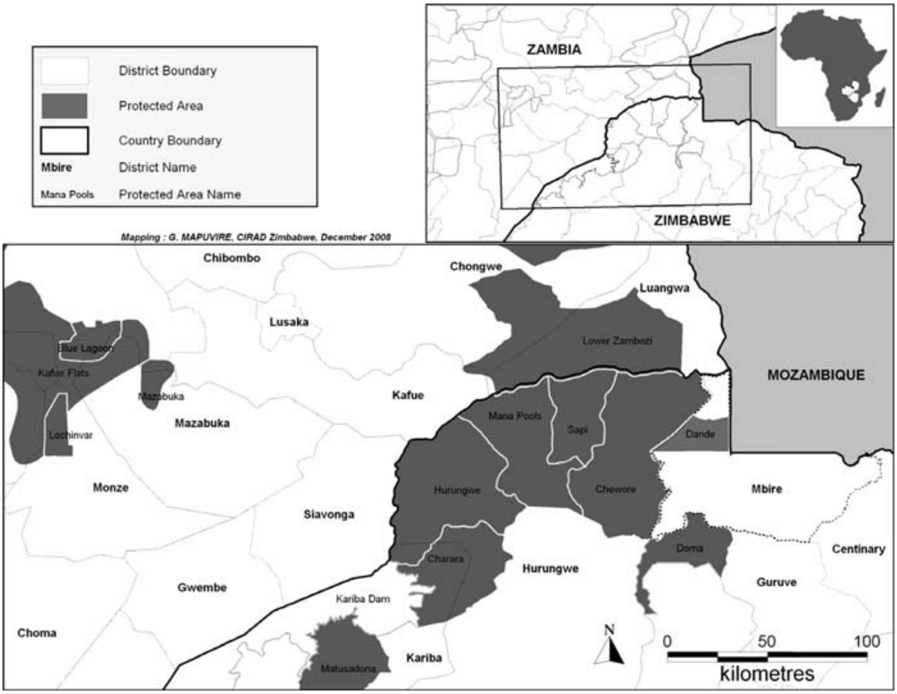

Fig. 4 Location of southern Zambia within the Mid Zambezi Valley area

the WAP complex due to habitat conversion of its periphery. For the period 1984–2004, the SRC declined from 98 to 96%, and would be expected to further decrease to 83% if the entire WAP periphery is converted to agriculture. Cotton production also requires large doses of pesticides, including some potentially harmful for the environment, such as endosulfan (EJF 2007). Endosulfan has a low solubility in water and has accumulated in species of fish (*Silurus* and *Tilapia*) in the WAP complex (Issa 2004).

The success of cotton farming in African savannah ecosystems is explained by the crop's adaptation to climatic conditions that characterise savannah: a marked dry season essential for a good opening of cotton bolls and hot temperatures close to the optimum (between 27 and 32°C) for vegetative growth (Parry 1986). Cotton does not tolerate excess water; on the contrary, its deep root system makes cotton relatively tolerant to dry spells and rainfall variations. Generally, 500–700 mm of rainfall is sufficient for normal crop development. In addition, cotton is particularly attractive for farmers in drylands, as there is virtually no alternative cash crop with a structured market that can compete with cotton. Credit schemes and the assurance that farmers can sell their entire production explain the ready adoption of the crop. In addition, market prices of seed cotton are generally known before the beginning of the production campaign in West Africa. Credit schemes enable farmers to access mineral fertilisers that benefit food crops included in the rotation. A variable proportion of fertilisers destined to cotton may also be "diverted" to food crops (Baudron 2007).

In both areas, the need to intensify cotton-cereal systems and agriculture in general gave birth to initiatives aiming at developing and diffusing cropping technologies based on the principles of conservation agriculture, particularly in southern Zambia (part of the Mid Zambezi Valley and its escarpment) and eastern Burkina Faso (the periphery of the WAP

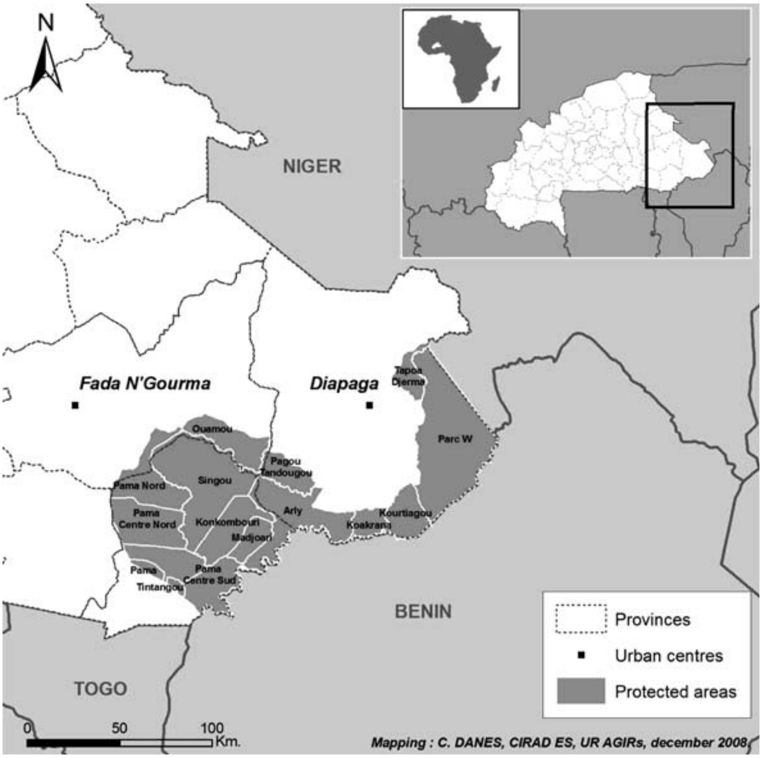

Fig. 5 Location eastern Burkina Faso within the "W-Arly-Penjary" complex

complex). Efforts focused on reduced-tillage systems for both manual and mechanised agriculture that allow residue retention and increase water infiltration close to the crop. Indeed, in the two case study areas, water is the most limiting factor to crop production (though nutrient-poor soils are also prevalent). Conventional land preparation is done by ploughing, which incorporate residues, and manual direct planting (for farmers with no or limited animal draught power).

For manual agriculture, permanent planting basins have been adopted by a number a smallholders in southern Zambia. The CFU[8] estimated that 78,000 smallholders adopted this technology during the 2002–2003 growing season (Haggblade and Tembo 2003; Baudron et al. 2007). Planting basins are permanent in the sense that they are re-dug every year at the same place, during the dry season. Planting basins aim to 'harvest' rainwater. They are structures roughly 20 cm deep in which seeds, manure and/or basal fertiliser are placed. In essence, they are very similar to structures used in traditional farming, such as the "zaï" system of Burkina Faso. In addition to these systems adapted to manual agriculture, animal-drawn implements were developed in these two countries. The Zambian 'Magoye ripper' developed in the MACO[9] research station (Baudron et al. 2007) and the IR12 and RS8 tillage tines tested and promoted by INERA[10] in Burkina Faso (Barro et al.

[8] Conservation Farming Union.

[9] Ministry of Agriculture and Cooperatives.

[10] Institut de l'Environnement et des Recherches Agricoles.

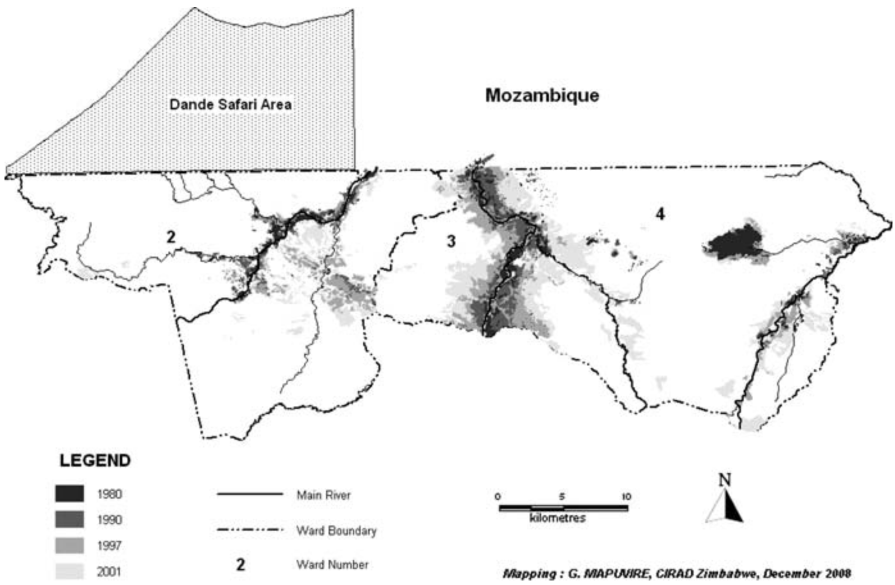

Fig. 6 Expansion of cultivated land in *Wards 2*, *3* and *4* of Mbire District during the 20 years following Zimbabwean independence (Source: Biodiversity Project 2002)

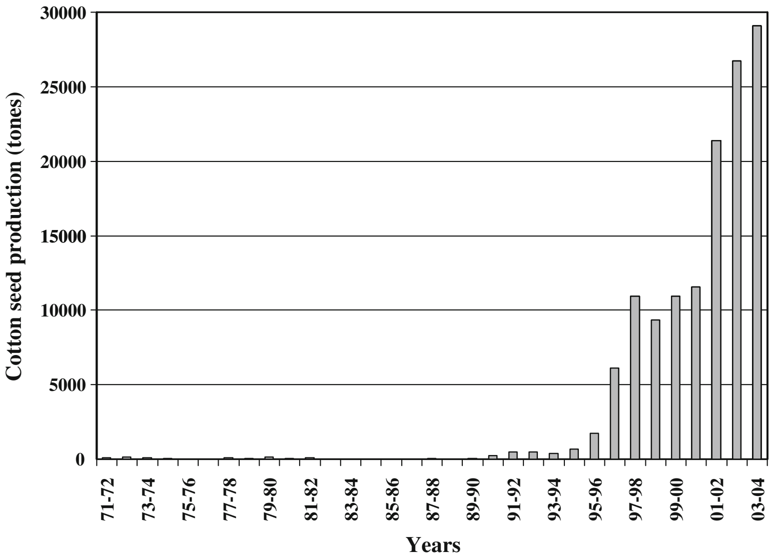

Fig. 7 Development of cotton seed production in Diapaga Province, Burkina Faso, in the past 30 years (Source: Guibert and Prudent 2005)

2005) are the most common and well-documented implements used for minimum tillage operations in the two case study regions. These implements open a furrow in the soil to a depth of 15–20 cm and allow surface crop residue mulching.

The quantity and quality of residues produced by the main crops alone are often too poor to improve yields through conservation agriculture. Therefore, intercropping systems combining cover crops, with the main crops was developed in many parts of the continent. In West Africa, INERA worked mostly with *Mucuna pruriens* (L.) DC. var. *utilis*, the velvet bean which quickly produces abundant biomass (Barro et al. 2005). SOCOMA,[11] a cotton company under the DAGRIS group, tested a wide-range of grain and forage cover crops, ranging from the grass *Brachiaria ruziziensis* R. Germ. and C.M. Evrard (Congo grass) to the grain legume *Cajanus cajan* (L.) Millsp. (pigeonpea; Baudron 2007). Within this project, intercrops of a cereal and a cover crop were grown in rotation with cotton, cotton being directly seeded in the mulch produced the previous year by the intercrop. Technologies were actually imported from Northern Cameroon, an area of similar agroecology (Raunet and Naudin 2006; Séguy 2003, 2004). Similarly, in southern Zambia, ZARI[12] and GART[13] tested various grain legumes and cover crops, amongst which cowpea (*Vigna unguiculata* (L.) Walp.), velvet bean, *Dolichos lablab* (L.) D.C., sunnhemp (*Crotalaria juncea* L.) and jackbean (*Canavalia ensiformis* (L.) D.C.) gave the most biomass (Golden Valley Agricultural Research Trust 2004).

In both southern Zambia and eastern Burkina Faso, stakeholders involved in the development and diffusion of conservation agriculture also promoted the re-introduction of trees in farmland, in particular of *Faidherbia albida* (Delite) A.Chev., an indigenous tree that produces biomass in the dry season, fixes significant amounts of atmospheric nitrogen, recycles nutrients and is recognised by a number of African communities (e.g. the Tonga in the Mid Zambezi Valley) who retain the trees in their fields (Roupsard et al. 1999). Furthermore, in the two areas, other projects aiming to produce organic cotton developed systems in which cotton is intercropped with catch crops (i.e. ‘catching’ pests). In the Mid Zambezi Valley, sweet sorghum (*Sorghum bicolor* (L.) Moench) and cowpea were the most interesting catch crops (Wilson 2002), whilst okra (*Abelmoschus esculentus* (L.) Moench) was used by farmers in eastern Burkina Faso (Baudron 2007; Helvétas Burkina Faso 2006). Most of these catch crops also help to cover the soil (e.g. cowpea) as well as producing biomass and are therefore compatible with conservation agriculture.

Limited yield data was available from conservation agriculture trials in eastern Burkina Faso. However, in Northern Cameroon where promoted technologies were identical and agroecological conditions similar, cotton yields under manual direct seeding in cereal-cover crop residues were equivalent or slightly larger given a similar rate of fertilisation (Raunet and Naudin 2006). Production gains, when observed, arose from improved water infiltration and reduced soil evaporation. Inclusion of cover crops in the production system is essential to achieve adequate soil cover. Whilst a sorghum crop in pure stand produce 2–3 t ha^{-1} of dry biomass at best, its association with *Brachiaria ruziziensis* can add another 2–3 t ha^{-1}, with no yield loss for sorghum (Séguy 2003, 2004). In the case of climbing cover crops, keeping cereal stalks on the field after harvest actually increases the final production of biomass, as the cereal stalks act as support for the cover crop. For example, Barro et al. (2005) found that velvet bean produced 1 t ha^{-1} of biomass when cultivated in pure stand, and 3–4 t ha^{-1} when associated with sorghum.

In southern Zambia, farmers using planting basins and hand-hoes produced on average 1.5 t ha^{-1} more maize and 460 kg ha^{-1} more cotton than farmers practising conventional ox-plough farming (Haggblade and Tembo 2003). These differences in productivity are, however, largely due to the fact that with the conservation agriculture practise, hybrid seeds and fertilisers were used, whilst most farmers using the conventional ox-plough grew

[11] Société Cotonnière du Gourma.

[12] Zambian Agricultural Research Institute.

[13] Golden Valley Agricultural Research Trust.

crops without agricultural inputs. The use of fertiliser alone accounted for 700 kg ha^{-1} of the extra yield for maize and 400–500 kg ha^{-1} for cotton. Nevertheless, planting basins increase rainwater use efficiency compared with conventional tillage methods, mainly by increasing water infiltration (Nolin and von Essen 2005; Rockström et al. 2009), but also because it is possible to plant with the first rains. Similarly, the use of the Magoye ripper increases productivity due to concentrated nutrients and soil moisture around the plant (Golden Valley Agricultural Research Trust 2004). However, the gains in yield with the Magoye ripper are smaller than those obtained with planting basins, probably due to loss in precision in both plant spacing and fertiliser application (Haggblade and Tembo 2003; Baudron et al. 2007).

In INERA trials in Burkina Faso sorghum produced 5 t ha^{-1} of stalks with reduced tillage using the IR12 and RS8 tillage tines, a practise locally known as ‘mechanical zaï’, against 3 t ha^{-1} with manual zaï and 1.5 t ha^{-1} with ‘scarification’, a conventional practise of reduced-tillage used by cotton farmers in West Africa, that tills the soil to a depth of about 5 cm, with an animal drawn implement such as the ‘houe Manga’ (Barro et al. 2005). Similar to the Zambian experience, the yield benefits arose from an improvement of soil structure and increased water infiltration. Indeed, after 2 years of manual or mechanical zaï, penetration resistance was halved. Higher yields are achieved with the mechanical zaï as compared with the manual zaï, since the soil can be de-compacted deeper with animal traction than with hand tillage.

Benefits at plot level as a result of conservation agriculture are encouraging, often giving increased yield due to increased water and nutrient use efficiency. Even in cases where yield increases are small, conservation agriculture advocates argue that the concept remains attractive to farmers, as it enables a quick and easy establishment of crops. This is particularly true with planting basins that can be dug throughout the dry season (Fig. 8). With an adequate soil cover, weeds are also smothered, adding to labour savings during land preparation. As a result, during the 2004 campaign in North Cameroon, net returns to land were calculated to be on average 76 € ha^{-1} more with cotton produced under

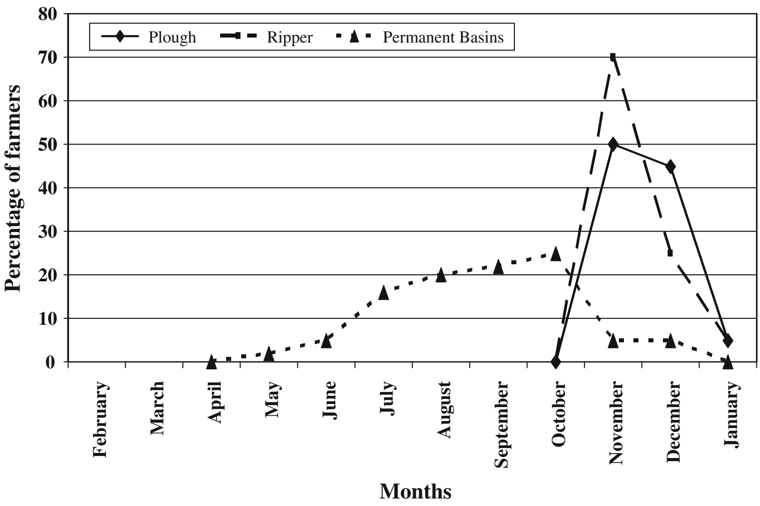

Fig. 8 Timing in land preparation for maize in southern Zambia, following different options of land preparation (from Haggblade and Tembo 2003)

conservation agriculture than with cotton produced conventionally, which yielded an average of 225 € ha^{-1} (Raunet and Naudin 2006).

However, the small proportion of farmers adopting these technologies, and the slow rates of adoption in sub-Saharan Africa are striking. Of the 16,835 smallholders exposed to conservation agriculture between 1996 and 1999 in Zambia, most of them in southern Zambia, only 5,220 adopted some form of conservation agriculture (Bwalya and Mulenga 2002). Adoption by farmers who were not directly targeted by a donor-funded project was rare in Zambia. “Dis-adoption” (abandon of the technology after few seasons of adoption) was recorded once incentives of input packages were stopped (Baudron et al. 2007). In West Africa, the wide majority of adoption of conservation agriculture technologies was also driven by development projects (Djamen et al. 2005). When adoption occured, it was only on small areas of land, representing a limited proportion of the total farm surface, and farmers continued to manage most of their land using their conventional practises (Haggblade and Tembo 2003; Baudron et al. 2007).

It appears that the limited adoption of conservation agriculture systems, despite reported benefits at plot level, is explained by a number of constraints at farm level. We see non-adoption as a rational decision rather than the expression of what Hobbs et al. (2008) disparagingly refer to as a “traditional mindset”. Firstly, conservation agriculture practises generally require an increase in investment, either in the form of purchased inputs or of labour, compared with conventional practises. In particular, not ploughing generally leads to increased weed pressure. To face this, the CFU in Zambia recommends an early and continuous weeding regime, which translates into six weeding operations per year for a maize crop, including post-harvest operations (Baudron et al. 2007). Farmers following such practises, even amongst those farmers who adopt conservation agriculture, are extremely rare. Ploughing remains the single most cost-effective weed control method, and extension agents in southern Zambia confirmed that conservation agriculture using permanent planting basins almost doubles the required weeding effort compared with conventional ploughing (Baudron et al. 2007). Even if the marginal return is high for these extra investments, most smallholders may not be able to undertake them due to limited resources and labour constraints (Erenstein 2002; Giller et al. 2001). Likewise, the purchase of specialised equipment (e.g. ripper, direct-seeder) is critical for successful adoption of conservation agriculture (Hobbs et al. 2008), but represents an almost impossible investment for resource-poor farmers. Rental schemes and the emergence of service providers could potentially reduce investment needs: for example the Zambian CFU argue that the Magoye ripper, being a dry season land preparation tool in contrast with the plough which must be used on moist soils, would benefit farmers who do not own neither the tool nor animal draught power, as they would have the entire dry season to borrow or hire it. However, in practise the Magoye ripper is rarely used during the dry season (Baudron et al. 2007).

Labour is an important constraint, not only in terms of total labour throughout the season, but also in terms of the segregation of tasks between gender and/or age groups and labour calendars, issues often hidden in the simplistic calculations of labour-demand commonly used by those who promote conservation agriculture. For example, conservation agriculture may result in a transfer of the labour burden from men, traditionally in charge of land preparation, to women, traditionally in charge of weeding, whilst changes in total labour demand may be small (Baudron et al. 2007). The peak labour of land preparation may be spread out by the possibility of digging planting basins throughout the dry season (Fig. 8), but such a practise may only be accepted when there are strong incentives such as “food for work”. Figure 8 shows that most farmers use the Magoye ripper at the onset of the rainy season, with a peak labour almost as pronounced as that for plough users, thus losing the benefit of early planting (CFU 2003). Farmers are indeed reluctant to use oxen in the dry season, when they are in poor condition due to low forage availability and when the soil is very dry and hard (Baudron et al. 2007).

As a response to the limited resources and labour of farmers, promoters of conservation agriculture often advise smallholders to "focus their effort on conservation farming plots as an insurance against drought and famine" (CFU 2003) managed at the "highest standard possible" (Oldrieve 2005) and to abandon the rest of their land. This is based on simplistic calculations using differences in crop yields from conservation agriculture trials and average yields from conventional systems. These calculations show that a small acreage managed with conservation agriculture largely outperforms extensive areas under conventional management. Despite the fact that these calculations often compare data from small-scale conservation agriculture trials with sub-regional or even national average yields, such reasoning completely ignores the vulnerability of smallholders to climatic variability or market price fluctuations. Smallholders, particularly in semi-arid areas, are risk prone (Rockström et al. 2002). Having a number of fields, with different soils, planted with different crops and managed differently (Tittonell et al. 2007) is an essential strategy to mitigate these risks.

Promoters of conservation agriculture also often argue that increased investment in the form of extra inputs and/or extra labour is required only in the first few years of adoption. For example, CFU (2003) argued that early and continuous weeding would decrease the weed seed bank over time and ultimately reduce the labour required in conservation agriculture. Research at the GART station in Zambia supported this view, as it demonstrated that labour for weeding is reduced by 50% after 6 years in trials during which weeds were not allowed to grow beyond 5–6 cm. Similarly, physical, chemical and biological improvement of degraded soil may only occur after several years of conservation agriculture practise. Improved soil fertility is seldom observable in the short-term. This limits adoption by smallholders, whom main concerns are to fulfil their immediate needs. We are convinced that only systems generating benefits in the short-term are likely to be adopted by smallholders.

Inclusion of cover crops in the cropping systems aims to 'boost' primary production and increase benefits in the short-term (e.g. soil protection, soil amendment, weed control). However, plants deliberately grown to improve the soil condition but that offer no direct benefit to farmers, as is e.g. the case with sunnhemp or velvet bean, have little chance of spontaneous adoption by smallholders. Although conservation agriculture using 'multipurpose' cover crops is now generally promoted (i.e. cover crops producing grain and/or fodder as well as having qualities to improve soil structure and fertility), the majority of these remains unattractive for farmers at most. 'Food cover crops' (e.g. *Eleusine coracana* L. and *Dolichos lablab* (L.) D.C.) are generally new and unfamiliar to farmers and their usual diet. They also often have no local market. 'Forage cover crops' (e.g. *Brachiaria ruziziensis* and *Stylosanthes guianensis* (Aubl.) Sw.) are attractive only in densely settled areas with limited grazing land. Moreover, managing an association of two or more crops requires appropriate knowledge and the learning period represents a risk of crop failure due to potential competition for resources between the different species. For example, the majority of farmers in the programme of conservation agriculture sponsored by SOCOMA had very poor cover crop establishment in their trial plot, due to late planting (Baudron 2007).

Even in cases where substantial residual biomass may be produced during the rainy season (from cereal and cover crops), biomass left on the field by the onset of the rainy season may be insignificant. The question of access rights to this residual biomass after harvest is central in communal areas where cattle are grazing freely. Indeed, in semi-arid areas, residual biomass is considered a public good as it represents the main source of forage during the dry season (Schelcht et al. 2005). As a consequence, many conservation agriculture promoters advocate fencing of fields and zero-grazing, with cattle fed from forage produced on-farm. This practise might be possible in densely populated areas (e.g. the highlands of Eastern Africa) and/or in agroecologies where livestock is relatively unimportant (e.g. tsetse-infested equatorial Africa), but not in semi-arid areas where cattle is a central component of rural livelihoods. In West Africa, fencing of the fields would add another threat to the transhumance system. Soil macro-fauna, termites in particular, represent yet another threat to residue retention in African savannah ecosystem. In a study carried out in southern Burkina Faso, Ouédraogo et al. (2004) found that 80% of sorghum residue disappeared after 4 months in the presence of macro-fauna, whilst only 1% disappeared when macrofauna was absent. Nevertheless, in a study carried out on a set of conventional cotton, maize and sorghum fields representative of the diversity of practises found in Mbire District, in the Mid Zambezi Valley, Baudron et al. (submitted) observed on average total above-ground biomass of 1.7 t dry matter ha^{-1} at the onset of the rainy season, despite the grazing by domestic livestock and wild mega-herbivores and despite substantial termite activity. In the case of cotton fields, the residual biomass cannot be kept but must be destroyed for phytosanitary reasons, only leaving biomass produced by weeds that developed during the dry season as a potential mulch, which is about half of the total above-ground biomass. This reinforces the importance of rotations in the set of recommendations for conservation agriculture, particularly in the case of cotton production. However, rotation is not a common practise in the two case study areas, firstly, because a given crop is often better adapted to a given soil-type (e.g. maize on alluvial soils and cotton in the interfluves of the Mid Zambezi Valley), and secondly, because a particular crop may also be preferred and grown across most of the farm, making rotation with other, minor crops impracticable (e.g. maize in southern Zambia, Nolin and von Essen 2005).

Agriculture is a politically guided management system (Campbell et al. 1997). Therefore, gains in productivity generated by conservation agriculture may only lead to intensification of cropping systems in supportive socio-political contexts (Pretty et al. 2003). Under other conditions, it may have the opposite effect of fuelling further agricultural expansion. For example, extensification may occur due to more rapid crop establishment through conservation agriculture. Indeed, in marginal lands with low population density, practises of intensification may not lead to reduction of unit costs of production, and may prove uneconomic due to increasing costs of input procurement with increasing distance to market (Erenstein 2006). In such areas, extensification may be a rational response. Conservation agriculture may improve the water budget at field level and reduce drought-spell related risk of crop failure, therefore creating or reinforcing the rationale to invest in external inputs (Rockström et al. 2002). However, the question of access to fertilisers and herbicides remains central for resource-poor farmers (Gowing and Palmer 2008).

Recommendations for the development, evaluation and diffusion of conservation agriculture

Evaluation at plot level of various technologies using conservation agriculture shows its potential to increase crop productivity, reduce negative environmental effects and improve sustainability. However, unless promoted by donors, adoption rates are modest. Developing the most productive conservation agriculture technologies on experimental fields and pushing these technologies onto smallholders' farms is an approach bound to fail—but by far the most commonly used approach. Parameters other than productivity explain adoption of a particular innovation, and constraints at farm scale cannot be ignored. Labour-saving and risk-mitigating technologies that have collateral benefits for the environment may have a higher potential of being adopted by farmers than technologies purely targeting yield and income.

Decisions whether or not to adopt particular conservation agriculture technologies are made at farm-level and depends on farmers' objectives and constraints. Thus, farm-level is the appropriate scale to evaluate impact of conservation agriculture options and their likelihood for adoption. Assessing how various technological options impact on overall farming systems and how they modify resource and labour allocation at farm level is paramount to understand which options 'fit best' the different categories of farms (Giller et al. submitted). The use of bio-economic models including decision rules on the allocation of resources and labour generated from observed farmers' behaviour may be useful for such complex evaluation (Affholder et al. 2008). Taking into account the notion of risk will also require use of dynamic models, through which the effects of weather variability and changes in market prices for example may be explored.

Farmers' norms, culture and perceptions are also important factors to consider. Many cover crops demonstrate a number of benefits, but simply prove too foreign to be accepted. Dual-purpose varieties of legumes already known by farmers (e.g. leafy soyabean, creeping leafy cowpeas), that offer good grain yield as well as producing much biomass, might be the most likely cover crops to be adopted (Giller et al. 2001). This observation suggests the need for selection of such dual-purpose varieties by plant breeders, moving away from selection based solely on grain production, as it has often been the case. Many local landraces are quite dual-purpose: their in situ conservation and use in conservation agriculture systems may be interesting to explore. Nevertheless, the fate of the residual biomass is influenced by other dynamics at the level of the village/community, in particular through communal grazing. In areas where cattle population is important, large-scale adoption of conservation agriculture will depend on negotiations at community-level, probably facilitated by the design of innovative technical options and/or new institutional arrangements.

It is important to understand farmers' response to market, laws and policies in order to target project interventions in areas where an enabling socio-political environment exists (or to create such an environment). Gowing and Palmer (2008) highlight that adoption of innovations is rarely spontaneous but often the consequence of an external priming agent. External help, in financial and non-financial forms, is required for the farmer to face transition costs (Pretty et al. 2003). Hobbs et al. (2008) advocate for sustained donor support to achieve significant, large-scale adoption of conservation agriculture. Political support is also required, but policies supportive to sustainable agriculture are at best patchy in the majority of both developed and developing countries (Pretty et al. 2003). Finally, access to and exchange of knowledge, through the creation and animation of innovation networks, including agrochemical companies and equipment manufacturers, is of prime importance (Gowing and Palmer 2008; Hobbs et al. 2008).

Conclusion

Integrated with other measures, such as effective policies, conservation agriculture may be an effective strategy to release pressure on biodiversity without threatening human needs in landscapes of global importance for conservation. To increase its adoptability by smallholders and propose technologies that would fit better into the farming systems, those promoting conservation agriculture need to scale up their approach from plot to farm level and ultimately to village and landscape. This will require a multi-disciplinary approach, involving both social and biophysical disciplines, and the participation of farmers at each stage of the development, evaluation and diffusion of conservation agriculture technologies. Utilisation of simulation models to explore alternatives and to facilitate negotiations amongst stakeholders may be a promising approach to increase our understanding.

Acknowledgments This is a collaborative work between the CIRAD-CNRS-UZ-NUST research platform "Producing and Conserving in Partnership" (RP-PCP) and the Competing Claims on Natural Resources programme (www.competingclaims.nl) funded by the International Research and Education Fund (INREF) of Wageningen University.

References

Affholder F, Jourdain D, Morize M, Quang DanDinh, Ricome A (2008) Eco-intensification dans les montagnes du Vietnam. Contraintes à l'adoption de la culture sur couvertures végétales. Cah Agric 17:289–296

Arias-Estévez M, López-Periago E, Martínez-Carballo Simal-GándaraJ, Mejuto J-C, Garciá-Río L (2008) The mobility and degradation of pesticides in soils and the pollution of groundwater resources. Agric Ecosyst Environ 123:247–260. doi:10.1016/j.agee.2007.07.011

Barro A, Zougmoré R, Maraux F (2005) Utilisation du mucuna et du zaï mécanique dans la réhabilitation des sols et l'amélioration des revenus des exploitations du Burkina Faso. Proceedings, Third World Congress on Conservation Agriculture, Nairobi, Kenya, 3–7 October 2005

Baudron F (2007) Production ou Conservation? Le dilemme du coton en peripherie du Parc Transfrontière du W du Niger. Création-diffusion de systèmes agroécologiques plus durables et plus respectueux de l'environnement. Ouagadougou, Burkina Faso. ECOPAS

Baudron F, Mwanza HM, Triomphe B, Bwalya M (2007) Conservation agriculture in Zambia: a case study of Southern Province. Nairobi, Kenya. African Conservation Tillage network, Centre de Coopération Internationale de Recherche Agronomique pour le Développement, Food and Agriculture Organization of the United Nations

Baudron F, Corbeels M, Monicat F, Giller KE (submitted) Cotton, not eradication of tsetse fly, drives conversion of globally-important conservation areas for agriculture; empirical evidences from the Mid Zambezi Valley, Zimbabwe. Global Change Biology (N Y, Print)

Biodiversity Project (2002) The mankind and the animal in the mid Zambezi Valley, Zimbabwe. CIRAD-Emvt, Montpellier, p 75

Bwalya M, Mulenga NC (2002) The way forward for Zambian farming in the 21st Millenium. African Conservation Tillage Network Year Book 2002

Campbell BM, Bradley P, Carter SE (1997) Sustainability and peasant farming systems: observation from Zimbabwe. Agric Human Values 14:159–168. doi:10.1023/A:1007358823524

CFU (2003) Conservation farming in Zambia. Zambia National Farmers Union, Lusaka

Chapagain AK, Hoekstra AY, Savenije HHG, Gautam R (2006) The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecol Econ 60:186–203. doi:10.1016/j.ecolecon.2005.11.027

Chivenge PP, Murwira HK, Giller KE, Mapfumo P, Six J (2006) Long-term impact of reduced tillage and residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soils. Soil Tillage Res 94:328–337. doi:10.1016/j.still.2006.08.006

Clerici N, Bodini A, Eva H, Gregoire JM, Dulieu D, Paolini C (2007) Increased isolation of two biosphere reserves and surrounding protected areas (WAP ecological complex, West Africa). J Nat Conserv 15:26–40. doi:10.1016/j.jnc.2006.08.003

Corbeels M, Scopel E, Cardoso A, Bernoux M, Douzet JM, Siqueira Neto M (2006) Soil carbon storage potential of direct seeding mulch-based cropping systems in the Cerrados of Brazil. Glob Chang Biol 12:1–15. doi:10.1111/j.1365-2486.2006.01233.x

Cowlishaw G (1999) Predicting the pattern of decline of African primate diversity: an extinction debt from historical deforestation. Conserv Biol 13:1183–1193. doi:10.1046/j.1523-1739.1999.98433.x

De Jager A, Onduru D, van Wijk MS, Vlaming J, Gachini GN (2001) Assessing sustainability of low-external-input farm management systems with the nutrient monitoring approach: a case study in Kenya. Agric Syst 69:99–118. doi:10.1016/S0308-521X(01)00020-8

DeFries R, Hansen A, Turner BL, Reid R, Liu J (2007) Land use change around protected areas: management to balance human needs and ecological function. Ecol Appl 17:1031–1038. doi:10.1890/05-1111

Desjardins T, Barros E, Sarrazin M, Girardin C, Mariottin A (2004) Effects of forest conversion to pasture on soil carbon content and dynamics in Brazilian Amazonia. Agric Ecosyst Environ 103:365–373. doi:10.1016/j.agee.2003.12.008

Djamen P, Maraux F, Ashburner J, Triomphe B, Kienzle J (2005) L'agriculture de conservation en Afrique francophone de l'ouest et du centre: état des lieux, enjeux et défis. Regards sur l'agriculture de conservation en Afrique de l'ouest et du centre et ses perspectives: contribution au 3ème Congrès mondial d'agriculture de conservation, Nairobi, Octobre 2005

Doussa S (2004) Les impacts de la culture cotonnière sur la gestion des ressources naturelles du Parc W : cas de l'enclave de Kondio. ECOPAS, Ouagadougou

EJF (2007) The deadly chemicals in cotton. Environmental Justice Foundation in collaboration with Pesticide Action Network UK, London

Erenstein O (2002) Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. Soil Tillage Res 67:115–133. doi:10.1016/S0167-1987(02)00062-4

Erenstein O (2003) Smallholder conservation farming in the tropics and sub-tropics: a guide to the development and dissemination of mulching with crop residues and cover crops. Agric Ecosyst Environ 100:17–37. doi:10.1016/S0167-8809(03)00150-6

Erenstein O (2006) Intensification or intensification? Factors affecting technology use in peri-urban lowlands along an agro-ecological gradient in West Africa. Agric Syst 90:132–158. doi:10.1016/j.agsy.2005.12.005

FAO (2008) http://www.fao.org/ag/ca. Accessed 10 April 2008

Farella N, Lucotte M, Louchouarn P, Roulet M (2001) Deforestation modifying terrestrail organic transport in the Rio Tapajos, Brazilian Amazon. Org Geochem 32:1443–1458. doi:10.1016/S0146-6380(01)00103-6

Findeling A, Ruy S, Scopel E (2003) Modeling the effects of a partial residue mulch on runoff using a physically based approach. J Hydrol (Amst) 275:49–66. doi:10.1016/S0022-1694(03)00021-0

Giller KE, Beare MH, Lavelle P, Izac A-MN, Swift MJ (1997) Agricultural intensification, soil bio-diversity and agroecosystem function. Appl Soil Ecol 6:3–16. doi:10.1016/S0929-1393(96)00149-7

Giller KE, Cadish G, Palm C (2001) The North–South divide! Organic wastes, or resources for nutrient management? Agronomie 22:703–709. doi:10.1051/agro:2002058

Giller KE, Rowe EC, de Ridder N, van Keulen H (2006) Resource use dynamics and interactions in the tropics: scaling up in space and time. Agric Syst 88:8–27. doi:10.1016/j.agsy.2005.06.016

Giller KE, Witter E, Corbeels M, Tittonell P (submitted) Conservation agriculture and smallholder farming in Africa: the heretics'view. Field Crops Res

Girdis DP (1993) The role of cotton in agricultural change, land degradation and sustainability in Southern Mali. Royal Tropical Institute, Amsterdam

Golden Valley Agricultural Research Trust (2004) Gart 2004 year book. GART, Lusaka

Gowing JW, Palmer M (2008) Sustainable agricultural development in sub-Saharan Africa: the case for a paradigm shift in land husbandry. Soil Use Manag 24:92–99. doi:10.1111/j.1475-2743.2007.00137.x

Guibert H, Prudent P (2005) Mise en place d'un programme d'évaluation des impacts environnementaux exercés par le front agricole pionnier dans l'aire protégée et la périphérie du parc du W. Ouagadougou, Burkina Faso. ECOPAS

Gumbo D, Shonhiwa F, Kojwang H, Timberlake J, Chidumayo E, Burgess N (2003) Conservation in the Miombo ecoregion—Southern and Eastern Africa. WWF, Harare

Haggblade S, Tembo G (2003) Conservation farming in Zambia. International Food Policy Research Institute, Washington DC

Helvétas Burkina Faso (2006) Programme de promotion du coton biologique au Burkina Faso, Rapport semestriel janvier-juin 2006

Heywood VH, Watson RT (1995) Global biodiversity assessment. Cambridge University Press, Cambridge

Hobbs PR, Sayre K, Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc 363:543–555. doi:10.1098/rstb.2007.2169

Issa MY (2004) Contribution à l'étude de l'impact de l'utilisation des pesticides sur la faune terrestre et aquatique: cas des grands mammifères et de quelques espèces de poissons dans les réserves de biosphère de la Pendjari et du W. Ouagadougou, Burkina Faso. ECOPAS

Koutika L-S, Bartoli F, Andreux F, Cerri CC, Burtin G, Choné T, Philippy R (1997) Organic matter dynamics and aggregation in soils under rain forest and pastures of increasing age in the eastern Amazon Basin. Geoderma 76:87–112. doi:10.1016/S0016-7061(96)00105-X

Lal R, Kimble JM, Follet RF, Cole V (1998) Potential of U.S. cropland for carbon sequestration and greenhouse effect mitigation. UDSA-NRCS, Washington DC

Main MB, Fritz MR, Reed FN (1999) Evaluating costs of conservation. Conserv Biol 13:1262–1272. doi:10.1046/j.1523-1739.1999.98006.x

McNeely JA, Scherr SJ (2003) Ecoagriculture: strategies to feed the world and save wild biodiversity. Island Press, Washington DC, p 318

Nolin J, von Essen C-F (2005) Conservation Farming in Zambia. MSc thesis. Uppsala, Sweden. Swedish University of Agricultural Sciences

Oldrieve B (2005) Conservation Agriculture, the state of the art in Africa, origins, movements and policies. River of Life Church, Harare

Ouédraogo E, Mando A, Brussaard L (2004) Soil macrofaunal-mediated organic resource disappearance in semi-arid West Africa. Appl Soil Ecol 27:259–267. doi:10.1016/j.apsoil.2004.03.003

Parry G (1986) Le cotonnier et ses produits, collection techniques agricoles et productions tropicales. G-P Maisonneuve et Larose, Paris, p 502

Poilecot P (2002) Wild resources in Southern Africa: the state of biodiversity. CIRAD-EMVT, Ministère des Affaires Etrangères, Fond Français pour l'Environnement Mondial

Pretty JN, Morisson JIL, Hine RE (2003) Reducing food poverty by increasing agricultural sustainability in developing countries. Agric Ecosyst Environ 95:217–234. doi:10.1016/S0167-8809(02)00087-7

Raunet M, Naudin K (2006) Lutte contre la désertification: l'apport d'une agriculture en semis direct sur couverture végétale permanente (SCV). Les dossiers thématiques du CSFD. No 4. Septembre 2006. CSFD/Agropolis, Montpellier, France, 40 p

Rockström J, Barron J, Fox P (2002) Rainwater management for increased productivity amongst small-holder farmers in drought prone environments. Phys Chem Earth 27:949–959

Rockström J, Kaumbutho P, Mwalley JM, Nzabi AW, Temesgen M, Mawenya L, Barron J, Mutua J, Damgaard-Larsen S (2009) Conservation farming strategies in East and Southern Africa: yields and rain water productivity from on-farm action research. Soil Tillage Res 103:23–32. doi:10.1016/j.still.2008.09.013

Roupsard O, Ferhi A, Granier A, Pallo F, Depommier D, Mallet B, Joly H, Dreyer E (1999) Reverse phenology and dry-season water uptake by *Faidherbia albida* (Del.) A. Chev. in an agroforestry parkland of Sudanese West Africa. Funct Ecol 13:460–472. doi:10.1046/j.1365-2435.1999.00345.x

Sala OE, Stuart Chapin F, Armest JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A, Leemans R, Lodge DM, Mooney HA, Oesterheld M, LeRoy Poff N, Sykes MT, Walker BH, Walker M, Wall DH (2000) Global biodiversity scenarios for the year 2100. Science 287:1770–1774. doi:10.1126/science.287.5459.1770

Schelcht E, Hiernaux P, Kadaouré I, Hülsebusch Mahler F (2005) Aspatio-temporal analysis of forage availability and grazing and excretion behaviour of herded and free grazing cattle, sheep and goats in Western Niger. Agric Ecosyst Environ 113:226–242. doi:10.1016/j.agee.2005.09.008

Scopel E, Macena F, Corbeels M, Affholder F, Maraux F (2004) Modelling crop residue mulching effects on water use and production of maize under semi-arid and humid conditions. Agronomie 24:1–13. doi:10.1051/agro:2004029

Scopel E, Findeling A, Chavez Guerra E, Corbeels M (2005) Impact of direct sowing mulch-based cropping systems on soil carbon, soil erosion and maize yield. Agron Sustain Dev 25:425–432. doi:10.1051/agro:2005041

Séguy L (2003) Rapport de mission au Nord Cameroun du 25 Septembre au 2 Octobre 2003. CIRAD Brésil, Brazilia

Séguy L (2004) Suivi-évaluation et proposition de recherche-action pour l'avancée du semis direct sur couverture végétale au Nord Cameroun. CIRAD Brésil, Brazilia

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: implications for C saturation of soils. Plant Soil 241:155–176. doi:10.1023/A:1016125726789

Smaling EMA, Bouma J (1992) Bypass flow and leaching of nitrogen in a Kenyan Vertisol at the onset of the growing season. Soil Use Manag 8:44–48. doi:10.1111/j.1475-2743.1992.tb00892.x

Tilman D, Downing A (1994) Biodiversity and stability in grasslands. Nature 367:363–365. doi:10.1038/367363a0

Tittonell P, Vanlauwe B, de Ridder N, Giller KE (2007) Heterogeneity of crop productivity and resource use efficiency within smallholder Kenya farms: soil fertility gradients or management intensity gradients? Agric Syst 94:376–390. doi:10.1016/j.agsy.2006.10.012

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. Science 277:494–499. doi:10.1126/science.277.5325.494

Wilson J (2002) Country report on the organic cotton project in Zimbabwe within the context of the whole cotton industry. A report for PAN UK's Pesticides and Poverty project. PAN UK. London, United Kingdom, September 2002

WWF (2007) Cleaner, greener cotton. Impacts and better management practices. WWF Freshwater Program, The Netherlands

Zingore S, Manyame C, Nyamugafata P, Giller KE (2005) Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. Eur J Soil Sci 57:727–736