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Adoptability of sustainable intensification technologies in dryland smallholder farming systems of West Africa

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Adoptability of sustainable intensification technologies in dryland smallholder farming systems of West Africa

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Foreword

Within the framework of CGIAR Research Program (CRP) 1.1: Dryland Systems, the compilation of a review of options, constraints and potential for agricultural intensification at a number of specific sites in West African dryland areas has been requested, using an integrated systems approach. CRP 1.1 aims to develop technology, policy and institutional innovations to improve livelihoods, for the poor and highly vulnerable populations of the dry areas (ICARDA 2011). In the introduction to Strategic Research Theme 3 of the project, it is stated that sustainable intensification aims at increasing input use to increase output, based on agroecological principles of sustainability. The program focuses on dryland systems in West Africa identified by two criteria: (i) those with the deepest endemic poverty and most vulnerable people and (ii) those with the greatest potential to impact on food security and poverty in the short and medium term. These areas have been sampled and 10 research locations have been selected and characterized. The first output of the Strategic Research Theme 3 is defined as: *Sustainable intensification options designed and developed*. A range of potential options for sustainable intensification has been described previously, and multiple reviews of successful and less successful innovations for and by smallholders in Africa have been published in scientific and grey literature (Dudal, 2001; Haggblade, 2004; Aune and Bationo, 2008; FAO, 2008; Reij and Smaling, 2008; Tenywa and Bekunda, 2009; Bayala *et al.,* 2011 Pretty *et al.,* 2011). This report provides an overview of the current technologies, and describes four of them in detail. The potential of the technologies for increasing productivity is assessed, and an attempt is made to perform an *ex ante* analysis of their fit, or in other words their 'adoptability', within four research sites. Through this exercise, we explored the way forward, to go from 'best bet' to 'best fit' options for sustainable intensification in West African drylands.

Summary

Agricultural intensification in Africa is a necessary development, if rural poverty is to be reduced and sufficient food is to be produced for the increasing and urbanizing populations. For agriculture to be sustainable in the long run, the intensification process should not greatly reduce environmental quality or degrade natural vegetation; hence the term 'sustainable agricultural intensification' has been defined as *a change in the production system towards increased input use leading to increased productivity, according to agroecological principles and without adverse environmental impacts or the cultivation of new land.*

Farming systems in West Africa are exposed to large climatic variability. Policies and markets have sometimes a positive and stabilizing influence, but more often they are absent, negative or highly volatile and unpredictable. In these environments of large climatic and institutional risks, smallholder farmers have developed livelihood strategies that minimize risk and maximize flexibility. These livelihoods are often based on a combination of shifting cultivation of cereal staple crops, vegetable gardening by women, livestock production, use of natural vegetation for food, medicine and firewood, and off-farm labor to provide cash income.

On a global scale, drivers such as population increase, climate change, urbanization and market development are causing rapid changes in land use and land cover. Such drivers are also active at national and regional levels, and they cause changes, for example, increased pressure on land. Farmers have to respond to these changes in order to 'hang in', that is to keep their livelihoods safe. If the environment of high risk persists, farmers are likely to choose strategies of extensification and diversification to respond to changes. When such strategies are impossible, due to insufficient land, farmers have no other choice than to either 'step out' of agriculture or intensify production on the limited amount of land that they have available. This process is called 'induced intensification'. Induced intensification can also occur when markets open up, so that farmers have the option to produce cash crops and thus stabilize and increase their income. If there is no land shortage and if markets are not available, then intensification is unlikely to happen as farmers prefer other livelihood strategies which are more suitable for their environment.

In West Africa, competition for land is on the rise, conflicts between livestock grazing and crop farming are becoming more common, and many young people are moving to urban centers which are rapidly expanding. It is not surprising that in these circumstances, agricultural intensification processes have been ongoing for decades. However, there are large differences between and within regions and communities regarding the extent of intensification. Some regions have better markets, infrastructure or climatic conditions than others, and farmers in these regions have more options for intensification. Within communities, wealthier farmers have more intensification options and are less vulnerable to risk as they have a buffer in case of climatic or other problems. Poor farmers have few resources and are often stuck in pertinacious 'poverty traps'. Because of the differences between farmers, communities, regions and countries, there is no single way in which sustainable agricultural intensification develops. Rather, there is a range of pathways and technologies, which can be modified and adapted to fit a specific farming system. We have identified around 100 technologies for intensification, divided over three main groups. The first group consists of technologies which are related to 'bridging the yield gap'. Under this group fall technologies such as the construction of zaï (improved planting pits), the application of livestock manure, good weeding practices and the application of pesticides. The second group consists of technologies which represent 'new production activities'. The novelty of a production activity depends on the current state of the farming system and the degree of commercialization. Taking non-commercial smallholder systems as a baseline, technologies grouped under 'new production activities' include the intensive cultivation of (improved) legume varieties in rotation or as an intercrop, introduction of agroforestry practices or small-scale water management for garden irrigation. The third group of intensification options consists of

technologies which involve a 'redesign of the farming system'. The introduction of these technologies assumes re-orientation of multiple production activities, generally towards a more commercial production system. Examples are small-scale commercial dairy production, the cultivation of cash crops, or the involvement in natural resource management activities.

Within the three groups, sub-groups have been identified which cluster the technologies based on their focus of activity, such as 'legume cultivation' or 'livestock production'. Additionally, we distinguish three scales on which the technologies are active: the field scale, the farm scale and the *terroir* scale. Some technologies such as relay cropping will lead to intensification in time, rather than in space. For this reason the time dimension was added to the field, farm and *terroir* scales.

Adoption is a word that is commonly used to describe the uptake of new technologies. We have defined adoption as *the long-term integration of a technology or part of a technology into the set of household livelihood activities, measured in terms of well-defined and quantifiable indicators.* It is common to present project results in terms of numbers of 'adopters' of a certain technology. Such results are informative only if the indicators of adoption are clearly described and well quantified. An analysis of the extent of adoption should be carried out well after the project has finished, so that farmer testing and experimentation is not mistakenly taken for actual integration of a technology into the set of household livelihood activities. For researchers, it is important to know what determines the likelihood that a technology is adopted by farmers, so that the technologies that are most likely to be taken up can be identified. From the large body of literature available, we have distilled 21 indicators of 'adoptability' which together can serve to determine the fit of a technology into a farming system. Sixteen indicators describe 'costs' or 'enabling conditions'. These include biophysical conditions (land and soil requirements, water needs), input conditions (capital, labor, information), economic conditions (market access, demand, credit availability), institutional conditions (enabling policies, land tenure) and cultural conditions (informal rules, access to fields and natural areas). Five indicators describe outcomes. These include direct outcomes (reduced risk, improved nutrition, short and long term financial returns) and indirect outcomes (ecosystem service provision).

Four intensification technologies out of the sample of over one hundred were selected to test and illustrate the indicators of adoptability. Two technologies were taken from the 'bridging the yield gap' group (zaï cultivation and fertilizer microdosing), one was taken from the 'new production activities' group (legume cultivation) and one was taken from the 'farming systems redesign' group (small-scale dairy production). An analysis of the adoptability of the four example technologies was developed based on the available case studies specific for West Africa, or other dryland systems in sub-Saharan Africa when the number of available case studies was too limited.

Key enabling conditions that were identified for the zaï technology are labor availability, availability of compost or manure, and land tenure. Additionally, the profitability of zaï construction was found to be driven by land shortage and soil degradation (especially crust formation). In regions with >800 mm/year rainfall, zaï do not function.

For microdosing, key enabling conditions are availability of fertilizers, cash availability and market access. In terms of outcomes, it has been noted that microdosing does not provide sufficient nutrients to prevent soil nutrient mining, and should therefore be combined with other soil fertility management technologies in order to prevent soil degradation and sustain productivity after the initial year(s).

Intensive legume cultivation requires access to seeds, Phosphorus fertilizers and insecticides, as well as labor availability, market access, and a stable demand for legume grains or stover. Apart from direct monetary benefits, legume cultivation can also enhance soil fertility. Legume fodder can play a role in small ruminant fattening or small-scale dairy production and can thus contribute to an increased integration of crop and livestock production within the farming system. Improved dual-purpose varieties of cowpea, among others, are available which provide grain and fodder simultaneously.

Small-scale dairy production, the fourth example option for intensification, is faced with a long list of enabling conditions, but the monetary returns can be very substantial. Commercial dairy production requires the proximity and accessibility of markets, where demand for dairy products must be large and prices quite stable to allow investments. Supporting policies are necessary which protect the national or provincial market against the inflow of cheap foreign products (especially milk powder) or which fix a minimum price for dairy. Feed, medicine and veterinary services must be available and affordable. Knowledge and skills are required to take good care of the animals. The purchase and maintenance of livestock requires a certain resource endowment, and small-scale dairy production takes place at the top of the ladder of agricultural intensification.

The four example technologies above were matched to four research locations in West Africa to identify 'best bet' options. The four research sites were taken from a rainfall gradient and differed substantially in terms of biophysical and socio-economic conditions. Dan Saga in Niger is very dry (533 mm/yr) but densely populated whereas Banizoumbou (also in Niger, 553 mm/yr) is equally dry but population pressure is low. Sougoumba in Mali, has a better rainfall (935 mm/yr) and is heavily commercialized, with a stable cotton market and good access to inputs. Dimabi, in Ghana, has the most rainfall of the four sites (1095 mm/yr) and is located very close to an urban center, but commercialization is less and access to markets and inputs is limited due to high transport costs.

Intensive legume cultivation appears to fit well in all of the research sites (though limitations in access to fertilizer can be a problem). Zaï technology fits only in the two drier regions and is likely to happen primarily in the more populated area of Dan Saga, as large labor inputs are required and returns on labor small, so that it becomes attractive only when land pressure is high. Small-scale dairy production is likely to be feasible only in the wetter areas, where sufficient feed can be produced. Microdosing could be employed by farmers in the drier regions in combination with the use of compost or manure in home fields, and by farmers in more developed regions for boosting cereal production for home consumption in the outfields. However, its limited sustainability due to nutrient mining effects must be kept in mind, especially when used in fields under continuous cultivation.

If research projects are to move sustainable agricultural intensification forward, the objectives and rationale of farmers and the tendency to extensify and diversify, rather than intensify, must be understood and taken into account. The enormous diversity of social and biophysical climates in West Africa calls for a flexible and locally targeted approach, rather than the design of one-size-fits-all solutions. The matching of technologies with research sites in this project shows the use of the set of adoptability indicators for identifying 'best bet' options. New or alternative technologies can be analyzed and matched based on the defined indicators. The indicators can be used as a framework for discussions between experts or in project teams on the strengths and weaknesses of a technology, or on the fit of a technology in a research site. Key constraints to adoption, such as market stability for small-scale dairy production, can be identified. If the constraints to intensification are too numerous or too large, then the intensification process is likely to be inhibited. In West Africa, constraints are often related to labor availability, market demand, price stability and infrastructure. These are typically socio-economic constraints at the community, regional or national level, rather than technical constraints at the household level. Understanding such constraints should be a first priority, as they have an overriding effect on opportunities for agricultural intensification.

Research can support farmers in the process of intensification through understanding and addressing the key constraints to the successful adoption of new technologies (for example by the implementation of a warrantage system to resolve cash problems) and through designing well-adapted 'best fit' technologies that farmers can test and then further adapt and integrate into their farming systems. If the technologies are indeed well-adapted and well-integrated, then productivity in the short and long-term can be increased without causing (further) environmental degradation, and the process of sustainable intensification will progress.

1. Introduction

1.1 Development and change in sub-Saharan Africa

Despite the fact that some sub-Saharan African economies are among the fastest growing in the world, food insecurity and famine are still common in the region. Food security is determined by three factors: availability, access and utilization (McCalla, 1999; Gregory et al. 2005). After more than 55 years of development aid in Africa, yields have remained similar to those obtained in the 1960s (Eicher, 2003; Pretty et al. 2011). Estimated population increase in the drylands of Africa is 3% per year, while food production increases are only 2% per year, thus limiting food availability (UNDC, 2006). The percentage of undernourished people in sub-Saharan Africa went from 26.5% in 2007-2009 to 26.8% in 2010-2012, and the area is home to around 234 million of the total of 868 million undernourished people in the world (FAO, 2012). Increase in agricultural productivity is particularly effective in reducing hunger and malnutrition (FAO, 2012), and growth in agricultural incomes is most beneficial for reducing poverty and food insecurity (Cervantes-Godoy and Dewbre, 2010). More effective agricultural development strategies are required to achieve such growth.

The theory of development has been re-analyzed by Dorward (2009), who tried to find common ground for discussion between supporters of the neo-liberal development paradigm and those of the civil-society paradigm, as identified by Kanbur (2001). The main area of dispute between the two paradigms is the choice, extent and timing of employment of economic policy instruments, especially free trade, in the development process. To accommodate dialogue, Dorward identified a key point of agreement: both paradigms assume that poor households have two key development objectives, which are to hold on to the wealth and welfare they already possess, and to advance their wealth and welfare. In the climatically and institutionally insecure environments of sub-Saharan Africa, holding on to existing wealth is a challenge in its own right which takes up a large share of a household's activities (Wood, 2003). Based on the two development objectives, Dorward (2009) coined three development trajectories: 'hanging in' (holding on to existing wealth and welfare), 'stepping up' (increasing wealth and welfare through larger productivity of existing activities) and 'stepping out' (increasing wealth and welfare through transition to new activities). These trajectories occur through the processes of accumulation, differentiation, specialization, diversification, intensification, commercialization and trade, or a combination of several of these. Not only households, but also lower scale units (individuals) and higher scale units (from local to global communities) follow the 'hanging in', 'stepping up', 'stepping out' trajectories in their development processes. The processes at different scales are interrelated as they tap into the same capital and asset pools and changes on one scale often affect others in multiple ways (Dorward, 2009).

Development of a system is a complex process. In an intriguing article about leverage points and the way systems change, Donella Meadows (1999) argued that changing just constants and parameters (such as taxes) or physical stocks and flows has little potential in terms of changing the outcomes of the entire system. As Hardin (1968) expressed: "there is no technical solution to the problem" (p. 1243). The real leverage points are found in the power divisions, the rules, the goals and the underlying paradigms of the system. On the level of intensifying the farming systems in West Africa, this indicates the importance of looking at the systems as a whole and their goals and paradigms, rather than solely focusing on technologies. In order to generate change, the goals and rules of the system must be well understood.

1.2 Drivers of change

A driver of change in agriculture has been defined as *any natural or human-induced factor that directly or indirectly brings about change in agricultural production systems* (Hazell and Wood, 2008: p. 501). Main drivers of agricultural change are population pressure, climate change, trade expansion, globalization of markets, low food prices, agricultural policies, *per capita* income, urbanization, public policy, changes in market chains, technology developments, property rights, infrastructure, market access and off-farm opportunities (Hazell and Wood, 2008).

Globally, land cover and land use are fast and radically changing as six billion people sustain themselves by extracting food, shelter, fiber and drinking water from their environment (Foley et al. 2005). Population growth is one of the key drivers of change in agriculture, but its relative importance and its expected effects are a source of dispute (Meyer and Turner, 1992). One of the first to write about the effects of population pressure on the human kind was Thomas Malthus. In his famous 'An Essay on the Principle of Population', Malthus (1798) gave as a core proposition that the correction of population increase by means of subsistence happens through constant "misery and vice" (p. 5). He states: "That population cannot increase without the means of subsistence is a proposition so evident that it needs no illustration. That population does invariably increase where there are the means of subsistence, the history of every people that have ever existed will abundantly prove" (p. 11). Over one-and-a-half century later, Ester Boserup and AV Chayanov almost simultaneously published alternative essays on the effects of population pressure (Boserup, 1965; Chayanov, 1966, cited in Turner and Ali, 1996). Chayanov, a Russian anthropologist, proposed that farmers seek to minimize labor investments, rather than to maximize profits. Chayanov theorized that "the amount of labor expended depended on the consumer–producer ratio of the household" so that "additional inputs to production would not follow unless the consumer–producer ratio changed" (Turner and Ali, 1996: p. 14984-5). Chayanov's proposition is in agreement with Boserup's central theory that agricultural productivity responds to population pressure, rather than the other way around. Additionally, Boserup objects to the Western idea of agricultural expansion in terms of bringing areas of virgin nature under cultivation. She argues that most traditional cultivation systems use shifting cultivation rather than permanent fields. Therefore, agriculture generally expands in the form of increased frequency of cropping, rather than cultivation of new, virgin lands (Boserup, 1965).

In his ground-breaking article The Tragedy of the Commons, Hardin (1968) sketched a bleak scenario for our common use of the earth's limited resources as the population keeps growing, which is in line with the Malthusian theory. Hardin convincingly argued that browbeating users of common resources into acting against their own interest is morally disputable, inherently contradictory and generally not effective. His proposed solution is mutual coercion through administrative law, so as to limit human reproduction (Hardin, 1968). Considering the commons in terms of natural resources, specifically, Dietz and colleagues (2003) argue that Hardin's scenarios and solutions are too simplistic. They postulate that effective prevention of degradation of commonly-owned areas, especially under increased pressure for land and resources, is possible but requires a complex system of formal and informal rules. Dietz and colleagues defined a range of conditions for effective governance of the commons, including clarity of information, trust of stakeholders in the governing body, a diversity of rules and governance systems (rather than a single one), easy and functional ways to deal with conflict, and willingness and ability to change. Simple solutions for complex issues such as the governance of public space may seem attractive but are generally likely to fail (Dietz et al. 2003). This is especially relevant in rural sub-Saharan Africa, where forests and rangelands are often under community management.

Four major land use and land cover changes are tropical deforestation, rangeland modifications, agricultural intensification and urbanization (Lambin et al. 2001). A panel of 26 land-use change experts agreed that that population pressure is almost never the sole, and often not even the main driver of land cover change (Lambin et al. 2001). They concluded that there are multiple socio-economic causes, and that the risk of deforestation, for example, is highest in “large, sparsely occupied forest regions in which the indigenous inhabitants have little or no power to influence the exogenous forces acting upon them and the land” (Lambin et al. 2001). In contrast to tropical forests, most rangelands are shaped by the interaction between human activities (the grazing of livestock) and natural processes (Lambin et al. 2001). Rangeland degradation by overstocking is not only a consequence of increased livestock numbers, but also of the erosion of traditional governance structures and of changing livelihoods, leading to land alienation and patterns of exclusion as well as local overgrazing. Rangeland conversion and fragmentation also results from the loss of the link between livestock and agriculture due to agricultural intensification. In order to make agricultural intensification sustainable, diversification is essential (Lambin et al. 2001), especially at early stages of intensification (Powell et al. 2004). Triggers of intensification are land scarcity (through population pressure), commoditization (through markets), and intervention (through governments or NGOs) (Lambin et al. 2001). Land scarcity may lead to sustainable intensification, but is likely to also cause poverty, transition to wage labor or migration for part of the households, especially amongst the poor. Commoditization changes the value of what is produced on a hectare of land, driven by market demands, and increases dependence on markets and capital (Room, 2000). Market instability reduces the sustainability of commercial intensification, and the transition to commercially orientated agriculture is likely to go hand in hand with increased financial risk, especially in countries with poorly regulated markets. The availability and accessibility of markets is directly linked to urbanization. Though urban areas cover less than 2% of the earth’s surface, the land use change effects of urbanization through rural-urban linkages are large. Urban lifestyles are often coupled with increased consumption of especially animal products, creating a large ‘ecological footprint’. In sub-Saharan Africa, rural and urban areas are linked, among others, through labor migration (mostly towards urban centers but sometimes the other way), flow of goods and money, and family ties (van Westen and Klute, 1986; Painter et al. 1994; Andersson, 2001; Lambin et al. 2001).

La Rovere and colleagues (2005) identified three main trends associated with increasing population pressure in the Sahel, which are increased area under cropping (or, more accurately, increased frequency of cropping (Boserup, 1965; de Ridder et al. 2004)), reduced availability of and access to grazing resources (van Keulen and Breman, 1990; de Ridder et al. 2004), and migration of labor in the dry season and herd transhumance in the wet season. Social drivers play a key role in the evolution of Sahelian agro-ecosystems (Saqalli et al. 2010). Land fragmentation due to inheritance rules that have been adapted over time so that all children receive an equal share of land and livestock, lead to a fast decrease in land available per family. However, such fragmentation also gives new families the flexibility to move out of farming and find other occupations, potentially leading to increased income (‘stepping out’) (Saqalli et al. 2010). The lack of access to land, which especially young people in sub-Saharan Africa are confronted with, is a serious threat, as the rural population is aging and as young people may not be able to find employment elsewhere and thus end up in a poverty trap (Sumberg et al. 2012). Local informal institutions can have a strong effect on the speed and direction of development processes (Mazzucato and Niemeijer, 2002). Political stability is another factor that strongly affects potential for intensification and the willingness to invest (Ebanyat et al. 2010). Large market demands for tropical export products from the late 1940s till the early 1970s drove the growth of agricultural productivity in Africa beyond population growth, but productivity fell again when prices went down (Wiggins et al. 2005). Market demand is a very powerful driver for change, but nevertheless it is often overlooked. Current increases in global food prices present opportunities for farmers, and the increased populations in urban areas provide another potential source of demand, but supply chain organization and market access are often lacking in rural areas so that farmers are unable to profit from rises in demand (Wiggins et al. 2005).

Climate change is an important global driver of agricultural change (Fischer et al. 2005; Gregory et al. 2005; Howden et al. 2007). If agriculture fails to adapt, the consequences of climate change can be severe (Jones and Thornton, 2003; Parry et al. 2005; Kurukulasuriya et al. 2006; Howden et al. 2007). Africa is the continent which is expected to be most strongly affected by climate change (Parry et al. 2005). In the Sahelian region of West Africa, climate change and adaptation have been particularly high on the research agenda, as the region has suffered from an extended drought period from the late 1950s until the late 1980s, with severe droughts in 1972-73 and in 1983-84 (Hulme and Kelly, 1993; Batterbury and Warren, 2001; Dai et al. 2004; Kandji et al. 2006). The drought caused famine, massive livestock deaths and large-scale migration away from the Sahelian regions (Roose et al. 1999; Fatondji et al. 2005; Kandji et al. 2006). Long-term consequences of the drought seem to be less severe than short-term effects, and the region has shown a large adaptive capacity (Batterbury and Warren, 2001).

1.3 Sustainable agricultural intensification: terms and definitions

1.3.1 Sustainable and agroecological intensification

Debate about the significance and the direction of sustainable intensification rages on (Garnett and Godfray, 2012) as different stakeholders and interest groups give their own twist to what the term does or should mean. Those who support fully industrial agriculture are equally able to use 'sustainable intensification' as a key phrase as are those who argue for a move towards organic agriculture as the main production system (Garnett and Godfray, 2012). Tiffen and colleagues (1994) defined agricultural intensification as *increased average inputs of labor or capital on a smallholding, either on cultivated land alone, or on cultivated and grazing land, for the purpose of increasing the value of output per hectare.* The sustainability element is not a part of this definition. The Royal Society (2009) includes sustainability in its definition by proposing that sustainable intensification is a system where *yields are increased without adverse environmental impact and without the cultivation of more land*. This definition focuses on plant production ('yields') only and excludes the livestock component. Also, the 'cultivation of more land' is mentioned, but as was argued by Boserup (1965), shifting cultivation with long-term fallows is the common practice in many agricultural societies, so that the idea of agricultural expansion through conversion of 'virgin nature' is generally not correct. Rather, expansion happens by increased frequency of cultivation, so that more land is under cultivation at the same time (Boserup, 1965). In the CRP 1.1 project proposal it is stated that sustainable intensification aims to "increase input use to increase output, based on agroecological principles of sustainability" (ICARDA 2011). We propose to integrate the previous three definitions into the following: *Sustainable intensification is a change in the production system towards increased input use leading to increased productivity, according to agroecological principles, without adverse environmental impacts and without the cultivation of new land.* This definition covers the intensification component (increased input use, leading to increased productivity) and the sustainability component (according to agroecological principles, without adverse environmental impacts and without the cultivation of new land), and it captures both the crop and the livestock components of the system.

Three aspects of the agricultural intensification process can be distinguished: i) slowing or halting of agricultural expansion, ii) increasing inputs to production, and iii) increasing input use efficiency (units output per unit input) (Keys and McConnell, 2005). It has been argued that increased input use efficiency should be a key element of sustainable intensification, rather than increased input use or increased output quantities *per se* (Garnett and Godfrey, 2012). 'Intensive' has been further specified as "knowledge, technology, natural capital, and land-intensive" (The Royal Society 2009). Especially in the West African context, 'labor-intensive' should be included in this list, as labor represents a large constraint to productivity (Adams and Mortimore, 1997; Mazzucato and Niemeijer, 2002). A reduction in volume of undesirable outputs per unit input is taken as an inherent element of increased productivity.

Agricultural systems are ecosystems controlled (to a large extent) by humans (Doré et al. 2011), hence the term 'agroecology' has been coined to describe the ecology of agricultural systems (Altieri, 2002). Agroecological intensification has been associated with sustainability and respect for biological processes. Milder and colleagues (2012) state that *agroecological management seeks to enhance the provision of on-farm ecosystem services — such as pest control, weed control, soil fertility, pollination, and nutrient cycling — that, in turn, support agricultural productivity on a sustained basis*. In the West African context, many aspects of ecosystem service provision are traditionally included in the farming system, such as intercropping to ameliorate pest or weed pressure, and nutrient cycling through the use of manure and compost. The interpretation of agroecological intensification in terms of purely organic production, excluding all uses of chemical external inputs, goes beyond the principles of sustainable agricultural intensification which are the starting point of the CRP 1.1 project of which this review is part. Nevertheless, making optimal use of the processes observed in natural ecosystems for the re-design of farming systems on the road towards agricultural intensification is sensible (Doré et al. 2011). This is especially true in the West African parkland systems where trees are already strongly integrated in the farming systems and where access to external inputs is often limited. Far-reaching mimicry of natural systems, as proposed for example by Ewel (1999) and van Noordwijk and Ong (1999) still needs to prove its potential, as scientific research into the functioning and productivity of such systems is limited (Noordwijk and Ong, 1999; Doré et al. 2011).

Aune and Bationo (2008) argue that agricultural intensification is like climbing a ladder. On the lowest rung are the options that require little capital investment but (sometimes) large labor investment. The risk of these options is generally small. When climbing the ladder, required capital investments get larger, and risks increase accordingly. At the top of the ladder, the system has been converted from subsistence orientated to commercially oriented. A similar ladder was proposed for smallholder livestock production systems, starting with poultry keeping and ending with dairy cattle production (Udo et al. 2011). Large institutional requirements mean that not all farmers are currently able to climb up to that highest rung of the ladder (Aune and Bationo, 2008). The analogy with a ladder is perhaps appropriate – if climbing up the different rungs requires substantial investment, and exposes farmers to economic risk, shocks may cause farmers to fall back to the bottom of the ladder. An example would be investment in dairy cows that may die of tick-borne diseases if veterinary care is not consistently guaranteed. Less risky investments may be advantageous – and resemble more closely a 'staircase', where farmers may fall down one step when shocks arise, but not directly to the bottom.

1.3.2 Induced intensification

When land is not a limiting factor, smallholder farmers tend to optimize outputs per unit of labor, rather than per unit of land (Chayanov, 1966, cited in Turner and Ali, 1996; Adams and Mortimore, 1997; Erenstein, 2006). In Sahelian West Africa, livelihood strategies of rural households generally involve extensification and diversification, rather than intensification, with off-farm labor providing an important share of the household income (Haggblade et al. 1989; Painter et al. 1994; Adams and Mortimore, 1997; Wood et al. 2004) and sometimes adding to agricultural investment (Babatunde, 2012). Only when land becomes scarce, specific resources (such as easily accessible irrigation water) are available, or market demands for agricultural products are large, optimization of output per land area becomes relevant (Adams and Mortimore, 1997; de Ridder et al. 2004). Intensification transitions may not be compatible with the objectives and activities of smallholder farmers, who may decide to diversify their livelihood strategies instead. Historically, flexibility is a key component of African agriculture (Niemeijer, 1996; Batterbury and Warren, 2001) and intensification generally happens at the expense of flexibility (Adams and Mortimore, 1997). The failure to understand the rationale for livelihood choices that African smallholder farmers make is one of the reasons why so many attempts to intensify agricultural production are unsuccessful (Muzari et al. 2012). Reducing risks in the farming environment through policy (such as fixed product prices) limits the need for flexibility and gives room for intensification (Adams and Mortimore, 1997), as is exemplified by the developments in the Malian cotton zone (Benjaminsen, 2001). In areas where population pressure is very high, the opportunities for agroecological intensification can be reduced due to lack of land and resources.

The induced intensification thesis explains changes in agricultural intensity, and is derived from the economic theory of induced innovation (Goldman, 1993). The economic theory of induced innovation says that “technical change is induced by changes in the availability and cost of major factors of production, particularly land and labor” (Binswanger and Ruttan, 1978, cited in Goldman, 1993: p. 45). In the African context, smallholder farmers will mostly aim to reduce labor inputs and risk, so that intensification, which generally requires increased labor investments and increased willingness to take risks through capital investments and specialization, will not happen unless it is induced (Boserup, 1965; Chayanov, 1966, cited in Turner and Ali, 1996). Agricultural intensification is induced by changes in factor availability (such as decreasing availability of land) and changes in market opportunities, but develops in different ways depending on the driving force and the local conditions (Goldman, 1993; de Ridder et al. 2004).

The induced intensification theory as posed by Boserup as a sole model for change was questioned by Lele and Stone (1989), who carried out a large-scale review of agricultural intensification processes in sub-Saharan Africa. The authors defined two types of induced intensification: autonomous (Boserupian) intensification, which is a spontaneous response to changes in factor availability or market opportunities, and policy-led intensification, which involves an “increased role of the state to enhance productivity” (Lele and Stone, 1989: p. 5). The authors argue that autonomous intensification alone is not sufficient to keep up with the fast changes in parts of Africa, especially in conditions that include fragile soils, poor rainfall and “circumstances of unequal political power between the mass of smallholders and the privileged few” (Lele and Stone, 1989: p. 5). The different theories of induced intensification all seem to imply that unless the conditions are conducive, intensification is unlikely to take off.

Responses to inducing factors can take several forms. Laney (2002) distinguishes innovative intensification and non-innovative intensification as potential responses, but also names additional options such as expansion or ‘no change’. Innovative intensification involves the adoption of new management techniques and/or the use of new inputs, leading to increased output per unit input. Non-innovative intensification is ‘business as usual’ but with increased rates of input, leading to a potential increase in absolute outputs but often to a decrease in output per unit input. In the West African situation capital inputs are generally small, for example, an average application of 10kg chemical fertilizer per hectare, per year (Kelly, 2006). Intensification is therefore unlikely to take off without an increase in input use, in the form of chemical or organic fertilizers, mechanization, labor or others (de Ridder et al. 2004).

The direction in which agricultural intensification develops depends to a large extent on the local circumstances and the drivers of intensification (Goodman, 1993; de Ridder et al. 2004). High population pressure in combination with good infrastructure gives room for more innovative intensification responses. High population pressure in remote areas, however, is more likely to cause expansion or increased frequency of cultivation (Goodman, 1993), or increased labor input for the recycling of organic materials (de Ridder et al. 2004). Non-innovative intensification, especially involving increased cropping frequency without additional soil improvement measures, is often not sustainable in the long term. In the Boserupian model, innovative intensification follows non-innovative intensification when further expansion is not possible and current practices cannot be sustained. This leads to a question if general thresholds of population density can be identified that need to be reached before intensification and innovation occur (de Ridder et al. 2004).

1.3.3 Land sparing versus land sharing

The push for agricultural intensification is not undisputed. Proponents argue that intensification leads to land sparing, which gives room for the creation of protected nature (Garnett and Godfray, 2012). Opponents argue that land sharing (limited intensification and provision of other ecosystems services besides food production within the farming system) is the better way to go, as good governance is often lacking in developing countries so that land sparing will not actually lead to the creation or maintenance of protected natural areas on spared land. The land sharing approach is supported by Rosenzweig (among others), who argues strongly for an approach of 'reconciliation ecology' where anthropogenic habitats are adapted to simultaneously provide a habitat for a wide variety of wild species, so as to supplement nature conservation areas (Rosenzweig, 2003). The author specifically mentions agriculture as a target system for reconciliation ecology.

In two case studies in southwest Ghana and northern India, a heterogeneous region of intensive cropping systems and natural areas was compared with a homogeneous region of extensive systems only (Phalan et al. 2011). Larger bird biodiversity was found in the heterogeneous cropping/nature regions in both countries, which supports the theory that land sparing, with intensified farming systems and protected nature as separated elements, leads to larger biodiversity than land sharing, with extensive farming systems and no protected natural areas (Green et al. 2005; Phalan et al. 2011). Biodiversity is used here as an indicator for ecosystem health, but it is not necessarily an indicator for the 'pristineness' of nature, as larger biodiversity is associated with an intermediate disturbance (Connell, 1978).

Agroecological or sustainable intensification aims to reconcile the land sparing and the land sharing approach, by intensifying land use through ecologically sound practices which maximize ecosystems services and minimize environmental damage.

1.4 Scope and content of the report

A large number of intensification technologies for West African agriculture exist (Table 2). Examples include the use of improved grain varieties with good drought tolerance, manual construction of simple water harvesting structures (zaï) or the design and introduction of irrigation schemes. Variations and specificities, such as a range of different improved varieties per crop, can be defined for each option, resulting in an extensive collection of available techniques. An attempt could be made to list all techniques, but the usefulness of such a list would be limited as intensification is, above all, an innovative and creative process.

This report focuses on a sub-set of four intensification technologies to test and illustrate a set of 'adoptability indicators'. The technologies are matched with four research sites to identify 'best bet' options.

Institutional and policy options for intensification, such as better market opportunities, fertilizer subsidies, or local bylaws for common property resource management, are not reviewed extensively. Instead, the report focuses on technology-related (mostly agronomic) options that can be applied at field, animal, farm and *terroir* scale. However, the necessary socio-economic, institutional, and policy-related enabling conditions for the technologies to be adoptable and effective are reviewed and discussed.

It is beyond the scope of this report to provide practical recommendations with regards to which technologies are most promising; rather, we present and illustrate a tool for the assessment and selection of intensification technologies and their fit within a research area, that can be applied in future research activities.

1.5 Objectives

In the introduction to this report, we explored past and future changes in land use in the world in general and in West Africa in particular, and introduced the major drivers of change. The main concepts and definitions in sustainable agricultural intensification have been discussed, which lays the groundwork for the following sections. In Chapter 2, we explore the specific intensification options that are available for West Africa, and propose a categorization based on the extent of intensification within the farming system and the scale on which the technologies are active. Chapter 3 introduces the adoptability approach, which provides a framework for the *ex ante* analysis of sustainable intensification technologies and their opportunities and challenges for implementation. A set of key indicators is defined and explained, based on the main determinants of adoptability as described in and derived from literature. In Chapter 4, a set of four example technologies is developed to illustrate the range of available intensification options and to test and illustrate the set of adoptability indicators. Relevant on-farm experiments and results are described, and each example is concluded with an analysis of the adoptability of the technology, based on the key indicators. In Chapter 5, the example intensification options are matched to a set of four research sites (taken from the 10 research sites defined in the CRP1.1 project proposal, see ICARDA, 2011). The research sites are described in detail, local drivers of change are identified, and the site properties are matched with the key adoptability indicators as defined for each of the example technologies. A hypothesis is developed about the relevance and implementation potential of each of the technologies in each of the research sites. Finally, in Chapter 6, a general conclusion proposes the way forward for agricultural intensification in West Africa.

A web-based bibliography of key papers and studies on intensification techniques, mostly in West Africa, is made available for future reference (for access, please contact the corresponding author).

2. Sustainable Intensification in Dryland West Africa

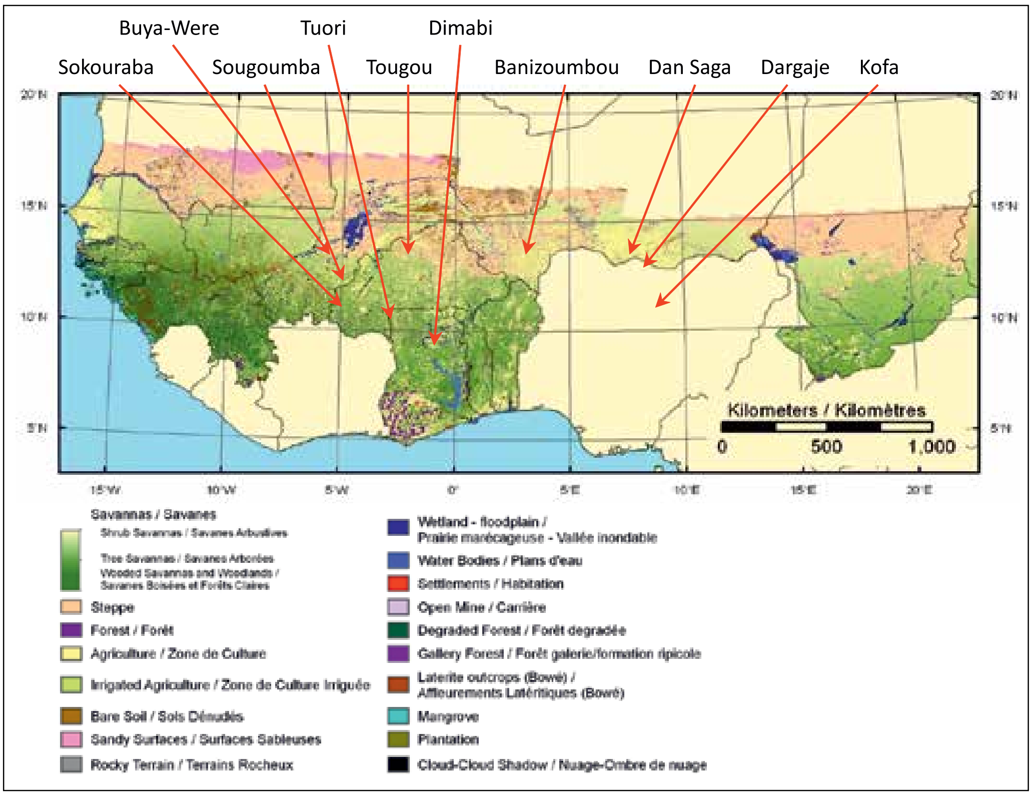
2.1 Climatic and environmental conditions

The West African drylands stretch from Dakar in the far west of Senegal to the north of the Central African Republic, in a more or less straight line between 10 and 15°N latitude (Fig. 1). The FAO defines drylands as regions with a growing season of between 1 and 179 growing days (FAO, 2000). A subdivision is made into dry sub-humid (120-179 growing days), semi-arid (60-119 growing days) and arid regions (1-59 growing days). UNEP and UNCCD define drylands as regions with a ratio of precipitation over potential evapotranspiration (P/PET) between 0.05 and 0.65 (UNEP, 1992). Regions with zero growing days or with a P/PET of <0.05 are classified as 'true deserts' rather than drylands.

Within the West African savannah region, five different savannah zones have been identified based on the P/PET ratio. These are the Sahel (P/PET<0.21), the Sudan savannah (0.21-0.40), the Northern Guinea savannah (0.40-0.66), the Southern Guinea savannah (0.65-0.88), and the derived savannah (0.75-1.0) (Sanford and Isichei, 1986, cited in van Noordwijk and Ong, 1999). The drylands include the Sahel, Sudan savannah and Northern Guinea savannah regions. The natural vegetation of the savannahs is strongly affected by water availability but also by nutrient availability (van Noordwijk and Ong, 1999). Belowground biomass often represents more than half of the total biomass production (Strugnell and Pigott, 1978; Long et al. 1992).

2.2 Literature

An abundance of scientific and grey literature and websites is available on the topic of agricultural intensification technologies in West Africa (Table 1). A number of well-cited articles and reports were



Map source: US Department of State Geographer, http://lca.usgs.gov/

Figure 1. Land use map of West-Africa with the ten CRP1.1 research sites.

used for orientation purposes (Boserup, 1965; Keys and McConnell, 2005; OASIS, 2007; Aune and Bationo, 2008; FAO, 2008; Keating et al. 2010; Bayala et al. 2011; ICARDA, 2011; Pretty et al. 2011; Garnett and Godfrey, 2012). To explore the large body of literature, Google Scholar was used as the preferred search engine because it captures more grey literature than other databases, such as CAB abstracts or Web of Science. A drawback is the limited specificity, leading to large numbers of results with little relevance. With combinations of between four and eight search terms it was possible to reduce the number of hits to <100. Based on the title, literature was selected that was specific for the research area (drylands of West Africa) and relevant for the research topic. For the four example technologies elaborated in Chapter 4, only literature describing actual experimental results (from field experiments or surveys) was included. Our method was not fully systematic as the purpose of this report is not to provide a systematic review. The bibliography represents a relevant share of the available literature on the topic of agricultural intensification in West Africa. Some francophone literature was included, but most searches were performed in English.

Table 1. Some Google Scholar searches and the number of hits.

Key words	Nr of hits
"yield" AND "intensification" AND (country list†)	22,800
"yield" AND "smallholder" AND (country list†)	18,400
"agricultural intensification" AND (country list†)	7,500
"intensification" AND "yield" AND "smallholder" AND (country list†)	6,500
"zai" AND "smallholder" AND (country list†)	181
"microdosing" AND (country list†)	130
"zaï" AND "smallholder" AND "microdosing" AND (country list†)	15

Citations and patents were excluded from the results.

†Country list: "West Africa" OR "Sahel" OR "Gambia" OR "Senegal" OR "Mali" OR "Burkina" OR "Ivoire" OR "Ivory Coast" OR "Ghana" OR "Togo" OR "Benin" OR "Nigeria" OR "Cameroon" OR "Chad" OR "Mauritania" OR "Niger"

2.3 Overview of intensification technologies

From the literature that was used for orientation (see previous section) and from literature that was read in a later stage, a large array of intensification options was extracted. A full list of available technologies for sustainable agricultural intensification in West Africa is presented in Table 2.

Table 2. Overview of sustainable intensification options for smallholder farmers in West Africa.

The options are grouped by degree of intensification and by type. The spatial scale or temporal dimension is indicated (P = plot, F = farm, R = region, T = time).

Bridging the yield gap	Introduction of new production activities	Farming systems redesign
*** Management of yield-limiting factors**	*** Legume cultivation**	*** Animal production**
P Zaï (improved planting pits)	P Improved fallows using eg. Sesbania or Mucuna	F Animal traction
P Half-moon pits	T Rotation with local legumes (cowpea, Bambara groundnut)	F Improved livestock disease management
P Terracing	P Intercropping with local legumes (cowpea, Bambara groundnut)	F Inland valley dairy production
P Contour bunds/furrows	P Intercropping or rotation with new legumes (soya bean, pigeonpea)	F Intensive small ruminant production
P Combination of zaï and contour bunds	T Relay culture	F Intensive poultry production
P Increased planting densities, LAI and ground cover	P Cowpea for fodder production	F Feed/fodder crop production and improvement
P No tillage		F Cultivation of fodder shrubs/ trees/ pastures
P Shallow tillage	* Improved food crop varieties	F Dry season cattle fattening with millet and cowpea stover
P Stone rows	P Hybrid pigeonpea	F Intensive small ruminant production
P Grass strips	P Crops with improved drought resistance and water use efficiency	F Intensive poultry production
P Animal penning in the field	P Improved maize varieties	F Cattle purchase and meat/milk production
P Animal penning for manure collection	P Crops with improved nutritional value	F Dairy goat purchase and meat/ milk production
P Integrated Soil Fertility Management	P Orange-fleshed sweet potatoes	F Purchase of genetically improved cattle
P Mulching of crop residues	P Millet with improved fodder qualities	F Purchase of genetically improved poultry
P Addition of household waste	P Improved cowpea IAR7	F Cottonseed cake purchase
P Organic biomass from millet threshing	P Use of resistant landraces	F Small-scale dairy production and processing facilities
P Green manuring		F Introduction of aquaculture
P Mulching with tree/shrub leaves and twigs	* Agroforestry	* Introduction of cash crops
P Using ants and termites (termitaria)	P Alley cropping	F Cotton
P Addition of homemade biochar	P Planting leguminous indigenous trees	F Rice as a food/cash crop (System of Rice Intensification, New Rice for Africa)

Continued

Table 2. *Continued*

The options are grouped by degree of intensification and by type. The spatial scale or temporal dimension is indicated (P = plot, F = farm, R = region, T = time).

Bridging the yield gap	Introduction of new production activities	Farming systems redesign
P Microdosing/picodosing with chemical fertilizer	P Planting (shade-tolerant) crops under trees	F Fresh fruits for processing
P Chemical fertilizer application	F Planting indigenous fodder shrubs	F Bioenergy crops
P Inoculation with arbuscular mycorrhizal fungi	F Live fences	F Horticulture / irrigated vegetable gardens
P Rhizobial inoculation of legumes	F Planting fruit trees for nutrition	F Cultivation on raised vegetable beds
P Addition of cattle/ donkey/ goat/ poultry manure	F Introduction of edible Australian Acacia species	F Sesame
* Management of yield-reducing factors	F Fodder banks with high-quality fodder species	F Cassava
P Good weeding practices	* Water management	* Improved cash crop varieties
P Push-pull technology with trap and repellent plants	F Lowland/ wetland/ inland valley cultivation	F Improved rice varieties for dryland cultivation
P Pesticide use	F Runoff agriculture	F Improved orphan crops
P Insecticide spraying at flowering time in cowpea	F Runoff storage in reservoirs	F Improved Tef (var. Quncho)
P Herbicide use	F Water storage from yards and rooftops in tanks	F Growing biofortified crops
P Post-harvest pest repellent through the use of local plants	* Alternative management practices	F Improved vegetable seed
P Integrated Pest Management	P Low external input agriculture	F GM crops
P Integrated Striga Management	P Return to traditional cultivation practices	F Bt-cotton
P Integrated Disease Management	P Conservation agriculture	F Bt-maize
* Improved management strategies	* Other	* Alternative farming systems
P Harvesting cereals at physical maturity to improve stover quality	F Introduction of indigenous vegetables	F Installation of irrigation systems
P Seed priming	F Establishment of local seed banks	F Certified organic agriculture
T Continuous cropping	T Dry season agriculture	F Smallholder seed enterprises
F Poultry production with leftover millet in good years		P Farmer managed agro-forestry system (FMAFS)
F Couscous production with bumper millet crop		* Natural resource Management
		R Integral protection of degraded land
		R Forest/ woodland/ rangeland rehabilitation
		R Rehabilitation of degraded lands through planting of leguminous indigenous trees

The options are grouped by degree of intensification and by type. The spatial scale or temporal dimension is indicated (P = plot, F = farm, R = region, T = time).

2.3.1 Classification of technologies and constraints

The list of options is highly diverse and classification is required to bring in some structure. We propose to separate the options into three groups which represent different degrees of intensification. These groups are, from the lowest to the highest degree of intensification:

- Bridging the yield gap; moving production from the current to the attainable or the economically optimal yield. Examples are improved water harvesting through the use of planting pits, fertilizer use, Integrated Soil Fertility Management (ISFM), or introduction of pest management techniques.
- Introduction of new production activities. The novelty of a production activity depends on the current state of the farming system and the current degree of commercialization. We take non-commercial smallholder systems as a baseline, and we assume that the activities grouped here may increase productivity and profitability of the system, but will not lead to a large-scale transition towards a commercially orientated production system. Technologies grouped under 'new production activities' include legume crops in rotation or intercropping, the introduction of agroforestry, use of improved food crop varieties, or use of alternative management practices (such as conservation agriculture).
- Re-designing the farming system. This group includes technologies which require, or contribute to, a change in multiple production activities towards the development of a production system which is at least partially commercially orientated. Examples are the introduction of cash crops or commercial livestock production, or transition to a different farm management system (such as certified organic farming).

Sub-groups can be created based on the integration scale of the technique. We distinguish three spatial scales (plot/field, farm and *terroir*), and a time dimension which includes crop rotations and relay cropping. Many options, such as the introduction of integrated soil fertility management, occur on several scales at once.

The plot is the lowest organizational scale, which is treated as a single management unit by the farmer. Fields can have one or several plots. Ridges and bunds may create spatial divisions within a field. Nevertheless, fields have some sort of delineations, and we define the field as a cultivation area with certain management homogeneity and with clearly defined boundaries. Decisions taken at plot and field level are tactical or operational as they are short-term and apply to current activities.

A farm is defined as the total set of production units which is directly managed by a household. Production units can be, for example, plants, fields, tools, buildings or animals. Decisions on farm level are operational or strategic as their effects can be seen in the medium or long term.

Terroir is a French term (Painter et al. 1994). The *terroir villageois* is defined as "*l'espace dont une communauté agricole, définie par les liens de résidence, tire l'essentiel de sa subsistance*" (Sautter, 1962, cited in Painter et al. 1994); or, in English: *the space from where an agricultural community, defined by ties of residence, derives most of its livelihood.* The *terroir villageois* describes the land in and around the village, including the fields and the rangelands, which are utilized and managed by the members of the village. There is no single English translation that covers the precise scope and content of the term *terroir villageois*, but possible alternative terms would be 'village area', 'village territory' or 'area within community boundaries'. Instead, we will use the French terms *terroir* or *terroir villageois* as they are the most exact. It must be noted here that *terroir* as a unit of analysis is useful but has its drawbacks (Painter et al. 1994), as *terroirs* are often spatially and temporally segmented, socially differentiated, and have multiple uses and occupancies. Decisions taken at *terroir* level are strategic, long-term decisions, which are generally taken in a community rather than in a household setting.

Finally, the intensification options are grouped by type. Within the first category, 'bridging the yield gap', one important type of intensification technology is 'management of yield-limiting factors', which includes technologies at plot or field scale such as fertilization or the construction of zaï pits. Plant phenotype depends on interactions between genotype, environment and management (G x E x M). Soil water and nutrient pools (but not other soil properties such as structure and type) fall under the 'management' rather than the 'environment' factor because they can be adapted quite easily (Ittersum and Rabbinge, 1997). Phenotypic characteristics, such as the quantity and quality of the grains, directly contribute to crop yield, along with management activities such as the timeliness and efficiency of harvesting. Within the second category, 'introduction of new production technologies', an important type of technology is the introduction of legumes into the cropping system, which happens on plot or time scale or both, depending on the choice for intercropping, rotation or relay cropping. Within the third category, 're-design of farming systems', technologies such as small-scale dairy production and agroforestry are included, which happen at farm or *terroir* level.

Like intensification technologies, constraints to sustainable agricultural intensification exist at many levels (Fig. 2). Though all intensification technologies mentioned in this paper are active at the lowest three levels of aggregation (field, farm and community/*terroir*), the actual integration and adaptation of these technologies, and the effects on farmers' livelihoods, is often directly influenced by policies, regulations and constraints at a higher level (Giller et al. 2008). Examples of constraints at higher level are trade regulations, agricultural policies, or the presence or absence of necessary infrastructure. Alleviating such constraints cannot be done at the farm or household level but requires the engagement of stakeholders at a higher level. Researchers can play the role of facilitator and contributor to the ongoing negotiation processes between stakeholders at different levels (Giller *et al.* 2008). We would like to emphasize that higher-level constraints can strongly influence the adoption and impact of intensification techniques and must be taken into account.

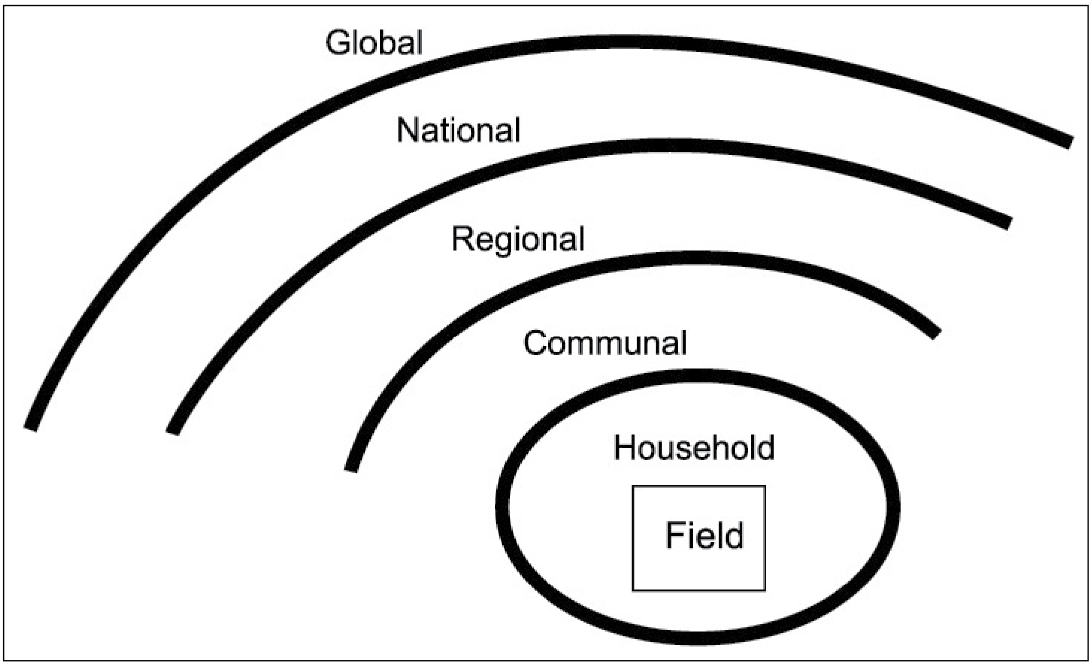


Figure 2. Different levels of constraints on agricultural intensification.

Adapted from Giller *et al.,* 2008

2.3.2 Alternative classifications

In a meta-study of responses to land pressure, Keys and McConnell (2005) distinguished 10 types of intensification mechanisms, based on outcomes for the production systems. Examples are changes in land intensity, labor and chemical inputs, crop mix, and water management. This grouping can be complementary to that proposed above, but does not take into account diversification towards livestock production.

Drechsel and colleagues (2005) proposed to divide intensification options over three groups, based on their origin and degree of integration in the current farming systems. These groups are i) traditional practices, which originated within communities; ii) exogenous practices, which were introduced into communities and were in some cases adapted to local circumstances; and iii) improved practices, which are derived from indigenous or exogenous practices as the consequence of experimentation and development. The terms 'traditional practices' or 'indigenous practices' are ambiguous as approaches lumped under this heading often owe their origin to a combination of local and introduced knowledge. We prefer to use the term 'local practice' which lays less claim on the approach being truly 'indigenous' (Vermeylen et al. 2008).

2.4 Discussion

Four example intensification technologies have been selected for further analysis. These four technologies are taken from the three degrees of intensification and the spatial and temporal dimensions defined above. The construction of zaï (improved planting pits) and fertilizer microdosing are technologies that potentially intensify agriculture by 'bridging the yield gap', and their action is at plot or field level. Intercropping or rotation with legumes can involve the 'introduction of new production activities' or the intensification of existing cultivation, and happens at plot/field and at farm level. Small-scale milk production requires 're-design of the farming system', and happens at the farm and *terroir* level.

3. Adoption, Adoptability, and Adaptation

3.1 Background and definitions

New farming technologies may be very promising in experimental fields, but their actual use in agricultural development depends on their potential to help households and communities 'hang in', 'step up', or 'step out' (Dorward, 2009). In the dynamic and diverse reality of African smallholder agriculture, it is no easy task to understand or predict this potential. An example of a technology package that has received much attention in the last decades is conservation agriculture. The success of the introduction of conservation agriculture has been expressed in terms of 'adoption' (Knowler and Bradshaw, 2007; Kassam et al. 2009; Erenstein et al. 2012) rather than 'impact' (Spielman and Pandya-Lorch, 2009). Whereas assessment strategies and guidelines have been developed to quantify technology impacts, adoption is an abstract term which is difficult to define (CIMMYT, 1993) and even more difficult to quantify (Erenstein et al. 2012). Reports on the success of a technology introduction based on its adoption numbers generally fail to define what 'adoption' is taken to mean (Place and Dewees, 1999; Ogunlana, 2004; Knowler and Bradshaw, 2007; Kassam et al. 2009; Erenstein et al. 2012). Assessing the adoption of new technologies by farmers can only really be done some years after a project has finished, to avoid data distortion due to the running project activities. When evaluating progress during the development projects, we argue that it is better to speak of 'testing', 'experimenting' or 'try-outs' by farmers (Misiko et al. 2008, 2011), rather than of 'adoption'.

We define adoption as the long-term integration of a technology or part of a technology into the set of household livelihood activities, measured in terms of well-defined and quantifiable indicators.

Failure to define the adoption indicators prior to the project, in quantifiable terms, makes a sound scientific assessment of the actual adoption of a certain technology difficult. The willingness to adopt a technology depends to a large extent on the fit of the technology in the farming system (Ojiem, 2006). Extent of adoption does not say much about the success of the project in terms of outcomes and impacts (Sumberg, 2004). In the case of sustainable intensification, the desired outcomes are increased input use, increased productivity, steady or decreased environmental impacts, and no expansion of cultivated area in new lands. For the example of zaï technology, this translates into changes in activity (use of zaï on a certain area of land), productivity (eg. 500 kg/ha of millet grain yield in zaï-planted fields compared to 200 kg/ha in previous years), input use (quantity of additional labor in hours per hectare), environmental impacts (increased water permeability and reduced water erosion) and cultivated area (number of hectares of degraded and unproductive land brought back into cultivation). These changes can be quantified and specified over space and time. A systems approach is useful for such quantification, and for placing the outcomes in a farming systems and/or terroir perspective.

Adaptation is defined as *the re-design and change of a technology to improve its fit to local conditions and/or to livelihood objectives and activities* (adapted from Nkala et al. 2011). Adaptation can be a sign that the technology has been integrated into the farming system and has been moulded to provide the best possible fit, as in the case of improved fallows with *Mucuna pruriens* in Central America (Buckles and Triomphe, 1999). For *mucuna* in Africa, the story is quite different. In the late 1980s and early 1990s, *mucuna* was strongly promoted in Benin for soil improvement and weed control (Vissoh et al. 1998; Schulz et al. 2003). Adoption was reported to be very substantial by Manyong and colleagues in 1996 (cited in Schulz et al. 2003) and in the following years several reports of increasing numbers of farmers cultivating *mucuna* in the region appeared (reviewed in Manyong et al. 1999). A graph of *mucuna* adoption presented by Manyong and colleagues (1999), however, shows a sharp decline in cultivated area and rate of adoption between 1996 and 1997, the final year of analysis. In the paper it is mentioned that the international NGO involved in the promotion of *mucuna* purchased tons of seed from local farmers for further dissemination, starting in 1992. The importance of a seed market was emphasized several times throughout the paper. It was not mentioned that the international NGO stopped purchasing seed after 1996, when the dissemination phase of the *mucuna* project was finished. Suddenly farmers no longer had a market to sell their seeds, and many decided to stop cultivating *mucuna* (Douthwaite et al. 2002; Schulz et al. 2003). This example emphasizes the importance of separating farmer participation and experimentation, which occurs when new technologies are demonstrated and disseminated, from adoption and adaptation, which happens on the longer term, after the dissemination phase is over.

Box 1. Adoptability: the case of improved dual-purpose cowpea varieties.

Cowpea is the most commonly grown legume in West-Africa, with a total cultivated area of almost 10 million hectares spread over Mauritania, Niger, Mali, Burkina Faso, Cameroon, Senegal and Nigeria (FAOStat, 2010). It is common practice to cultivate two cowpea varieties: early-maturing varieties for grain production and late-maturing varieties for fodder (Inaizumi et al. 1999). In the early 1990s two Improved Dual-Purpose Cowpea (IDPC) varieties, developed by IITA together with several partners, were released and demonstrated in farmer participatory trials in Kano region in northern Nigeria (Kristjanson et al. 2005). IDPC varieties provide fodder and grain at the same time, which greatly increases the efficiency of land and labor use. In a demonstration site in northern Nigeria, some seeds of the IDPC variety IT89KD-288 were taken without permission from an experimental field by one farmer in 1993 and were re-sown in the next year (Inaizumi et al. 1999). Four years later, dry-season dual-purpose cowpea was cultivated by over 1,500 farmers in the research area. Informal seed distribution systems played a major role in the technology diffusion.

The popularity of IDPC varieties was found to depend on a number of factors. An important reason for farmers to cultivate IDPCs was their larger grain yield and early maturity (Inaizumi et al. 1999; Kristjanson et al. 2005). The latter is beneficial because cowpea is planted late in the rainy season to prevent competition for light with the cereals, and is therefore vulnerable to dry spells which occur regularly in the short and unreliable rainy season of the Sudan savannah region. The positive impacts of IDPC cultivation on households, especially increased income and improved food quality for the family, were reasons for farmers to increase the area cultivated with IDPC (Kristjanson et al. 2005). Farmers named external input costs as a main reason both for adoption (Inaizumi et al. 1999) and for non-adoption (Kristjanson et al. 2005). Whereas the farmers interviewed by Inaizumi and colleagues preferred to cultivate dual-purpose cowpea because it does not require fertilizer, a number of farmers interviewed by Kristjanson and colleagues did *not* cultivate IDPC varieties because of the perception that they require insecticides in order to be productive. Other reasons to cultivate IDPC varieties were reduced need of machinery, water and labor (Inaizumi et al. 1999). In general, market accessibility and demand were found to be main determinants of adoption (Inaizumi et al. 1999; Kristjanson et al. 2005). Population pressure, which affects for example land and labor availability, was identified as another important determinant (Kristjanson et al. 2005).

Lack of seed availability was found to be a major constraint for IDPC cultivation (Inaizumi et al. 1999; Chianu and Tsujii 2004; Kristjanson et al. 2005). Other constraints were insect attack in the field and in storage, nematode problems, lack of land (Inaizumi et al. 1999) and lack of access to insecticides (Kristjanson et al. 2005).

The introduction of new technologies can be achieved through intervention (by government extension agencies or NGOs) or by spontaneous or induced farmer-to-farmer diffusion. Technology transfer through diffusion has been defined as *the process by which an innovation is communicated through certain channels over time among the members of a social system* (Rogers, 1995; Box 1). As a method for technology spread, diffusion can be more effective than extension or formal training in reaching large numbers of farmers (Alene and Manyong, 2006). However, farmer-to-farmer technology transfer is likely to be less complete, especially in terms of management knowledge, than formal training, which may lead to sub-optimal management and yields (Alene and Manyong, 2006).

Adoptability of a technology is defined as *a qualitative assessment of the potential of a technology to be adopted in a specific target system*. According to this definition, adoptability depends not only on the technology to be adopted, but also on the target system. Adoptability can be influenced by, for example, the costs and benefits of a technique, the fit of a technique with farmers' objectives, the market demand for the production outputs, or the availability and requirements regarding labor, natural resources and inputs. Adoption of a new technology is more likely to happen in areas with high intensification potential, compared with areas that have a poorer natural resource base or limited market access. Ten research sites with contrasting biophysical and socio-economic conditions have been selected in West Africa to analyze and enhance the process of sustainable agricultural intensification (ICARDA, 2011).

3.2 Indicators of adoptability in the West African context

Drechsel and colleagues (2005) defined nine groups of adoption constraints and drivers, based on an expert workshop on resource conservation techniques. These include 1) the returns to land, labor and capital as well as 2) its availability; 3) production costs; 4) land tenure; 5) perceptions, values and personal objectives; 6) risk and stability; 7) access to information; 8) farmers' perceptions of the technology and 9) policy support. In the publication, the authors refer to technology information sheets, but these are not elaborated and appear not to have been developed further (Liniger et al. 2011). Important determinants for adoption that are often overlooked or ignored are returns to labor, investment costs, perceived risk, period between investment and returns, and cultural or historical barriers (Drechsel et al. 2005).

Based on this and other previous work by, among others, the Ethiopian Livestock Feeds (ELF) project (Duncan, 2012), CSIRO (the ADOPT tool, http://www.csiro.au/) and Aune and Bationo (2008), we propose a set of indicators that describe the adoption potential of a technology, in the context of smallholder farming systems in dryland West Africa (Table 3). This general list is by no means exhaustive. Nevertheless, these are key indicators that together will provide a good understanding of and insight in the determinants of adoption potential.

An in-depth analysis of farmers' objectives and of their reasons for selecting certain farming practices and discarding others is described by Baudron and colleagues (2012). The authors argue that the lack of integration of Conservation Agriculture (CA) into the farming systems in the Zambezi valley of Zimbabwe is due to a conflict between the enabling costs of conservation agriculture and the objectives of and constraints to smallholder farming in the region. From the results of a household survey, the authors conclude that farmers are in fact more likely to opt for extensification than for intensification, as they try to spread out and reduce the risks, make optimal use of different soil types, and obtain larger yields with smaller labor investment. Ploughing, which is abandoned in the CA technology package, is a way to allow for the cultivation of more land in the small planting window directly after the first rains. Increased land pressure may make extensification more difficult, but weed pressure and competition for crop residues remain important factors that limit the integration of CA (Rufino et al. 2011; Valbuena et al. 2012).

Table 3. Indicators of adoptability for smallholder farming systems.

Category	Indicator
Enabling conditions/ costs	
Land, natural resources, climate	Land area
	Rainfall, Aridity Index (AI), length of rainy season
	Availability of water sources
	Soil fertility/ quality
	Rangeland extent/ quality
Inputs	Internal/ re-allocated inputs
	External/ purchased inputs
	Labor
	Information and skills
Economic	Credit availability
	Markets
	Price level and stability
	Demand
Institutional	Policy
	Land tenure
Social/ cultural	Culture/ tradition
Outcomes/ benefits	
Direct outcomes	Risk
	Nutrition
	Short-term financial results
	Long-term financial results
Indirect outcomes	Ecosystem service provision

Table 3 lists the key indicators of adoptability that we have identified. Sixteen fall in the category of 'enabling conditions' or 'costs'. These indicators determine which conditions are required for the technology to be integrated in the farming system and to contribute to sustainable intensification. Five of the enabling conditions are biophysical and eleven are socio-economic. The remaining five key indicators are the direct and indirect outcomes of technology adoption. Below, the indicators are discussed per category.

3.2.1 Biophysical conditions

- Land area (in terms of surface, in hectares or square meters). Agricultural intensification assumes increased production on a limited amount of space, or, as is stated in the definition: "without the cultivation of new land".
- Rainfall/ aridity index/ length of growing season. This factor is determining for the range of crops and cultivars that can be grown in the area.
- Availability of water sources. This is relevant especially for irrigation practices.
- Soil fertility/ quality. In West Africa, many soils are inherently poor and a reduction in fallow periods, due to pressure for land, has led to increased soil degradation in many areas. Plant growth in highly degraded soils is poor and responsiveness to fertilizers is reduced (Tittonell and Giller, 2013). Other soil fertility issues include crust formation, Al saturation, which reduces P availability, and salinization (Breman and van Reuler, 2001.

- Rangeland extent and quality. This condition is especially important for cattle production, considering that natural pastures often provide a large share of the cattle feed (Powell et al. 2004; Schlecht et al. 2006; Moritz, 2012).

3.2.2 Inputs

Agricultural inputs have be classified as 'capital' and 'labor' (Moritz, 2012), or as 'primary inputs' (mainly water and nutrients), which cannot be replaced by other inputs, and 'secondary inputs' (all other inputs, such as pesticides and labor) which can be replaced, eg, pesticide application by the release and attraction of natural enemies (Ittersum and Rabbinge, 1997). In the context of adoptability, we discern internal/ re-allocated and external/purchased inputs, as well as labor and information or skills.

- Internal/ re-allocated inputs. These inputs come from within the system or *terroir* and include, for example, manure, mulch, and leaf litter from agroforestry plots. Competition for internal inputs can be very strong (Giller et al. 2009, Rufino et al. 2011), especially when productivity is poor (Valbuena et al. 2012). Internal/ re-allocated inputs may mistakenly be seen as 'free' inputs, but their replacement value can be quite large.
- External/ purchased inputs. These include, for example, fertilizer, seeds, and livestock supplements. Directly linked to this indicator are access to credit and markets (Section 3.2.3).
- Labor (in terms of required or available man-hours). Labor is a major determinant of smallholder strategies in agriculture, as it is often the main constraining factor during planting, weeding and harvesting. When available, off-farm labor generally provides an important share of the household income (Adams and Mortimore, 1999). Strategies to alleviate labor shortage, such as animal traction, are mostly expensive and therefore not affordable for poorer households.

Information and skills. This condition includes farmers' schooling and training as well as the availability of extension services and other sources of information (Alene and Manyong, 2006).

3.2.3 Economic conditions

- Credit (in terms of availability and access). Lack of access to credit is a major constraint for farmers' investments. Cooperatives and warrantage systems can help to relieve the credit constraint.
- Markets (in terms of vicinity, size and accessibility of the local, regional or national markets). Market proximity can act as a strong driver for intensification, as agricultural products can be sold to generate cash income and inputs are more accessible.
- Demand. This indicator is relevant on the output side, as it gives an indication of the possibility for selling the products. A large demand can be an important driver for the adoption of new technologies, especially those that require large investments. On the input side, increased demand may lead to higher prices and to an increased or decreased availability, depending on the strength and flexibility of the market.
- Price level and stability. This indicator is relevant on the input and on the output side. A low price or a lack of price stability (as is common in West African countries where prices are driven by the world market and no protective systems are in place) will reduce the profitability of a technology and increase the risks. Technologies that require large investments may not be suitable in areas where prices are low and stability is limited.

3.2.4 Institutional conditions

- Policy (including all supporting policies on the regional, national and global aggregation scale (see Fig. 2) that are required to allow a technology to function). Often, a limited requirement for policy support is an advantage in the West African situation, as poor institutional support and weak governance are common problems.

- Land tenure (in terms of land ownership and land rights issues, as well as access to rangelands). In West Africa, land rights are often still arranged according to traditional laws, which may reduce security and willingness to invest in, for example, soil fertility. Where governments are trying to take over the regulation of land rights, insecurity often increases (Boubacar, 2000; Adjei-Nsiah et al. 2004).

3.2.5 Culture/ tradition

The 16th enabling condition, *culture/ tradition*, is a very broad one, which includes issues such as access of livestock into farmers' fields, local informal networks, and the role and rights of women (Mazzucato and Niemeijer, 2002). The example of mulching as a yield-improving technique illustrates the influence of culture/tradition on adoptability. Mulching of crop residues may appear to have few enabling constraints because of its low costs and large potential benefits, but it implies that crop residues are to be left in the field, for which the traditional practice of free grazing of animals in the dry season must be altered (Giller et al. 2009; Rufino et al. 2011; Valbuena et al. 2012). The grazing of crop residues by cattle is interwoven in the social structure of villages in sub-Saharan Africa, and such a practice will not easily be abandoned (Rufino et al. 2011). Additionally, crop residues are highly desirable products, and alternative uses than mulch may be more profitable.

3.2.6 Direct outcomes

Apart from the 16 enabling conditions named above, we distinguish four direct outcomes of technology adoption, which are

- Changes in risk (in terms of food and income). Intensification that involves investments can lead to increased risks (Aune and Bationo, 2008) but also to decreased risks, for example when the purchase of cattle has created a buffer for times of economic hardship.
- Changes in nutrition (in terms of quality and diversity). Legumes, vegetables, fruits and animal products can provide proteins and vitamins that may improve the overall diet.
- Short-term financial returns (in the first five years)
- Long-term financial returns (beyond the first five years).

3.2.7 Indirect outcomes

We have defined one indirect outcome, which is related to ecosystem services. This category captures outcomes such as improved soil fertility, decreased erosion, or long-term protection of rangeland quality. However, it must be kept in mind that the main rationale for sustainable agricultural intensification is for the household to maintain or improve its situation ('hanging in' or 'stepping up', Dorward (2009)). Increased ecosystems service provision that does not lead to improved household wealth or welfare even in the long term is unlikely to trigger agricultural development unless revenues can be earned (van Noordwijk et al. 2012) or if there is a clear non-material benefit to the household.

3.3 Conclusion

The list of indicators presented above was designed to capture the main elements that determine whether or not a certain technology fits within a target farming system. The list contains conditions as well as outcomes, and includes biophysical as well as socio-economic factors. The different indicators are illustrated through four example technologies in Chapter 4. In Chapter 5 the four example technologies are matched to four research sites, and the 'best bet' options are identified and discussed.

4. Four Example Intensification Technologies

In this chapter, four example intensification technologies are discussed, based on case studies from West Africa (and sometimes other parts of dryland sub-Saharan Africa). Each technology is discussed in a separate section. All sections are organized in a similar way. They begin with an introduction of the technology, then continue with a discussion of the experimental data from case studies that were found in literature, and end with a discussion of the adoptability of the technology.

To assess and to visualize the adoptability and the main bottlenecks, we have constructed tables in which the enabling costs and the outcomes of the technology are presented. It should be kept in mind that the assessments presented in the tables are qualitative interpretations for the purpose of comparing technologies and illustrating the proposed indicators of adoptability. These qualifications are open for discussion and adaptation. We strongly recommend that intensification-orientated projects include in-depth discussions of potential technologies and their fit in target research areas when exploring new regions or technologies, rather than relying on existing assessments such as ours.

In the tables (Table 5, 30-31) the enabling costs have been color-coded, ranging from green (low enabling costs), through yellow (low/medium enabling costs) and orange (medium enabling costs) to red (medium/high or high enabling costs). The outcomes were similarly color-coded. It was assumed that outcomes are generally positive (otherwise the technology would not be proposed as an 'intensification option'), and the colors are therefore reversed, with strong positive outcomes shaded in green and limited or absent benefits shaded in red. Trade-offs are described in the 'comments' box. The final column of each table shows the alternative costs per indicator, for example replacing labor with mechanization (capital) or replacing manure with chemical fertilizers.

The enabling costs and the alternatives were assessed based on the case studies and are therefore specific for the West African situation. They serve to illustrate the main strengths of the technology as well as the likely constraints for implementation.

4.1 Zaï (improved planting pits)

Zaï pits concentrate and capture nutrients and collect water, which make them suitable for enhancing yields on marginal or degraded drylands. They enhance surface roughness, decrease wind velocity, and capture water runoff as well as dust and other particles that would otherwise be lost. To maximize runoff capture, the zaï pits are orientated along the contour lines, with the soil that is removed from the pit placed as a half circle on the side of the pit that faces the lower end of the slope (Fig. 3). Such type of water harvest has enormous potential considering that only an estimated 15 to 25% of water in semi-arid regions is used for productive evapotranspiration, while the rest is lost as runoff or evaporation in absence of a crop (Ponce 1995). Stewart and Steiner (1990) calculated that sorghum requires about 100 mm/year of evapotranspiration to produce any grain at all, and that every additional millimetre leads to an extra production of 15 kg/ha of sorghum grain.

Zaï pits are dug into crusted soils to a depth of 10-20 cm. The pits are 20-40 cm in diameter, and they are generally spaced at regular distances in the field. About two handfuls of organic material (such as crop residues, manure or compost) are placed in each pit, to provide nutrients for the developing plants (Fatondji et al. 2005). Digging of zaï pits is estimated to take at least about 60 working days of five hours each per hectare (Ouedraogo and Kaboré, 1996; Kaboré and Reij, 2003). The pits can be dug during the dry season, when alternative demands on labor are less.

In response to intense land pressure and degradation coupled to recurrent droughts and harvest failures in the Yatenga region in Burkina Faso, NGOs and farmers started to experiment with soil and water conservation techniques (Kaboré and Reij, 2003). The farmers focused on the technique of

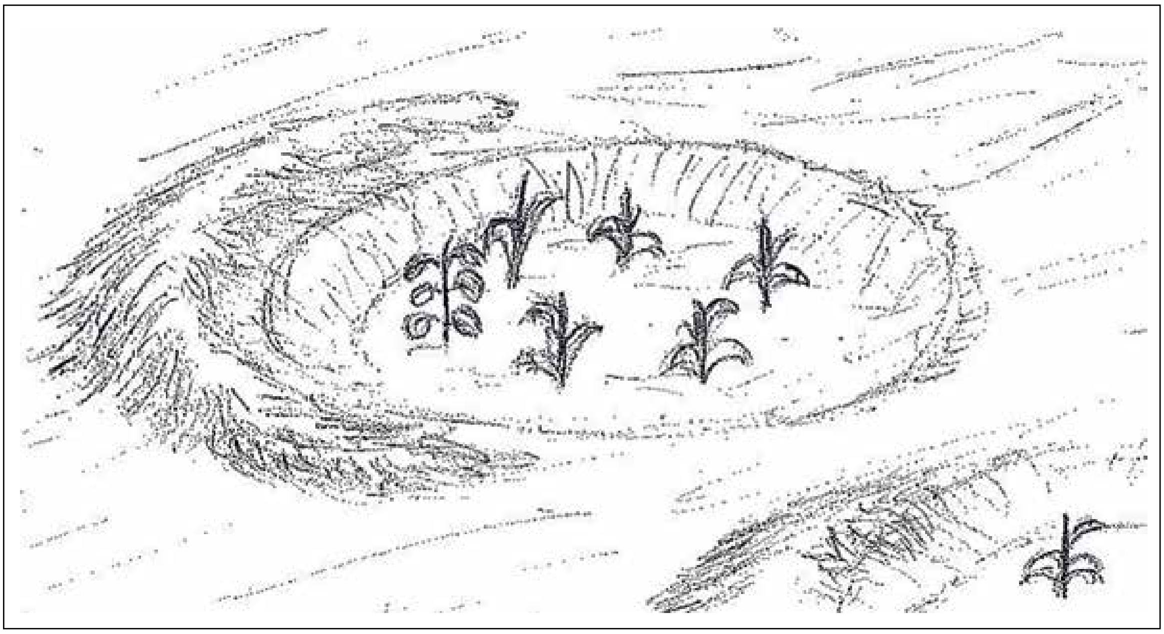


Figure 3. Schematic representation of a zaï planting pit.
Adapted from Critchley (1991).

improved planting pits (zaï) while the NGOs concentrated on contour stone bunds. The combination of both has proven to be powerful in reclaiming degraded lands, as stone bunds reduce the speed of water runoff and prevent destruction of the planting pits. Initially, zaï were used by farmers to rehabilitate barren lands with heavy crusts. Experimentation led to an increase of the zaï diameter (from 10-15 to 20-30 cm) and depth (about 20 cm), and to the addition of organic material to the pits. The organic material attracts termites, which make channels in the soil that enhance infiltration of rainfall, leading to significant increases in crop yields (Ouedraogo and Kaboré, 1996; Evans et al. 2011). The construction of zaï in Yatenga, in Burkina Faso, led to immediate increases in yield, and was spread by farmer-to-farmer learning throughout the region. NGOs facilitated further spread by arranging field visits for farmers from other regions, such as the Illela district in Niger (Hassan, 1996).

4.1.1 Experimental evidence

Fatondji and colleagues (2005) describe experiments in 1999 and 2000 in Niger with different zaï pit sizes and nutrient management techniques, which aimed to provide understanding of the interactions between water catchment and nutrient management and the effects on pearl millet grain yield and total biomass production. For this purpose, two sites with contrasting soils and rainfall regimes were selected. Damari (13°12’N, 2°14’E) has a long-term annual rainfall of 550 mm/year, compared with 450 mm/year in Kakassi (13°50’ N, 1°29’ E). Both sites presented clear signs of degradation, such as crust and hardpan formation and gullies, and they were almost bare of vegetation despite having been fallow for several years. Drought risks are larger in Kakassi than in Damari due to less rainfall and poor soil permeability, but soil fertility in Kakassi was better, with limited AI saturation and a clay content of 25% compared with 13% in Damari. Both sites experienced dry spells during the growing season, leading to reduced grain yields.

Table 4. Millet total dry matter production and grain yield responses to zaï planting without amendments.

	Total dry matter yield (kg/ha)				Grain yield (kg/ha)			
	Damari		Kakassi		Damari		Kakassi	
Treatment	1999	2000	1999	2000	1999	2000	1999	2000
Zaï, 25 cm ⌀	303a	213a	2125b	1938b	17a	19a	434b	388b
Zaï, 50 cm ⌀	280a	193a	2775b	1415ab	8a	19a	526b	260ab
Flat	96a	101a	752a	768a	1a	6a	118a	94a
$LSD_{0.05*}$	221	172	795	855	12	27	203	262

Adapted from Fatondji et al. 2005.
*LSD0.05 = least significant difference at probability 0.05.

The experiment combined three planting strategies (traditional flat planting and zaï pits with a diameter of 25 or 50 cm) and three types of amendments (crop residues, compost, and cattle manure). Local pearl millet varieties were planted at a density of 10,000 hills/ha. When amendments were applied, the rate was 300 g Fresh Weight/hill.

Planting in zaï pits resulted in significant increases in millet total biomass production and grain yields in Kakassi, even without organic amendments (Table 4). This was probably due to the inherent soil fertility and the capture of sand and plant materials in the pits (Fatondji et al. 2005). In Damari the pits without amendments gave the same poor yields as the control planting without pits, which was close to zero (Table 4). No significant yield difference was found between pit sizes of 25 and 50 cm in diameter.

The addition of 300 grams of dried millet straw or compost per planting pit (or hill, in case of flat planting; equivalent to 3 tons/ha) did not significantly increase grain yields in Damari or Kakassi. The amendments effects cancelled out the effect of the zaï planting pits on biomass production in Damari, where flat planting and zaï planting resulted in similar biomass production when amendments were added [500-900 kg Dry Matter (DM)/ha]. The same was observed for grain yields. In Kakassi, biomass production was found to be significantly larger in zaï pits without amendments or with compost amendment, but not with the millet straw amendment, which gave a relatively good yield also without a planting pit. Total biomass production increased from 800-1,400 kg DM/ha for flat planted plots to 2,300-2,500 kg DM/ha for zaï planted plots with or without straw or compost amendments.

The addition of 300 g of manure in each planting pit or hill significantly increased grain yields in Damari, with average yields of 700 kg grain/ha in flat planted plots and over 1,100 kg grain/ha in zaï planted plots. In Kakassi, manure addition did not have a significant effect on grain yield in flat planted plots, but it had a large effect in zaï planted plots. This implies that additional water made available through zaï planting increased the nutrient use efficiency. The water harvesting effects of the zaï pits appeared to have functioned mainly by retaining water which could be used by the plants during short dry spells (Fatondji et al. 2005).

An experiment with sorghum, similar to the one described above, was carried out in Burkina Faso (Roose et al. 1999). Rainfall varied between 466 and 703 mm/year in two study sites during the 1992-1993 study period, with rainfall in 1993 being about 100 mm less than in 1992 but better distributed. The study sites, Pouyango (12º49'N; 2º8'W) and Taonsongo (12º48'N; 2º15'W) on the Mossi plateau, have contrasting rainfall and soil fertility properties. Taonsongo has a deep, rich, brown soil, but around 150 mm/year less rainfall than Pouyango, which has a shallow, infertile soil. Planting pits were dug on two degraded sites and amended with 3 t/ha fresh leaves of neem (*Azadirachta indica* L.), 3 t/ha straw compost (dry dung, straw, and crop residues), 10-20-10 kg/ha NPK, or a mixture of the last two.

Zaï planting and the addition of amendments strongly increased both grain yield and biomass production (Fig. 4). Control yields in Pouyango (flat planting without amendments) were only 63 kg/ha on average in 1992. Planting in pits with amendments increased yields to 184 (leaves), 690 (compost), 829 (NPK) and 976 kg/ha (compost + NPK). In 1993, grain yields went from 22 kg/ha (control) to 83 (leaves), 257 (compost), 408 (NPK) and 550 kg/ha (compost + NPK). The large difference in yields between 1992 and 1993 was probably attributable to reduced water availability and to high weed pressure. In the more fertile soils in Taonsongo, control yields in 1992 were 150 kg/ha, and the use of pits with amendments increased these up to 395 (leaves), 654 (compost), 1,383 (NPK) and 1,704 kg/ha (compost + NPK). In 1993, rainfall was only 466 mm, and control yields were only 3 kg/ha. Pit planting improved yields when amendments were added, up to 24 kg/ha (leaves), 123 kg/ha (compost), 667 kg/ha (NPK) and 924 kg/ha (compost + NPK), but only the last two treatments were significantly different from the control. As no control treatments of flat planting with amendments were included, it is not possible to draw conclusions about the actual effect of the zaï on yield. Zaï planting without amendments led to slight yield increases in all cases, but none of these was significant.

The zaï planting led to spontaneous regeneration of natural vegetation within the planting pits (Roose et al. 1999). Twenty-two herbaceous species and 13 shrub and tree species were found after two years of zaï planting followed by five years of lying fallow, on land that was previously barren. Other studies have also shown the role of zaï in the regeneration of natural vegetation (Sawadogo et al. 2001; Reij et al. 2005). Seeds are transported to the holes by water runoff, wind, or in manure, and germinate in the favorable environment. Farmers selectively retain the seedlings when weeding, in order to stimulate the re-development of a cover of useful natural vegetation in their fields.

The most common tool for mechanized digging of zaï is described by Clavel and colleagues (2008). An 8 or 12 mm thick tapered iron blade (depending on soil structure) is horizontally attached to the bottom of a common tillage tool (Fig. 5). The blade is dragged through the soil by an ox or donkey, first in lines along the contour and then in perpendicular lines. At the intersection of two lines, a zaï is

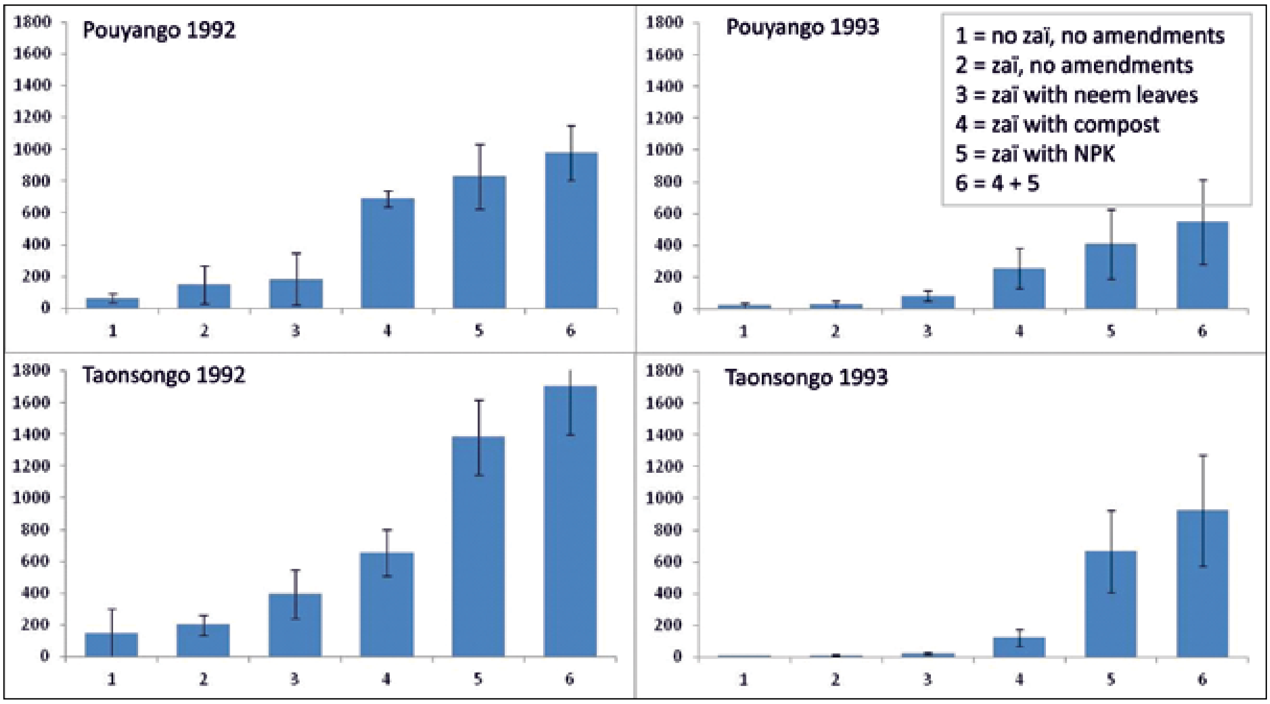


Figure 4. Effects of zaï planting and the application of different amendments on sorghum yields in two research sites in Burkina Faso, in the years 1992 and 1993.

Data from Roose et al., 1999. Error bars represent the standard deviation.

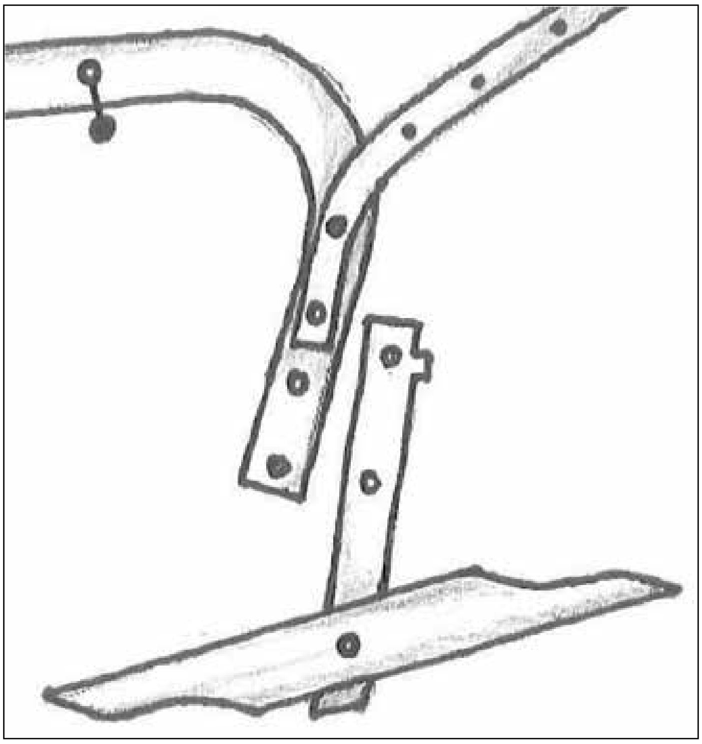


Figure 5. Schematic representation of a zaï mechanical digging tool.

Adapted from Clavel *et al.,* (2008).

created. Barro and colleagues (2005) describe a study in Burkina Faso, where the speed and depth of mechanized zaï digging as well as the yield response of a sorghum crop were tested in two research sites. The two sites, Saria (80 km west of Ouagadougou, 12°16'N; 2°9'W) and Pougyango (20 km east of Yako, 12°59'N; 2°9'W) have an average annual rainfall of 800 and 630 mm/year, respectively, with a single rainy season. The soils of the two sites are similar in depth, but the Saria soil was more gravelly whereas the soil in Pougyango was more clayey and had a heavier crust.

In experimental plots, six treatments were compared: flat planting at 2-3 cm depth, ploughing with animal traction and planting at 5-7 cm depth, manual zaï digging to a depth of 10-15 cm and with a diameter of 20-40 cm, mechanic zaï digging followed by manual removal of soil from the pits, and mechanical zaï digging without removal of soil from the pits. Five tons per hectare of manure was added, two weeks before sowing in the zaï plots and at planting in the other treatments. The study was carried out in two consecutive years (2000 and 2001) and the treatments were applied in the same plots in both years.

The mechanical zaï construction resulted in more shallow pits in Saria (around 7 cm depth) compared with manual digging (11.5 cm), whereas in Pougyango the mechanically dug pits were actually deeper (11.6 cm) than the manually dug pits (10.5 cm). The difference can be explained by the soil structure. In Pougyango the clay content of the soil was larger, so that it broke up in bigger clumps in response to mechanical digging. In Saria, the manual digging of zaï took around 470 hours/ha. Mechanized digging took 28 to 41 hours, both with and without manual removal of the soil from the pits, which is a more than tenfold labor reduction. In Pougyango, where the soil resistance was less, manual digging took 390 hours/ha on average, whereas mechanized digging took between 18 and 25 hours, a reduction of up to 20 times. The amount of draught power required for mechanical zaï digging with the tool described by Clavel and colleagues (2008) depends on soil conditions such as structure and moisture. It was found to be around 121 Newton in Saria and 103 Newton in Pougyango, which is well within the power range of a donkey or oxen.

Grain production in Saria showed no significant difference between treatments in the year 2000 (1.2-1.7 t/ha). In 2001 the manually dug zaï (1.6 t/ha), the mechanically dug zaï from which soil was manually removed (1.5 t/ha), and the ploughed fields (1.5 t/ha) yielded significantly more than the flat planted control plots (0.7 t/ha) and the mechanically dug zaï with the soil not removed (0.8 t/ha). In Pougyango, a different trend was observed, with a significant yield increase in the zaï-planted fields in both years. The largest yields were obtained in the mechanically dug zaï with the soil manually removed (0.6 and 1.4 t/ha in 2000 and 2001), followed by the mechanically dug zaï without soil removal (0.4 and 1.4 t/ha), and the manually dug zaï (0.4 and 1.4 t/ha). The ploughed (0.2 and 0.4 t/ha) and the untreated fields (0.2 t/ha in both years) yielded significantly less (Barro et al. 2005).

The economic valuation described by Barro and colleagues was based on the Value-Cost Ratio (VCR), which was calculated by dividing the added value of the activity (yield increase) over the costs of the activity (such as labor costs). Barro and colleagues found a VCR of 2.31 for the manual digging (due to high labor costs), 8.16 for the mechanical digging with manual soil removal, and 15.03 for the mechanical digging without soil removal. How the costs and revenues were estimated is unclear, but the good grain production in the mechanically dug zaï shows that there is potential for mechanization, which can greatly reduce the labor requirements and thus resolve a major bottleneck for widespread zaï implementation.

Sidibé and colleagues (1994, summarized in Kaboré and Reij, 2003) conducted a monetary valuation of zaï pit production on the Central Plateau of Burkina Faso. They quantified the labor and input (tools) costs and the returns for a system where compost was used to provide organic material to the zaï pits. A hectare of intercropped sorghum and cowpea, planted in zaï pits amended with compost, required 959 labor hours per ha, including the digging and filling of a compost pit and the application of the compost, and the sowing, weeding and harvesting activities. The return on labor was found to be around US$ 1.15 per day, assuming a working period of six hours per day, adding up to approximately US$ 180 per hectare per season. In some degraded areas in Niger, the introduction of zaï pits to reclaim degraded lands has resulted in increased land trading, and prices doubled in the years after the technology was introduced (Hassan, 1996). This shows that farmers are truly confident about the potential of zaï to rehabilitate unproductive lands.

Reclamation of degraded areas is a first step in the intensification of land use, as most of the areas reclaimed were previously under cultivation but were abandoned because of severe degradation.

4.1.2 Adoptability of zaï planting

The success of zaï in Burkina Faso and Niger is based on several important pillars. First, the zaï are used to reclaim strongly degraded lands with virtually no current production. Thus they give a clear return on investment, as crops can be planted in areas that were previously unproductive. Yields are produced from the first year onwards, so the benefits are short-term as well as long-term. Additional effects of planting in zaï are increased nutrient use efficiency and better water and dust capture. The plants in zaï pits are clearly less affected by dry spells, and in years of poor rainfall zaï-planted fields give a yield where flat-planted fields do not (Ouedraogo and Kaboré, 1996). Zaï pits also enhance regeneration of natural vegetation.

Implementing zaï demands a large labor investment. However, the pits can be dug during the dry season, when there are less alternative demands on labor. Preparation of the pits saves ploughing time when the rains arrive, so that farmers can start sowing immediately. Nevertheless, labor investments are considerable and returns on labor are quite poor.

Another important constraint for the implementation of zaï is the need for at least 3 t/ha of manure or good quality compost. Chemical fertilizers are an alternative, but are a more costly option. There are several other biophysical constraints that must be considered. Zaï are said to function best in areas with at least 400 and at most 800 mm rainfall per year, depending on the soil type and structure (Roose et al. 1999; Bayala et al. 2012). Too much water will lead to waterlogging in the pits and to nutrient leaching (Roose et al. 1999; Fatondji et al. 2009). Zaï digging is most profitable in areas that are strongly degraded. In very sandy soils with an unstable structure, the pits may collapse with the first rains (Lahmar et al. 2012). Addition of stone bunds on gently sloping fields prevents the destruction of the zaï by fast-flowing water and helps to retain the water in the field.

Four qualitative cost levels have been estimated, based on an assessment of data found in literature: low (green), low/medium (yellow), medium (orange) and high/medium or high (red). The 'alternatives' column shows the potential to reduce or replace the enabling costs. The 'outcomes' or benefits are assumed to be positive and have been formulated as such; if negative outcomes or trade-offs are expected, they are mentioned in the 'comments' column. Benefits can be low (red), low/medium (orange), medium (yellow), or high (green).

Table 5. Enabling costs and outcomes of the zaï technology.

Category	Indicator	Level	Comments	Alternatives
Enabling conditions/ costs				
Land, natural resources, climate	Land area	Low	Unproductive/ degraded areas can be reclaimed	
	Rainfall, AI, length of rainy season	Low/ medium	400-800 mm	
	Availability of water resources	Low	Irrigation not required	
	Soil fertility/ quality	Low	Most functional in hard crusted barren soil Amendments (compost, manure, residues, fertilizer) are required	
	Grazing land extent/ quality	Low	Most profitable on highly degraded land	
Inputs	Internal/re-allocated inputs	High/ medium	3 t/ha of manure or good quality compost	Many (low-quality residues amended with fertilizer, leaf litter, fertilizer only)
	External/ purchased inputs	Low/ Medium	Depending on the availability of manure or good quality compost	Few (N may be replaced by legumes but P remains necessary)
	Labor	High	300-450 man-hours per hectare for digging, up to 960 hours for a complete season including composting	Few (mechanization is possible but requires tools and oxen)
	Information, skills	Low/ Medium	Can be efficiently transferred from farmer to farmer	

Continued

Table 5. *Continued*

Category	Indicator	Level	Comments	Alternatives
Economic	Credit availability	Low		
	Markets	Low		
	Price level and stability	Low		
	Demand	Low/ Medium	Some demand is required, otherwise the labor investment will not pay off	
Institutional	Policy	Low		
	Land tenure	Medium	The investment pays back relatively fast, but secure land tenure will enhance willingness to invest	
Social/cultural	Culture/tradition	Low		
Outcomes/ benefits				
Direct outcomes	Risk reduction	High		
	Nutrition	N/A	Bulk crops	
	Short term financial results	Low/Medium	From zero to around 180 $/ha/yr, when practiced on fully degraded areas	
	Long term financial results	Low/Medium	If well managed, productivity is maintained or increased, and higher-value crops may potentially be grown	
Indirect outcomes	Ecosystem service provision	High	Rehabilitation of degraded land, regeneration of natural vegetation, prevention of erosion	

4.2 Microdosing

Microdosing, also known as micro-fertilization, is the spot application of small amounts of chemical fertilizers in the planting hole. Alternatively, fertilizer may be applied by broadcasting (where fertilizer is spread evenly over the field), banding or side dressing (where fertilizer is placed along the row) or top dressing (Diwakar, http://vasat.icrisat.org).

In hard, crusted soils, farmers typically dig a hole to sow the seeds. They line the hole with manure, if available, and apply fertilizer directly into the hole together with the seed, when the first rains have passed. The loose soil in the hole, in combination with manure and fertilizer, provides a moist and nutrient-rich environment for optimal root development. Fertilizer quantities applied through microdosing are much less than recommended fertilization rates. Experimental rates range from 0.3 to 6 grams per hill, planting pocket, plant or bunch of plants, which is equivalent to between 2 and 150 kg/ha, depending on the mode of application and the planting density (Aune et al. 2007).

Microdosing was developed by ICRISAT in West Africa (Tabo et al. 2006) and tested in a number of large-scale on-farm trials in Mali (Tabo et al. 2006, 2007, 2008, 2011; Aune et al. 2007), Burkina

Faso and Niger (Buerkert et al. 2001; Tabo et al. 2006, 2007, 2008, 2011), Togo (Buerkert et al. 2001), Sudan (Aune and Ousman, 2011) and Zimbabwe (Twomlow et al. 2008). Unfortunately, no long-term studies on the soil fertility effects of microdosing have been carried out to date, and it has been argued that the application of very small fertilizer quantities will lead to fast depletion of soil nutrients in the deeper soil layers and, hence, to soil degradation (Breman and Giller, in preparation). There is an urgent need to set up randomized long-term trials and assess the soil fertility dynamics over time, in order to decide whether microdosing has a potential as an option for intensification and if so, under what conditions.

Below, we discuss the evidence that is currently available, with the note that these are generally short-duration (max 4 years) on-farm trials, so results should be interpreted with caution.

4.2.1 Experimental evidence

Several microdosing strategies were tested in a large-scale study in Mali, Burkina Faso and Niger. These were A) 4-6 g/hill of NPK (15-15-15) (=40-60 kg/ha), B) 2 g/hill of diammonium phosphate (DAP) (= 20 kg/ha) and C) 2 g/hill of DAP at sowing plus 1 g/hill urea topdressing at thinning (= 20 kg/ha DAP + 10 kg/ha urea). These treatments were compared with zero fertilizer and with 100 kg/ha NPK broadcast in farmers' fields. The total sample contained around 2,000 experimental fields in 2002-2004 (Tabo et al. 2006, 2007, 2008, 2011). Field technicians supported the farmers during planting, fertilizer application, weeding and harvesting. The farmers followed a sowing system where one farmer dug a planting hole while the other applied the seed and fertilizer and closed the hole. Microdosing treatment B and C were tested only in Niger, while treatment A was used in Burkina Faso and Mali.

In Burkina Faso, average millet grain yields from the microdosed plots were 680 and 823 kg grain/ha in 2002 and 2003 respectively, similar to yields from broadcast plots (667 and 801 kg/ha) but 44 to 75% larger than yields from the zero fertilizer plots (473 and 471 kg/ha) (Table 6). Sorghum grain yields were comparable, with 789 and 857 kg/ha on the microdosed plots (an increase of 47 to 82% compared with the zero fertilizer treatment), 772 and 802 kg/ha on the broadcast plots and 534 and 472 kg/ha on the zero fertilizer plots. Net gains from millet and sorghum production with microdosing treatments were three times and two-and-a-half times larger, respectively, than with fertilizer broadcasting treatments.

Table 6. Millet and sorghum grain yield responses to fertilizer microdosing.

	Millet grain yield (kg/ha)				Sorghum grain yield (kg/ha)			
	Burkina Faso		Mali		Burkina Faso		Mali	
Treatment	2002	2003	2002	2003	2002	2003	2002	2003
Zero fertilizer	473	471	469	768	534	472	508	858
40-60 kg/ha NPK (15-15-15)	680	823	756	1463	789	857	1053	1447
100 kg/ha NPK	667	801	635	1193	772	802	821	1302

Adapted from Tabo et al. 2006, 2008, 2011.

In Mali, the effects of microdosing were more pronounced than in Burkina Faso. Millet and sorghum yields from microdosed plots were significantly larger than yields from both zero fertilizer and broadcast fertilizer plots in 2002 and 2003 (millet with microdosing: 756 and 1,463 kg/ha, broadcast fertilizer: 635 and 1,193 kg/ha, zero fertilizer: 469 and 768 kg/ha, respectively; and sorghum with microdosing: 1,053 and 1,447 kg/ha, broadcast fertilizer: 821 and 1,302 kg/ha and zero fertilizer: 508 and 858 kg/ha, respectively). Net profits of millet grain production were US$ 200/ha for the microdosing treatment, US$ 150/ha for the fertilizer broadcasting treatment, and US$ 119/ha for the zero fertilizer treatment. Labor costs were not taken into account in this calculation.

In Niger, microdosing increased millet yields with about 300 kg/ha (44%), on average. Net returns were US$ 124/ha for the DAP + urea microdosing treatment, US$ 109/ha for the DAP-only microdosing treatment, US$ 104/ha for the NPK broadcasting treatment and US$ 86/ha for the zero fertilizer treatment.

In the four papers that report the experiments described above (Tabo et al. 2006, 2007, 2008, 2011) it remains unclear whether planting density in the control plots (farmers' practice) was actually less (5,000-6,000 hills/ha) than in the microdosed plots (10,000-20,000 hills/ha). If so, then planting density alone could explain the yield differences between the control and the microdosed plots. The number of hills per hectare in plots fertilized with recommended fertilizer rates was not given. Additionally, no information is available on the statistical significance of the results, as the statistical methods are not explained and only standard errors of mean are provided. In the 2006 paper, an overview graph of millet grain yields in different agroecological zones of the Sahel under different fertilizer treatments, including microdosing, suggests that none of the results is significant. For sorghum, the significance of the results is unclear.

A very small fertilizer application of between 3 and 7.5 kg/ha of NPK (15-15-15) was tested in Mali (Aune et al. 2007). The method, which involved the application of approximately 0.3 g of fertilizer per seed pocket, equivalent to between 3 and 7.5 kg/ha, depending on planting density, was compared with a second microdosing technique with doses of 6 g per pocket, equivalent to 60-150 kg/ha depending on planting density. The experiments were run for three years in two different sites in Mali.

In Bafaloubé in 2000 and 2001, the 6 g fertilizer/pocket treatment gave the largest sorghum grain yields (938-1,531 kg/ha) (Table 7). The 0.3 g fertilizer/pocket treatment significantly increased yield in both years, up to 819-1,112 kg/ha compared with 538-832 kg/ha in the zero-fertilizer control (Table 7). Though the total yield was less for the 0.3 g/pocket treatment, the output per unit input (37 kg grain per kg fertilizer in both years) was around 10 times larger than for the 6 g/pocket treatment (4.7 and 2.6 kg grain per kg fertilizer in 2000 and 2001 respectively). Pearl millet yields were generally less than sorghum yields: 210-225 kg/ha for the controls, 311-371 kg/ha for the 0.3 g/pocket treatment and 469-556 kg/ha for the 6 g/pocket treatment (Table 7). Yield increase in kg grain per kg fertilizer was between 13.4 and 47.6 for the 0.3 g/pocket treatment and between 1.7 and 5.4 for the 6 g/pocket treatment. With regards to the significance of the results, the authors state that there is "a significant effect of fertilizer application on sorghum yield in all three years", which suggests that both the 0.3 and the 6 g/pocket treatments give a significant yield effect. Table 7 in the paper also suggests this.

Table 7. Millet and sorghum grain yield responses to two fertilizer microdosing strategies.

	MILLET		SORGHUM	
	Macina	Koro	Bafaloubé	
Treatment	2001	2003	2000	2001
Rainfall (mm)	652	474	662	579
Control without fertilizer	210	228	832	538
0.3 g fertilizer	311	371	1112	819
6 g fertilizer	469	556	1531	938

Adapted from Aune et al. 2007.

It was observed that DAP, which was used for one year on one site instead of NPK, burned the plants when there was drought after sowing, both with the 6 g/pocket and the 0.3 g/pocket treatment. A slight burning effect was also observed with NPK.

Average labor demands were five man-hours per hectare for the 0.3 g/pocket treatment (where seeds and fertilizer were mixed 1:1 before sowing) and 14.6 man-hours per hectare for the 6 g/pocket treatment. The VCR of the 6 g/pocket treatment was below 2 for all sites and years, indicating a poor economic feasibility. The 0.3 g/pocket treatment gave a VCR of more than 4 in three out of four cases, indicating a very good economic feasibility, even in drought-prone environments with large climatic risks. Generally, the VCR should be above 2 and preferably above 4 for a technology to be attractive to farmers working in risk-prone environments such as dryland areas (Koning et al. 1997).

The testing of the microdosing technology in Zimbabwe, carried out by ICRISAT in collaboration with local extension staff and a number of NGOs, involved the handing out of 25 kg of Ammonium Nitrate (AN) fertilizer, along with a simple leaflet on microdosing techniques, to 160,000 resource-constrained households per year. Demonstration plots were established for training and for detailed recording of inputs and results (Twomlow et al. 2008). A total of about 2,000 paired plot trials were established and from over 1,200 of these, good quality data was collected during a three-year period, starting in the 2003/04 growing season (Table 8). The region of Zimbabwe where the research was conducted is characterized by an average yearly rainfall of 450-750 mm, which falls during a single rainy season between October/November and March/April. The length of the growing season varied between 107 and 140 days during the research period. Soils in the research area are generally very sandy. Microdosing under farmer management was carried out by applying one beer bottle cap of AN fertilizer on every hill at the 5-to-6-leaf stage, which is equivalent to 50 kg/ha fertilizer or 17 kg N/ha. The APSIM model was used to test the potential of the microdosing technique *in silico* (Twomlow et al. 2008).

With the application of 17 kg N/ha through microdosing, maize grain yields went from between 880 and 1,546 kg/ha without fertilization to between 1,060 and 2,084 kg/ha with fertilization. This yield increase of 30-50% was observed over a wide range of soil, management and climatic conditions (Table 8). At the time of research, farmers could make a profit by producing at least between 4 and 7 kg of grain per kg N, but generally returns were much larger, ranging between 15 and 45 kg grain per kg N.

Maize grain production in response to nitrogen application was found to be quite stable up to fertilizer rates of approximately 30 kg N/ha. After this point responses started to level out (Twomlow et al. 2008). Grain yields at 0 kg/ha N were on average 0.9 t/ha. The observed grain yield response to fertilizer was approximately 11 kg per kg fertilizer up to the 30 kg N/ha point. At a price of approximately US$ 2 per kg fertilizer and US$ 0.40 per kg grain at the time of the research, the value cost ratio (VCR) for microdosing was over 2, which can be a good incentive for farmers to invest (Koning et al. 1997, Twomlow, 2008). Hybrid maize responses to nitrogen fertilizer were stronger than responses of open-pollinated varieties (OPVs) or farmer seed maize (Twomlow 2008, Table 8). The strong response to nitrogen was not found in the sorghum and millet experimental plots. Phosphorus deficiency may have been the cause of the weak response, leading to poor root development and reduced nutrient uptake (Twomlow, 2008).

Table 8. Maize yield response to fertilizer microdosing in ton grain/ha/yr.

Season	Rainfall (mm)	Maize variety and top dressing regime						e s.e.*
		Farmers' retained seed		OPV ZM421		Hybrid SC403		
		Zero N	17 kg N/ha	Zero N	17 kg N/ha	Zero N	17 kg N/ha	
2003/04	443	0.9	1.1	0.9	1.4	1.1	1.6	0.18
2004/05	548	0.9	1.2	1.4	1.7	1.4	2.0	0.09
2005/06	806	1.1	1.3	1.5	1.7	1.5	2.1	0.12

The last column shows the experimental standard error. Adapted from Twomlow et al. 2008.
*experimental standard error

Generally, maize grain yield increases were consistent, although management strategies (such as timing of fertilizer application and weeding) varied widely. Nevertheless, over 90% of the farmers achieved a significant yield increase with 17 kg/ha AN fertilizer on different soil types and in different rainfall conditions (Twomlow et al. 2008).

In the Zimbabwean trials, fertilizer was handed out to the farmers as part of an emergency relief program. The next challenge would be to motivate farmers to purchase the small quantities of fertilizer themselves and to sustainably adapt their management system to include small quantities of fertilizer.

The individual and interacting effects of phosphorus and nitrogen microdosing on legume and cereal yields were analyzed in a large-scale experiment in eight sites located in Niger, Burkina Faso and Togo. The experiment lasted for four years, in which the rainfall ranged from 510 to 1,300 mm/year over the different sites and years (Buerkert et al. 2001). Cereal yields increased significantly in response to P microdosing in the drier research sites, and in response to N microdosing in the wetter areas. A strong P x N interaction was observed (Buerkert et al. 2001). The results show that the choice of fertilizer for microdosing deserves further attention. Whereas Tabo and colleagues (2006, 2008, 2011) and Aune and colleagues (2007) used mainly NPK fertilizers, the trials set up by ICRISAT in Zimbabwe used AN fertilizer, which led to phosphorus limited yield increases in some sites (Twomlow, 2008). More extensive trials are required to understand the effects of different nutrients applied through microdosing on grain yields, so that recommendations can be developed for 'best fit' approaches in terms of fertilizer type and quantities. In addition, the effects of the different types and quantities of fertilizers on nutrient concentrations in the different soil layers must be carefully analyzed, to increase understanding of the observed responses to microdosing and to assess the soil fertility effects in the medium and long term.

4.2.2 Adoptability of microdosing

There are concerns about the sustainability of applying very small amounts of fertilizer per hectare (Aune et al. 2007; Tabo et al. 2008) and long-term testing will be required to assess the effects on soil fertility in the long run. A small dose of fertilizer at planting will help the development of a strong root system and will make nutrients available in the lower soil layers which otherwise may not be reached. However, after a few years these lower layers will become depleted and for the larger yields to be sustained, additional nutrient applications will be necessary (Aune et al. 2007). Even for the short term, withdrawing nutrients from the lower layers of soils that are already poor may be ill-advised (Breman and Giller, in preparation).

The availability of cash inputs for fertilizer purchase and labor for fertilizer application are key constraints to microdosing. In the field, farmers have developed practical techniques for the measuring and application of the fertilizer to reduce labor needs. In southern Africa, bottle caps have been used as a measuring tool, whereas in West Africa three-finger pinches are taken as the appropriate quantity (Aune et al. 2007; ICRISAT, 2009).

Short-term returns are large in terms of risk reduction, because microdosing will enhance yield even in drought years, and initial investments are relatively small. In the longer term, the efficacy is likely to decrease as the soil nutrients are depleted. Short-term economic returns are quite limited despite typical yield increases of 35-80%, with net gain increases of between US$ 40 and 80 per ha. Considering that farms are often only a few hectares in size, total monetary returns are modest. Long-term yields and financial benefits are estimated to be small because the microdosing technology may add lesser nutrients to the soil than are removed. Depletion of soil organic matter is an additional concern. Aune and colleagues (2007) argue that microdosing with very small fertilizer quantities is simply a first step towards long-term sustainable intensification of smallholder farming systems. Microdosing should be replaced by larger nutrient applications as soon as possible, or it may be combined with alternative soil fertility management activities such as mulching of crop residues, application of manure or fertilizer, or cultivation of legumes. Optimal nutrient application strategies will allow for maximum utilization of the other available resources according to Liebscher's Law of The Optimum (de Wit, 1992), and from this perspective, larger nutrient quantities are preferable and microdosing serves as a starting point rather than as a best management option in the long term. Microdosing with specific nutrients (especially P) in combination with other soil fertility improvement strategies, such as diversification through rotations or intercrops with legumes, might have potential for improving productivity in the short term, if it contributes to meeting the crop nutrient demands.

Four qualitative cost levels have been estimated, based on an assessment of data found in literature: low (green), low/medium (yellow), medium (orange) and high/medium or high (red). The 'alternatives' column shows the potential to reduce or replace the enabling costs. The 'outcomes' or benefits are assumed to be positive and have been formulated as such; if negative outcomes or trade-offs are expected, they are mentioned in the 'comments' column. Benefits can be low (red), low/ medium (orange), medium (yellow), or high (green).

Table 9. Enabling costs and outcomes of the fertilizer microdosing technology.

Category	Indicator	Level	Comments	Alternatives
Enabling conditions/ costs				
Land, natural resources, climate	Land area	Low	In fields that are already under cultivation	
	Rainfall, AI, length of rainy season	Low	Increased yields also under drought conditions	
	Availability of water sources	N/A		
	Soil fertility/quality	Low	A basic level of soil fertility is required for fertilizers to take effect	
	Rangeland extent/ quality	N/A		

Continued

Table 9. *Continued*

Category	Indicator	Level	Comments	Alternatives
Inputs	Internal/ re-allocated inputs	None		
	External/purchased inputs	Low/ Medium	Purchase of chemical fertilizer. Quantities are generally between 2 and 60 kg/ha, costs depend on quantities and fertilizer prices	Several (cooperative purchase, supply chain linking)
	Labor	Low/ Medium	Typically between 5 and 15 man-hours per hectare, depending on placement technique. Mixing seed and fertilizer before placement has similar labor requirements as seeding only	Few (mechanization, leads to labor reduction but increased capital costs)
	Information, skills	Low	Simple techniques such as the use of bottle caps for measuring fertilizer quantities are available	
Economic	Credit availability	Low/ Medium	Fertilizer amounts are small so that credit may not be required	
	Markets	Medium	Markets must be available for fertilizer purchase. Introduction of a warrantage system is beneficial	Several (warrantage, cooperatives, supply chain linking)
	Price level and stability	Low	High VCR, impact of fertilizer or grain price fluctuations are limited	
	Demand	Low		
Institutional	Policy	Low		
	Land tenure	Low		
Social/cultural	Culture/tradition	Low		
Outcomes/ benefits				
Direct outcomes	Risk reduction	Medium	Yield increase even in low rainfall years	
	Improved nutrition	N/A	Bulk crops	
	Short term financial results	Low/ Medium	Yield increases typically 30-80%, VCR is generally >2, often >4. Net gain increases between 38 US$ and 81 US$ per hectare	Few (combine with other yield-improving technologies)
	Long term financial results	Low	Continued very low fertilizer application rate will lead to nutrient mining and soil depletion. Addition of extra nutrients is necessary for sustaining high yield levels	Few (additional soil fertility management activities required)
Indirect outcomes	Ecosystem service provision	Low	Nutrient mining in the longer term	Few (additional soil fertility management activities required)

4.3 Intercropping or rotation with legumes

Yearly losses of nitrogen from agricultural soils are estimated to be between 20 and 70 kg per hectare in Africa (Stoorvogel et al. 1993) and between 36 and 80 kg/ha in West African savannah systems (Bationo et al. 2011). The main causes are wind and water erosion, removal in crops, leaching, and gaseous losses. West African systems traditionally include long fallow periods where fields are left bare and natural vegetation is allowed to regenerate. Increased land pressure leads to reduction in fallow periods to only one or a few years and sometimes no fallow at all, so that alternative measures are needed to replenish the nitrogen pool. Cultivation of legumes in intercropping or rotation and retention of part of the residues in the field can be a method to increase the soil nitrogen pool. West African farmers traditionally intercrop cowpea with sorghum and millet, but at very low densities. The effects of cowpea rotation or intercropping on agricultural systems in the West African savannah were reviewed by Carsky and colleagues (2002). Test crop yields in 11 case studies under little or no nitrogen application showed consistent cereal yield increases in response to cowpea cultivation, varying between 300 and 1,400 additional kilograms of grain per hectare. Measured quantities of N fixed in cowpea above-ground vegetative biomass were highly variable, ranging from -2 to +125 kg N/ha, with averages around 20 kg N/ha, which may be added to the soil pool if the stover is retained in the field (Carsky et al. 2002). Increased densities of cowpea or other legumes in cultivation systems can enhance the beneficial effects and increase the productivity of the system. In the West African situation, legumes have two main advantages over mineral nitrogen fertilizers, which are lower costs (or none at all if farmers' seed is used) and the avoidance of farmers being market dependent (Breman and van Reuler, 2001). The most commonly cultivated legumes in West Africa are groundnut (*Arachis hypogaea*), cowpea (*Vigna unguiculata*), soyabean (*Glycine max*), pigeonpea (*Cajanus cajan*) and Bambara groundnut (*Vigna subterranea*) (Bationo et al. 2011). While cowpea, pigeonpea and Bambara groundnut are well adapted to dry environments, soyabean is not recommended when yearly rainfall is below 700 mm (Dugje et al. 2009). In severely degraded fields, planting of a *Mucuna pruriens* monocrop may help to reduce weed pressure and improve soil fertility, with gains of up to 66 kg N/ha measured by Houngnandan and colleagues (2001) in Benin. However, *mucuna* does not produce marketable grains, and the benefit of improved soil fertility often does not compensate the loss of grain production for a year.

Limited availability of manure and high fertilizer costs, and their preferential use, lead to a gradient of declining soil fertility with increasing distance. Fields close to the homestead receive significantly more inputs than outfields (Prudencio, 1993; Tittonell et al. 2005, 2007). Rotation or intercropping with legumes in outfields can reduce labor requirements due to the weed and pest reducing properties of some intercrops or rotation crops (Houngnandan et al. 2001; Samaké et al. 2006). Part of the positive effects of legume rotation may be attributable to other factors than N-fixation, as cereal-cereal rotations were found to have a strong yield-increasing effect as well, though less so than cereal-cowpea rotation (Carsky et al. 2002). These observations confirm the importance of pest and weed reducing properties of crop rotations. Bagayoko and colleagues (2000) showed that an additional benefit may be the enhanced presence of arbuscular mycorrhiza in millet-cowpea or sorghum-groundnut rotations. Anten (2012, unpublished data) estimated that mixed systems are generally 20-60% more productive because of niche exploitation, risk reduction and/or damage resistance (suppression of pathogens and weeds, reduction in wind velocity), and facilitation (for example maize stalks functioning as a stake for climbing beans). The layout of the intercropping system has an influence on the productivity, and for cowpea it was shown that a two-row cereal to four-row cowpea layout is more productive than the standard one-to-one layout (Tarawali et al. 2002; Mohammed et al. 2008; Ajeigbe et al. 2010).

In a review of the current and potential role of legumes in soil fertility management in West and Central Africa, Bationo and colleagues (2011) state that crop rotation is far more sustainable than intercropping, despite mentioning earlier the positive effects of legume intercrops on weed suppression. In regions with a short, single rainy season, rotation with a legume means that no cereals can be grown for a year on the plot under rotation. Carsky and colleagues (2002) argue that rotation has larger yield effects than intercropping, based on three case studies, but from the presented table it is unclear whether the loss of cereal yields in years under legume are included in the analysis. Intercropping may lead to optimized nutrient use efficiency (Giller and Cadisch 1995) and does not involve the loss of a cereal crop for a year. It has been demonstrated that it is possible to obtain a full cereal grain yield in fields where cowpea and millet are grown together without the addition of extra fertilizer (Samaké et al. 2006).

A rotation with legumes where all biomass is removed from the field before the next planting may appear beneficial to the following non-leguminous crop, but this benefit generally stems from a 'nitrogen sparing' effect. Nitrogen sparing occurs as a legume crop uses less of the soil nitrogen pool than other crops, because part of the N is fixed rather than taken up. However, the nitrogen balance is still negative, although less so than for other crops, and the beneficial effects will not be sustained on the long run. This emphasizes the importance of leaving crop residues in the field, if the purpose is to increase soil nitrogen and organic matter content (Giller and Cadisch, 1995, Peoples et al. 1995). Soil N and P contents in West Africa are particularly small, with a yearly natural availability of 15-20 kg N/ha (Breman and Van Reuler, 2001). Whereas the limited soil N availability can enhance legume growth, the lack of phosphorus can be a serious constraint. Phosphorus or molybdenum deficiencies decrease legume growth and limit nitrogen fixation (Breman and van Reuler, 2001). Small amounts of soil N will increase the comparative advantage of nodulation, but the presence of some 'starter N' in the soil has a positive effect on plant development (Giller and Cadisch, 1995; Breman and van Reuler, 2001). This positive effect is due to the enhanced plant growth and establishment in the period before the start of nitrogen fixation. Intercropping of cereals with legumes leads to a better use of the available nitrogen, as cereals generally establish and grow faster, rapidly depleting the N source so that nodulation is not inhibited. Application of fertilizer for nutrient provision, especially phosphorus and, to a lesser extent, potassium, can greatly enhance plant growth and will therefore have a positive effect on total nitrogen fixation. Lack of soil phosphorus greatly reduces legume growth and thus limits the N fixation capacity. One kg of fertilizer P adds approximately 4 kg of legume N, equivalent to approximately 40 kg of legume grain (Koné et al. 1998, cited in Breman and Van Reuler, 2001). These rough numbers may help to assess the net returns of P fertilization on legumes. As legumes add protons to the soil, they may enhance the solubility and the availability of P which gives an additional beneficial effect (Carsky et al. 2002; Bado et al. 2006a). Breman and Van Reuler propose a phosphorus application of 25 kg P/ha on legume crops for optimal growth and returns. Microdosing of P may be an interesting alternative to reduce costs without decreasing yields and N fixation. However, in West Africa the availability of fertilizers in general and specifically of those that do not include large quantities of nitrogen can be a major constraint.

Apart from sufficient phosphorus, legumes require the presence of the right strains of rhizobia, sufficient molybdenum, and a manageable degree of pest and disease prevalence for optimum growth (Breman and Van Reuler, 2001).

4.3.1 Experimental evidence

In a quantitative review on the effects of conservation agriculture practices on cereal yields by Bayala and colleagues (2012), it is concluded that "when water is the limiting factor [<800 mm], (coppicing and) rotation-association practices should be avoided as they will exacerbate the competition [for water]" (Bayala et al. 2012: p. 20). This is a surprising conclusion as soil fertility constraints are known often to have a more limiting effect on productivity in African farming systems than water availability (Breman and De Wit, 1983; van Keulen and Breman, 1990). Other studies of legume rotation or intercropping under water-limiting conditions (eg. Blade et al. 1997; Samaké et al. 2006) did not show any clear water competition effects. Four of the six rotation-association studies that were reviewed by Bayala and colleagues were further scrutinized (the other two were unavailable online). All four studies assessed the effects of rotation, but not of association, on cereal yields (Bagayoko et al. 2000; Kouyaté et al. 2000; Bado et al. 2006a-b). Of these four studies, two were in areas with poor rainfall and two were in areas with better rains, and all showed a positive effect of rotation on sorghum and millet yields. The conclusions of Bayala and colleagues (2012) seem to be supported by limited experimental data, and it is likely that water competition does not cancel out the positive effects of intercropping or rotation with herbaceous legumes on cereal yields.

Impacts of intercropping or rotation with cowpea on millet yields and striga infestation were analyzed in a village in the Sahelian zone of Mali (Samaké et al. 2006). During the 4-year research period, well-adapted local cultivars of pearl millet (cv. Toroniou) and cowpea (cv. IT89DK-245) were cultivated on outfields that had been left fallow for zero (F0), two (F2), five (F5) or seven (F7) years. Cultivation was done either as a millet monocrop for four years, as a millet monocrop for three years after one year of cowpea monocrop, or as a three year millet/cowpea intercrop after a year of cowpea monocrop. No additional inputs were added to any of the fields. Seasonal rainfall during the research period was less than the 10-year average of 570 mm/year, with 581, 522, 438 and 460 mm/year in 1998, 1999, 2000 and 2001, respectively. The rainfall in the year 2000 was especially poor, with an early-season drought that made re-sowing necessary and strongly reduced the length of the growing season. Average millet grain yields in the first and third year after cowpea cropping (1999 and 2001) were 590 and 434 kg/ha, respectively, compared with 433 and 323 kg/ha in the plots under continuous millet (Fig. 6). The millet yields in the millet/cowpea intercrop were 585 and 545 kg/ha in the first and the third year, leading to a total millet yield over four years that was the same as under continuous millet cropping, despite the zero yield during the first year without millet, when cowpea was grown in monocrop, and despite the cowpea intercropping in the other three years. In the second year after rotation (2000), millet yielded poorly and no differences were observed between treatments, probably due to the poor rainfall.

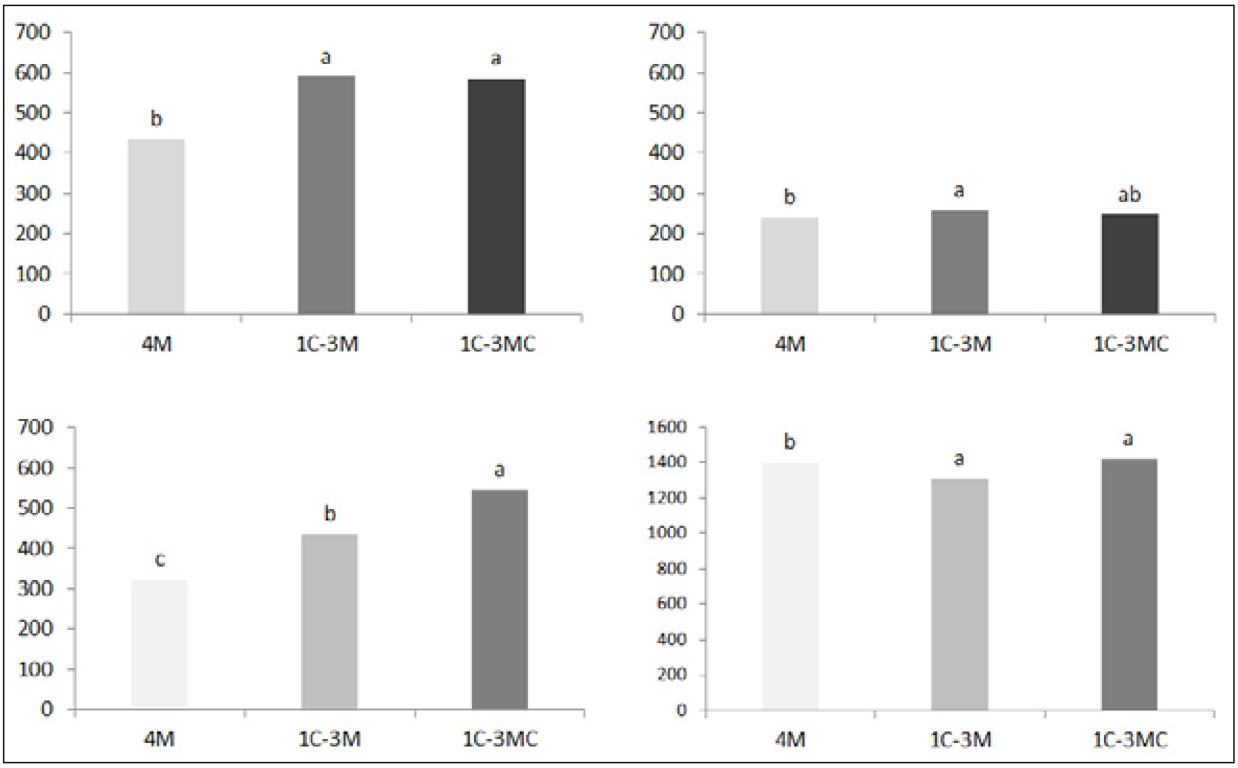


Figure 6. Grain yields of millet grown in rotation and/or association with cowpea.

Yields in three consecutive years are presented. 4M = continuous millet, 1C-3M is one year cowpea (1998), three years millet; 1C-3MC = one year cowpea (1998), three years millet/cowpea intercrop. Data from Samaké *et al.,* 2006.

Rotation with cowpea did not lead to significant reductions in total millet yield over four years, and 419 kg/ha of cowpea could be harvested from the cowpea monocrop in the first year. From the rotation and intercropping treatment, a full millet yield plus 949 kg/ha of cowpea could be harvested. There was no effect of fallow period on cowpea yields. Total millet yields significantly increased after the 2-year and 7-year fallow, with yield gains of 290 and 380 kg/ha, respectively, but not after the 5-year fallow. Dividing the four-year millet yield over the total years of production including fallow years shows a decrease in yearly productivity as the fallow period increases, due to the increasing number of zero-production years that are not sufficiently compensated by yield increases in productive years. Increased fallow period suppressed *Striga hermonthica* infestation in a more or less linear fashion. Cowpea rotation or intercropping did not have any effect on weed pressure.

In the 2000 drought year, millet yield was poor but cowpea yield from the millet/cowpea intercropped fields increased compared with the previous year, to about 340 kg/ha. Similar results were observed by Bielders and Michel (2002), which shows that cowpea cultivation as an intercrop can reduce risk of crop loss due to moderate droughts. Additionally, cowpea provides good quality fodder which can be used for livestock fattening. The millet straw increased in quality when grown in rotation or association with cowpea, due to enhanced N uptake (Samaké et al. 2006). Overall soil quality also benefitted from cowpea cultivation combined with two years of fallow, showing increased organic carbon and nitrogen concentrations. However, soil organic matter build-up through cowpea cultivation alone is not realistic as the organic matter production is insufficient and decomposition is too rapid (Carsky et al. 2002).

The effect of groundnut and cowpea rotations on millet yields and soil fertility were assessed by Bationo and Ntare (2000) in Niger over a 5-year period, in three research sites, namely Sadore (rainfall average 560 mm/year), Bengou (850 mm/year) and Tara (700 mm/year). The experiments were established on fields that had been left fallow for the past several years. Nevertheless, soil N and P concentrations and Soil Organic Carbon were small. The cultivars that were used in the experiments (millet CIVT (110 days to maturity), cowpea TN5±78 (75 days) and groundnut 55±437 (90 days)) are recommended for cultivation in Niger (Bationo and Ntare 2000). All plots received 13 kg P/ha as Single Super Phosphate and 25 kg K/ha as Potassium Chloride. Urea-N was applied at rates of 0, 15, 30 or 45 kg/ha. Crop residues were removed each year according to local practice.

Cowpea and groundnut yield were virtually no grain, due to insect infestation in the cowpea crop and poor pod setting in the groundnut crop. However, the vegetative growth of both cowpea and groundnut was highly valued as fodder. Nitrogen fertilization significantly increased dry matter production of both cowpea and groundnut, indicating limited N fixation by the legumes. The authors speculate that the soils may be deficient in molybdenum, which is required for effective nitrogen fixation (Bationo and Ntare, 2000). Millet yields were significantly increased after cowpea cultivation, with a total of 950-1000 kg grain/ha compared with a total of 550-800 kg grain/ha for the continuous millet crop without N fertilizer. The yield increase was 57, 28 and 87% in Sadore, Bengou and Tara, respectively. Average millet yield increase was much smaller after groundnut cultivation, with 20, 15 and 79% respectively, compared with continuous millet cultivation. With increased rates of N application, rotation still had a positive effect on millet yields, indicating that rotation with legumes has other positive effects besides N fixation. Cowpea and groundnut yielded much more fodder in millet rotations than in continuous legume cropping systems in two of the three sites. A fallow-millet treatment was also included and was found to supply more nitrogen than legume rotations. Nevertheless, legume-millet rotations gave larger yields than the fallow-millet treatment, indicating again that other effects other than just N fixation play a role.

The studies above do not specifically mention labor requirements for legume cultivation. Considering that labor availability is a major constraint in West Africa, some indication of the labor needs for intensive cultivation of cowpea or other legumes is necessary to assess the adoptability. Cowpea planting in maize-cowpea intercropping trials in Nigeria was estimated to take 10 working days (WD) per hectare (Fabunmi and Agbonlahor, 2012). As cowpea was used for green manure, residues had to be spread over the field as mulch or incorporated into the soil, which was estimated to take another 10 (mulching) to 20 (incorporation) working days/ha. In comparison, maize planting was estimated to take 10 WD/ha, maize weeding was estimated at 40 WD/ha and maize harvesting at 10 WD/ha (Fabunmi and Agbonlahor, 2012). A total labor requirement for sole maize production of 49.5 WD/ha was found in Zimbabwe by Waddington and colleagues (2007). In the same study, the authors estimated a labor requirement of 25.8 WD/ha for cowpea cultivation in intercrop, and a labor requirement of between 33.5 and 56.6 WD/ha for other legumes. Rusinamhodzi and colleagues (2012) and Woomer and colleagues (2007) noted that intercropping requires additional labor investments for field operations, but did not quantify these investments. Mortimore and colleagues (1997) indicate that cowpea as an intercrop gets a 'free ride' in terms of labor, as land preparation must be carried out anyway. With regards to weeding, spreading varieties of cowpea may reduce weed pressure, but weeding in an intercropped field does require more skill.

4.3.2 Adoptability of intensive legume cultivation

The positive responses of grain yields to intercropping or rotation with cowpea and other legumes demonstrate that putting nitrogen fixation to work for enhanced agricultural production in Africa is not necessarily a matter of developing new technologies, but more likely a matter of developing a strategy for implementation of existing technologies (Giller and Cadisch, 1995). Intensification of legume production has three potential benefits: increased legume grain yields become available for sales or consumption, increased quantities of legume stover become available for animal feed or soil fertility improvement, and cereal productivity will increase due to enhanced soil fertility and reduced pressure of pests, weeds and diseases. Increased legume grain yields will contribute to the household income if markets are available and accessible. Legume stover can have a direct market value if it is sold or if the household is involved in animal-fattening activities and a more indirect value if the stover is grazed by livestock of other farmers or incorporated in the soil.

The enabling costs of intensive legume cultivation depend to a large extent on the cultivated species and varieties, and on the desired outputs. In general, a basic degree of soil fertility is required for the legume seedlings to establish and for N-fixation to commence, so the availability of manure or fertilizers (especially phosphate) is an important condition. The amount of labor required depends on the purpose and intensity of the cultivation system. If legume grain production for the market is the main purpose of cultivation, then fertilizer P is generally required to boost crop yields and pesticides may be needed (especially for cowpea) to control insect damage. Application of insecticides can triple or quadruple cowpea grain yields in the Sudan savannah regions (Ajeigbe et al. 2012) and yields are generally poor when insecticides are not applied. If legume biomass production is the main objective, then little pesticide is required (Ajeigbe et al. 2012). Biomass is produced even under marginal conditions, but fertilizer application (especially P) will increase production and positive effects of legume cultivation on soil fertility. This is also relevant if improved cereal yield is the main objective of legume cultivation. Rotation and intercropping will reduce pest, weed and disease pressure on cereals and increase soil nutrients, especially if part of the stover is incorporated in the soil. The optimal production system would provide legume grain and fodder, and improve cereal production. Carsky and colleagues (2002) recommend a number of strategies to optimize rotation benefits, which are careful choice of variety (preferably slow-maturing unless growth period is very short, and with small P demand), and good management of soil and crop (P application and protection against insect pests). In practice, fast-maturing varieties with a good market value are likely to be preferred by smallholders in the Sahelian system, and soil fertility improvement is unlikely to be their main focus of legume cultivation (Adjei-Nsiah et al. 2008).

Four qualitative cost levels have been estimated, based on an assessment of data found in literature: low (green), low/medium (yellow), medium (orange) and high/medium or high (red). The ‘alternatives’ column shows the potential to reduce or replace the enabling costs. The ‘outcomes’ or benefits are assumed to be positive and have been formulated as such; if negative outcomes or trade-offs are expected, they are mentioned in the ‘comments’ column. Benefits can be low (red), low/medium (orange), medium (yellow), or high (green).

Table 10. Enabling costs and outcomes of legume intercropping or rotation.

Category	Indicator	Level	Comments	Alternatives
Enabling conditions/ costs				
Land, natural resources, climate	Land area	Low	In fields that are already under cultivation	
	Rainfall, AI, length of rainy season	Low	Depending on the water requirements of the legume variety	Several (breeding short-season varieties, irrigation)
	Availability of water sources	Low		
	Soil fertility/ quality	Low/ Medium	Sufficient phosphorus availability, molybdenum, some nutrients for establishment	Many (application of P fertilizer, compost, manure)
	Rangeland extent/ quality	N/A		
Inputs	Internal/re-allocated inputs	Low	Manure or mulch is beneficial but not essential if P fertilizer is available	
	External/ purchased inputs	Low/ Medium	P fertilization is essential for legume growth and nitrogen fixation	Few (manure may be used as alternative P source)
	Labor	Medium	Extra labor required for sowing, harvesting and application of pesticides	Several (mechanization)
	Information, skills	Low	Basic skills required, such as knowledge about sowing densities and management	
Economic	Credit availability	Low/ Medium	Depending on cultivation intensity, credit may be required for the purchase of seed, P fertilizer and pesticides	
	Markets	Medium	Markets must be available for purchase of P fertilizer and seeds and for the sale of legume grains	Several (warrantage, cooperatives, supply chain linking)
	Price level and stability	Low		
	Demand	Low/ Medium	Cultivation of legumes that cannot be sold is unattractive	Few
Institutional	Policy	Low	P fertilizer must be available	
	Land tenure	Medium	Prevention of grazing by livestock. Investment in soil fertility is more likely in case of secure tenure	

Continued

Table 10. *Continued*				
Category	Indicator	Level	Comments	Alternatives
Enabling conditions/ costs				
Social/ cultural	Culture/tradition	Medium	Part of the crop residue must be left in the field in order to improve soil properties. Animal grazing of residues must be limited. The area under cereal cultivation may be reduced. Acceptance of new food types may be an issue	Depending on the incentives
Outcomes/ benefits				
Direct outcomes	Risk reduction	Medium	Cultivation of drought resistant legumes such as cowpea	
	Improved nutrition	High	Legumes provide protein and dietary diversity	
	Short-term financial returns	Medium	Depending on P application and overall intensity of the system. Higher in combination with livestock fattening	Many (P application, improved varieties, combined with livestock fattening)
	Long-term financial returns	Medium	Additional soil fertility management techniques are required to sustain production. Higher in combination with livestock fattening	Many (P application, improved varieties, combined with livestock fattening)
Indirect outcomes	Ecosystem service provision	Medium	N-fixation, increased diversity	

4.4 Small-scale dairy production

In the agro-pastoral systems of West Africa, cattle provide a number of goods and services such as income, manure, traction and risk insurance. Pastoralist households have been defined by Rass and colleagues (2006) as those households that derive more than 50% of their income from livestock, whereas agro-pastoralist households derive between 25 and 50% of their income from livestock. However, multiple definitions are in use.

Population pressure, encroachment of grazing lands by agricultural fields and market demand are the main drivers of intensification in pastoral systems (de Ridder et al. 2004, Moritz, 2012). As animal grazing happens often in areas that are not suitable for agriculture, intensification per land unit in these areas may not be feasible. Moritz (2012), however, argues that intensification in this case refers to increased production per animal unit, rather than per land unit. Such intensification requires increased use of capital and, where possible, labor inputs, to increase outputs (Moritz, 2012). Gender issues may arise as intensification of dairy production through stall feeding often relies to a large extent on labor input by women (Ouedraogo and Kaboré, 1996). Environmental issues must be addressed for the intensification to be sustainable, as livestock grazing is said to be a major cause of rangeland degradation and biodiversity loss in West Africa (Darkoh et al. 2003).

Where cropping and animal husbandry occur separately, competition between the two will increase when cropping expands and the number of cattle rises (Powell et al. 2004; de Ridder et al. 2004). At a certain point, depending on the local and regional conditions, the competition will become so strong that the integration and intensification of both systems is to be expected. FAO (1996) defined mixed farming systems as those in which more than 10% of the dry matter fed to animals comes from crop by-products or in which more than 10% of the total value of production comes from non-livestock farming activities.

The most common cattle breeds for milk and meat production in West Africa are N'Dama (*Bos taurus*), which has the great advantage that it is resistant to trypanosomosis (Somda, 2005), and Zebu (*Bos indicus*) (Millogo et al. 2008). Milk production of both breeds is quite poor, but they are well adapted to local conditions and are disease resistant. Traditional milk products are sour milk, sour yoghurt, butter and cheese (Yahuza, 2001). These products have a limited shelf life and transportable distances are therefore small.

Aune and Bationo (2008) and Udo and colleagues (2011) suggest dairy production takes place somewhere on the upper rungs of the intensification ladder, as households must have a certain resource endowment to possess cattle. The transition to small-scale commercial dairy production can be made through more intensive management of productive animals in an existing herd (Moritz, 2012), or through the purchase of one or several (preferable crossbred) cows in case the household did not yet own a herd (Udo et al. 2011). Stall feeding with good quality crop residues or supplements is a central element of intensified small-scale dairy systems (Udo et al. 2011; Moritz, 2012). Stall feeding is known to have additional advantages apart from increased milk quantities and quality, such as increased availability of manure and more optimal crop residue management, but a large labor investment is required, especially by women, which can inhibit uptake (Kaliba et al. 1997). Stall-feeding dairy cattle requires continual attention, 365 days per year.

In areas where crop production is possible (rainfall > 300 mm/year), integration of crop and livestock production may improve the overall productivity of the system, as cattle provide milk, meat, draught power, and manure for fertilization of fields and gardens, and crops are a major source of animal feed. For dairy production to be a cash-generating activity, sufficient feed as an input is required, and markets must be available nearby to sell the milk. Delgado and colleagues (1999) predicted an increase in dairy consumption of 3.8 – 4% per year in Africa between 1993 and 2020. Recent studies from The Gambia, Mali, Nigeria, Cameroon, Senegal and Burkina Faso, which will be discussed in detail below, all show acceptable returns on investment for dairy production systems, but also demonstrate the problems and constraints related to underdeveloped local markets and large dependence on imported milk products, especially milk powder (Somda 2005, Bonfoh et al. 2005, Debrah et al. 1995, Yahuza 2001, Millogo et al. 2008, Dieye et al. 2005, Moritz 2012).

4.4.1 Experimental evidence

In Senegal, local small-scale dairy processing facilities around the city of Kolda, in the Soudanian savannah (precipitation around 1,000 mm/year), were investigated (Dieye et al. 2005). Five small-scale facilities had been set up as private or cooperative enterprises, supported by development projects. The facilities processed 25 to 150 liters of milk per day, which were delivered to the plants by bicycle in 5-20 liter containers from farms in a 15 kilometer radius around Kolda. The end products were 250 or 500 ml packages of fermented milk, pasteurized fresh milk, or liquid butter. For the producers, the amounts delivered to the small dairies represented 52% of the total farm produce in the rainy season and 75% of the produce in the dry season. Increased milk production from 1996 onwards was the consequence of improved housing and feeding strategies (Dieye et al. 2005).

Due to a (flawed) perception of increased hygienic value of milk from the small dairies compared with imported powdered milk, consumers were willing to pay double prices for the local milk, which made the production very profitable.

In Burkina Faso, production chains for dairy were found to exist around the major urban centers of Ouagadougou and Bobo-Dioulasso (Sidibé et al. 2004; Millogo et al. 2008). Rainfall varies from 700 to 800 mm/year in the Ouagadougou area and from 900 to 1,200 mm/year in the Bobo-Dioulasso area.

In the Bobo-Dioulasso area, Sidibé and colleagues (2004) investigated all farmers with at least one milk cow in a 50 km radius around the city center. They found that 70% of the farmers had herds of >30 animals. Average milk production per cow was larger in the systems with smaller herds (<30 animals) for several reasons. In these systems supplementary feeding was more common, animals were more often crossbred, and disease incidence was less. This indicates a more intensive management of the small herds.

The dairy production chains in the peri-urban areas of Ouagadougou and Bobo-Dioulasso were investigated by Millogo and colleagues (2008) through a large-scale survey, and milk samples from different points in the dairy chain were analyzed. Both farmers (producers) and processors were included in the surveys.

A sample of 22 producers that were delivering to the processing units and living within 50 km of the city center participated in the survey. The average number of cattle per farm in the study group was 76. The survey identified two types of farmers: full-time dairy farmers, and employees in the public sector or traders that did farming as a part-time additional activity. The full-time farmers were generally less educated and used local Zebu breeds, whereas the part-time farmers were higher educated and sometimes used cross-breeds with better milk production. Full-time farmers used a more traditional approach to farming. Animals were kept outside, in natural pasture, and were herded to specific grazing areas based on the farmers' insight and preferences. The herds were large, with on average over 10 lactating cows that produced 1-2 liters of milk per day. The produce, which sometimes varied with the season, was sold to dairy processing units and provided an important income source. Additionally, most farmers grew crops around their houses and used the residue as cattle feed. The part-time farmers more often kept their animals in barns, and natural pastures around the farm were used for grazing. Part-time farmers relied on hired labor to manage the animals in the pasture and to guard the barn. The use of concentrates (cottonseed cake) and improved breeds was more common in this system, and consequently milk production was larger, with up to 2-4 liters per cow per day.

In total, two-thirds of the farmers fed their cattle with cottonseed cake or cereal bran during the dry season, and about half made hay and/or silage for dry season feeding. The use of cottonseed cake significantly increased milk production. Diseases were seen as a major constraint to dairy production by the farmers, and they worked together with veterinarians or technical assistants to keep their animals healthy. Additional perceived constraints were the lack of feed during the dry season, the lack of training, and the small number of specialized dairy farms.

Farmers milked once or twice per day, always by hand. About half of the farmers did not clean the udder before milking. The milk was collected in 20 liter containers and transported quickly to the dairy processing unit, either by bicycle or by car/motorbike. Milk prices at the processing unit were US$ 0.44-0.55 per liter in the rainy season and US$0.55-0.77 per liter in the following dry season.

The dairy processing units processed on average between 100 and 150 liters/day, and employed around five people each. The main activities were pasteurization and yoghurt production. Six of the nine surveyed processing units said they received support from the government. Marketing occurred mainly through informal networks, by making contact with local shops and through participation in trade fairs. Milk hygiene was found to be a real issue, but small measures such as cleaning the udder and the worker's hands before milking and keeping the storage materials clean could greatly improve the milk hygiene and shelf life.

In the Gambia, a large survey of dairy producers throughout the country found that the production system with local breeds was viable and able to generate reliable income (Somda 2005). For the survey, farmers who owned at least three milking cows were selected. The farmers were grouped into two groups, namely resource-poor and medium-resource. Medium-resource farmers owned an average of 72 cattle (mostly N'Dama) per household, including 23 females that were over three years old. They sold between 6 liters of milk per day in the dry season and 17 liters/day in the rainy season. Resource-poor farmers owned 54 cattle on average, including 18 females that were over three years old. They sold around 4 liters of milk per day in the dry season and 11 liters/day in the rainy season. Most dairy sales happened at the farm gate (74%) whereas only 16% of the producers sold at local markets. The estimated net incomes for resource-poor and medium-resource farms were US$ 640 and US$ 1,030 per year, respectively. The average VCR was between 3 and 5, indicating good returns on investment. However, the variation was very large, and net cash incomes ranged from as little as US$ 59 per year to as much as US$ 3,857 per year. Fixed costs were high, especially for the medium-resource farms, and selling the animals would be more profitable than keeping them in some cases. Total productivity and income stability need to be increased in order for smallholder dairy production in the Gambia to become a truly viable sector.

A report on the dairy industry in Nigeria by Yahuza (2006) describes a pilot project with small-scale dairy processing units in Kaduna state, which is characterized by a rainfall of 600-1,000 mm/year and the availability of good dry-season grazing areas. Over 90% of the cattle, mostly of the Bunaji breed, were managed by traditional pastoralist families. The project organized producers into groups and milk was collected, processed and marketed on their behalf. At the time of writing, there were 36 identified associations with 1,820 members in Kaduna state. Milk production was estimated at 0.36 liters per cow per day in the dry season and 1.27 liters per cow per day in the wet season. Yearly milk supply to the Kaduna processing plant was over 100,000 liters in 2000.

In Mali, traditional dairy production systems with Zebu cattle face major biophysical constraints in the form of high prevalence of subclinical mastitis and lack of good quality feed in the dry season, both of which negatively affect milk production and quality (Bonfoh et al. 2005). In the peri-urban areas around Bamako, cattle farming is still a largely extensive activity, especially further away from the town center (Bonfoh et al. 2005). The area is characterized by a yearly average rainfall of 900 mm, which falls in a single rainy season. In a case study in the region, the dairy farms beyond the 25 km radius from Bamako center were identified as traditional pastoral systems, based on local landraces and natural pastures (Debrah et al. 1995). Milk production in these systems was typically poor, between 1.0 and 1.26 liters per cow per day. Closer to town, within the 25 km radius, more diversified agro-pastoral holdings were found which combined crop production and other activities with semi-intensive milk production. Variations between the individual production systems in this area were large, but around 90% of the farmers owned at least five cattle from an exotic breed and milk production was relatively good compared with that in the village, ranging from 1.82 to 5.32 liters per cow per day. A third type of milk production system was found in the communal parks in Bamako district. Cattle owners in this area had limited access to private land, and production depended on the communal grazing area. Local breeds were used and milk production was relatively poor but better than in the village, between 2.1 and 4.67 liters per animal per day (Debrah et al. 1995).

In the village areas away from the center, most of the milk was sold locally. The agro-pastoral farms close to Bamako center sold most of their produce to a large processing plant, whereas the communal park farmers sold some milk locally and some in the urban markets. Buyers were found to be both direct consumers and middlemen. Net gains were largest for the village producers (US$ 0.09 to 0.24 per liter), followed by the agro-pastoralists close to the urban center (US$ 0.02 to 0.20 per liter) and the communal park dairies (US$ -0.40 to 0.28 per liter) (assuming an exchange rate of 500 CFA per US$). These patterns of returns are strongly related to the differences in costs between the different systems and their management and performance, which varied widely. Greatest costs are for feed, labor, transport and veterinary interventions.

Laboratory sampling of milk produced in the area revealed a number of issues, including frequent occurrence of subclinical mastitis (72% of the samples), microbial contamination, water addition to increase milk volume (21% of the samples) and contamination with antibiotic residues (6% of the samples) (Bonfoh et al. 2002a, b, 2003).

In Ghana, a survey among dairy producers showed that few farmers used feed supplements, although they were aware of the feed deficiencies in the dry season and were knowledgeable about some of the potential measures to improve food intake by their cattle (Oddoye et al. 2004). A variety of reasons for not using supplements was given, such as poor availability (crop residues), lack of knowledge (crop residues, urea supplementation, tree leaf feeding), 'never thought about it' (tree leaf feeding), or high costs (agro-industrial by-products such as wheat bran). Adoption of improved feeding technologies was significantly related to ownership constructions, as herd owners that were directly involved in farm management were more likely and able to respond to welfare issues than hired herders. Poor interaction between extension agents and farmers was found as another main reason for the weak adoption of dry-season feeding strategies.

In the far north of Cameroon, pastoralists developed an intensive animal production system in response to population pressure and urbanization in the 1980s (Moritz, 2012). The pastoralist households in the peri-urban village of Wuro Badaberniwol, which generally belong to the wealthier class, used two complementary management techniques: transhumance with hired herders or mobile pastoralists for part of the herd, and feeding with purchased cottonseed cake or other crop residues for the animals that remained in the village. The intensification in the 1980s did not lead to increased sales of animals, which shows that the goal of the households was to prevent a decline in animal numbers and to get the animals through the dry season, rather than to make maximum profit. However, the high costs of cottonseed cake feeding prevent stall feeding from being feasible year-round, so that transhumance in the rainy season remains an important element of the system.

Use of cottonseed cake for feeding is labor-intensive. The animals must be fed twice per day, and as the cake is expensive, the cattle are fed individually, which takes up to three hours per day. The pastoralists in Wuro Badaberniwol cultivate cotton as a source of cottonseed cakes, rather than for the cash that the sale of the cotton itself generates. The manure of the cattle is sometimes not used at all and accumulates in mounds. Thus, intensification towards productivity per unit animal clearly differs from intensification of productivity per unit of land in its activities and outcomes.

The increased productivity requires considerable additional capital investments, with a cost of US$ 16.50/animal/year for the animals in peri-urban Wuro Badaberniwol fed on cottonseed cakes. Two other study sites showed a cost of US$ 2.10 per cow in a mobile pastoral village and US$ 3.15 per cow in an agro-pastoral village (Moritz, 2012). In the intensive system of Wuro Badaberniwol 60% of the costs per animal was for cottonseed cake purchase. Animals fed on cottonseed cake reproduce more often, produce more milk, and can be sold for higher prices in the market, which more than compensated for the increased production costs. On the other hand, the returns on investment were larger in agro-pastoralist and mobile pastoralist systems than in intensive systems (Moritz, 2003). Risk reduction appears to be the main reason why farmers still preferred to opt for stall feeding with cottonseed cake; animal losses are 9.2% on transhumance compared to 4.5% in the village. However, the sustainability of the system from an economic perspective may be limited, due to the scale requirements, where owners of small herds actually may make a loss (Moritz, 2012). Additionally, dependence on markets and vulnerability to price fluctuations of especially cottonseed cake, increase the livelihood risks with which poorer households can cope less easily.

The availability of sufficient dry-season feed would enhance milk production and quality and reduce dependence on natural pastures, which are at risk of degradation due to the high grazing pressure. Feeding with cheap supplements such as millet stover can greatly enhance milk quality (Bonfoh et al. 2005). Milk and meat production of cattle and small ruminants are determined to a large extent by the intake of digestible organic matter (DOM), but basic nitrogen requirements must be met before the animals can profit from increased carbohydrate intake. The addition of legume stover to the diet can greatly enhance productivity. However, too much N-rich fodder will not add to productivity, as the surplus N will be lost and the lack of carbohydrates in the fodder may lead to less-than-optimal growth. Therefore, increases in legume stover availability are especially effective in regions with a surplus of N-poor crop residues such as cereal straw (Breman and Van Reuler, 2001), so that the two can be fed in combination. Recommended species for cultivation in fodder banks are stylosanthes, pigeonpea and *Leucaena leucocephala*. In the areas under natural vegetation in West and Central Africa, the main edible legumes are *Mucuna pruriens, Dolichos lablab, Canavalia ensiformis, Crotalaria juncea, Crotalaria spectabilis, Crotalaria breviflora,* and *Sesbania rostrata* (Bationo et al. 2011).

A case study in Niger investigated the nutritional potential and limitations of Sahelian millet-cowpea feed systems (Fernandez-Rivera et al. 2005). Rainfall in the research area, encompassing the villages of Banizoumbou, Tigo-Tegui and Kodey, in the Fakara region, was 450 mm/year on average. Common cropping systems combined pearl millet and cowpea, and livestock herds included cattle, sheep, goats, and some equines and camels. The animals were generally corralled at night to facilitate manure collection. During the dry season, animals were allowed to graze in the harvested fields, whereas in the rainy season most animals, apart from some lactating cows and sick animals that were unable to walk, were taken on transhumance. A survey of 542 households and monitoring of 434 herds provided extensive data on the system performance. Under-nutrition was common and was attributed to poor soil fertility and little rainfall, but also to lack of labor, financial constraints and access and tenure issues. Transhumance, night grazing and supplementation were found to increase the animal feed intake and weight gain, but each of these strategies had its own drawbacks, such as reduced manure availability through night-grazing and the high costs of supplementation (Fernandez-Rivera et al. 2005). There was insufficient cowpea cultivation in the research area to prevent feed shortages, and intensification of livestock production would require increased legume yields or the purchase of feed supplements from elsewhere.

Tarawali and colleagues (2002) estimated that one hectare of improved cowpea could provide a farmer with 50 kg extra meat due to better animal nutrition, and 300 kg extra cereal grain due to improved soil fertility as a result of nitrogen fixation and improved quality and quantity of manure. In the same article an experiment with three treatments is described for a cowpea-sorghum intercropping systems in Kano, northern Nigeria (average rainfall 690 mm/year). Three treatments were originally established, namely the traditional one with local varieties (control) and two best-bet treatments with improved varieties, one with purchased inputs (fertilizer nitrogen applied to the sorghum rows only, and insecticide applied to the cowpea at flowering time) and one without. The best-bet treatments used an alternative intercropping layout (2 rows of sorghum and 4 rows of cowpea at 75 cm spacing). All treatments received 3 t/ha of manure. After the first year, it turned out that farmers were willing to pay for the inputs because of their positive effects on yield, and therefore the second best-bet treatment was modified to incorporate the inputs, but to use local sorghum varieties. Local tradition allows free grazing of all livestock during the dry season, and this practice was therefore incorporated in the experiment.

Sorghum yielded 400 to 500 kg grain/ha and around 1,000 kg fodder/ha. Yields were not much affected by the different treatments, but the quality of the stover from the improved sorghum variety was much better than from the local variety (60% versus 30% digestible matter). Cowpea yields dramatically increased in the best-bet treatments, with 750 to 1,000 grain/ha for the best-bet option with inputs compared with 150 to 300 kg grain/ha for the control. Cowpea fodder production was 700 to 1,500 kg/ha for the best-bet treatments, compared with 300 to 450 kg/ha for the control. There was a large inter-annual variation, and the differences between the treatments were much smaller in 1999 than in 1998.

The best-bet options were supposed to include a double cowpea crop (second cowpea planting after harvest), but the farmers in the research area were reluctant to harvest the first cowpea crop because the rains lasted longer than expected. The second cowpea crop in a double-cropping system generally yields stover but little grain. In another research area where double cropping was implemented, farmers visually assessed the fodder quality of the two crops based on leafiness and greenness, and concluded that the second crop clearly yielded better fodder.

For a feeding trial, farmers were asked to feed their livestock on-farm with the residues harvested from the different plots (Tarawali et al. 2002). The farmers were allowed to supplement with other feed once the crop residues had run out, and they did so especially in case of the control trials, but also sometimes with the best-bet options. Livestock productivity was measured for small ruminants only. The samples were small and the results quite variable and the results must be interpreted with caution.

The best-bet option with improved varieties and additional inputs gave a significantly larger weight increase (3.54 kg in the last six weeks compared with 2.19 kg for the control) but manure quality and quantity were not affected. Though the feed supplements beyond the harvested crop residues were monitored, they were not included in the weight-gain calculations. The residues from the best-bet option with inputs lasted longer than residues from the control. The significant greater weight gain shows that the best-bet option with inputs has the potential to increase livestock productivity.

An analysis of the costs (including the purchase of labor, manure, fertilizer and pesticides) and returns (estimated based on a scenario where all crop residues are sold, rather than fed to the animals) showed a modest increase in value-cost ratio for the best-bet option with inputs (2.65, compared with 2.44 for the best-bet with local varieties and 2.56 for the control). Calculating the revenues based on livestock products is likely to increase the returns, especially considering the influence of residue quality which is not reflected in the residue price (Tarawali et al. 2002). Even though the results described above have many gaps and leave room for questions, they demonstrate the potential of increased fodder production in dryland areas with limited rainfall (690 mm/year) through the cultivation of improved legumes and the implementation of best management practices.

4.4.2 Adoptability of intensified small-scale dairy production

Livestock or crop-livestock systems in the semi-arid and arid regions of the Sahel are often extensive. Intensification of the systems requires additional inputs, either through purchase, labor, or the use of extra land. The use of extra grazing land does not fit the definition of sustainable intensification, but more importantly, it is often not practically feasible. Pressure on grazing land is already large and increasing, which results in degradation of the natural pastures and restricted quantities and quality of feed production. Intensification through stall feeding can be a way to increase production and prevent resource degradation.

The requirements for extra inputs (such as good quality sorghum or millet stover, cowpea or other legume stover, cottonseed cake or other industrial by-products) can only be met by farmers through the investment of cash, land and/or labor. Some or most of the feed must be produced on-farm or purchased, if the milk production is to be sustained during the dry season. Farmers or laborers must have sufficient knowledge and skills to take good care of the animals, act adequately in case of disease and collect and store the milk according to basic hygiene standards. Veterinary services must be ensured to prevent loss of animals to disease.

Increasing production costs will need to be compensated by increased revenues, but competition from imported milk powder and the short shelf-life of the dairy products limit marketability. Farmers have been shown to be reluctant to invest, especially in more remote areas (Oddoye et al. 2004; Bonfoh et al. 2005).

The high costs of intensification are reflected in the adoption table below, which shows many 'high' and 'medium' annotations. Many of these can be resolved, for example through the purchase of inputs, but the required cash investments may be inhibitive.

Four qualitative cost levels have been estimated, based on an assessment of data found in literature: low (green), low/medium (yellow), medium (orange) and high/medium or high (red). The 'alternatives' column shows the potential to reduce or replace the enabling costs. The 'outcomes' or benefits are assumed to be positive and have been formulated as such; if negative outcomes or trade-offs are expected, they are mentioned in the 'comments' column. Benefits can be low (red), low/medium (orange), medium (yellow), or high (green).

Table 11. Enabling costs and outcomes of small-scale dairy production.

Category	Indicator	Level	Comments	Alternatives
Enabling conditions/ costs				
Land, natural resources, climate	Land area	Low/Medium	Intensification per unit land is required, especially in peri-urban regions. Land is needed for production of feed	Few (free grazing, purchase of feed)
	Rainfall, AI, length of growing season	Low/Medium	Good quality natural pastures and feed supplements (crop residues or cottonseed cakes) are needed	Few (feeding with purchased feed)
	Availability of water sources	Low/ Medium	Water must be available for drinking	Several (transhumance, water harvesting)
	Soil fertility/ quality	Low/Medium	Production of sufficient quantities of good quality crop residues is desirable	Many (cultivation of dual-purpose varieties, purchase of supplements, fertilizers)
	Rangeland extent/ quality	High	High reliance on natural pastures in all systems. Additional feed sources are needed for milk production and quality	Many (purchase of supplements, production of legumes)

Continued

Table 11. *Continued*				
Category	Indicator	Level	Comments	Alternatives
Enabling conditions/ costs				
Inputs	Internal/re-allocated inputs	Medium	Crop residues for dry-season feeding	Few (natural pastures or purchased supplements)
	External/ purchased inputs	Medium/high	Depending on system intensity and starting point. Main costs are for cattle purchase, feed, labor, housing, transport and veterinary interventions	Few (in most cases purchased inputs needs will increase due to overgrazing of natural pastures)
	Labor	High	Milking once or twice per day, feeding, milk sales and/or processing, transport, herding	Few (hired labor, costs may be inhibitive)
	Information, skills	Medium	Feeding, milking, disease and herd management, hygiene	Many (training, farmer-to-farmer learning, involvement of extension)
Economic	Credit availability	Medium/high	Credit may be needed for cattle purchase, feed, labor, housing, transport and veterinary interventions	
	Markets	Medium/high	Local or urban markets must be nearby, products have limited shelf life	Few (improved hygiene and storage to improve shelf life, fodder production on-farm)
	Price level and stability	Medium/high	High competition from imported milk products (powder), supplement prices are market dependent and affect profitability. Prices are seasonal	Few (cooperatives, reduced production costs)
	Demand	High	High investment costs, labor intensive	Few (price regulation, market stimulation)
Institutional	Policy	Medium	Support for establishment of small-scale processing units, veterinary support	
	Land tenure	Medium	Access to natural pastures required	Few
Social/cultural	Culture/ tradition	Medium	Traditional systems tend to move towards increased herd size rather than production intensification	Situation-dependent (strong drivers of change cause intensification/ commercialization)

Continued

Table 11. *Continued*				
Category	Indicator	Level	Comments	Alternatives
Enabling conditions/costs				
Outcomes				
Direct outcomes	Risk reduction	High	Large cattle herds serve as a buffer for unexpected occasions	
		Low	Owning few crossbred cattle is risky in case of disease or market collapse	
	Improved nutrition	High	Addition of protein to the diet	
	Short term financial returns	Medium/high	Depending on production intensity and management	Several (increased intensity and better management; market-dependent)
	Long term financial returns	Medium/high	Depending on production intensity. Concerns exist about the sustainability of cottonseed cake production and about natural pasture degradation	Several (increased intensity and better management; market-dependent)
Indirect outcomes	Ecosystem service provision	Low/Medium	Increased soil fertility, nutrient cycling. Risks: rangeland degradation	

5. Sustainable Intensification in Four Key Research Areas

5.1 Description of research sites and local drivers of change

A total of 10 research sites along two transects were selected for the CGIAR Research Program on Dryland Systems (CRP1.1), one transect representing those sites with most potential for intensification, and on representing the poorest and most degraded sites with the highest need for managing risk and vulnerability (ICARDA, 2011). The 10 sites are depicted in Figure 1.

For this report, a subsample of four research sites was selected, namely Dan Saga (Niger), Banizoumbou (Niger), Sougoumba (Mali) and Dimabi (Ghana). Selection criteria were rainfall, with the four sites representing the complete range of rainfall quantities covered by the 10 research sites (533, 553, 935 and 1,095 mm/yr, respectively), and completeness of site-specific information. Unfortunately, essential information is missing for all sites. Especially demographic data (such as population numbers and historical development) and natural resource data (spatial organization and quality of communal areas) are essential for identifying 'best bet' options for each of the research areas.

Land use maps of West Africa are available, for example on the ESA website (ESA, http://ionia1.esrin.esa.int/) and the USGS website (USGS, http://lca.usgs.gov/). Figure 1, 7 and 8, adapted from the USGS website, show the different land uses in West Africa in the year 2000. Banizoumbou, Dan Saga and Sougoumba are located in highly and intermediately cultivated tree-shrub savannah areas, respectively (Fig. 7a, b). Dimabi is located in the densely populated area close to Tamale (Fig. 8), where population increase and urbanization have led to high land pressure in the last 35 years.

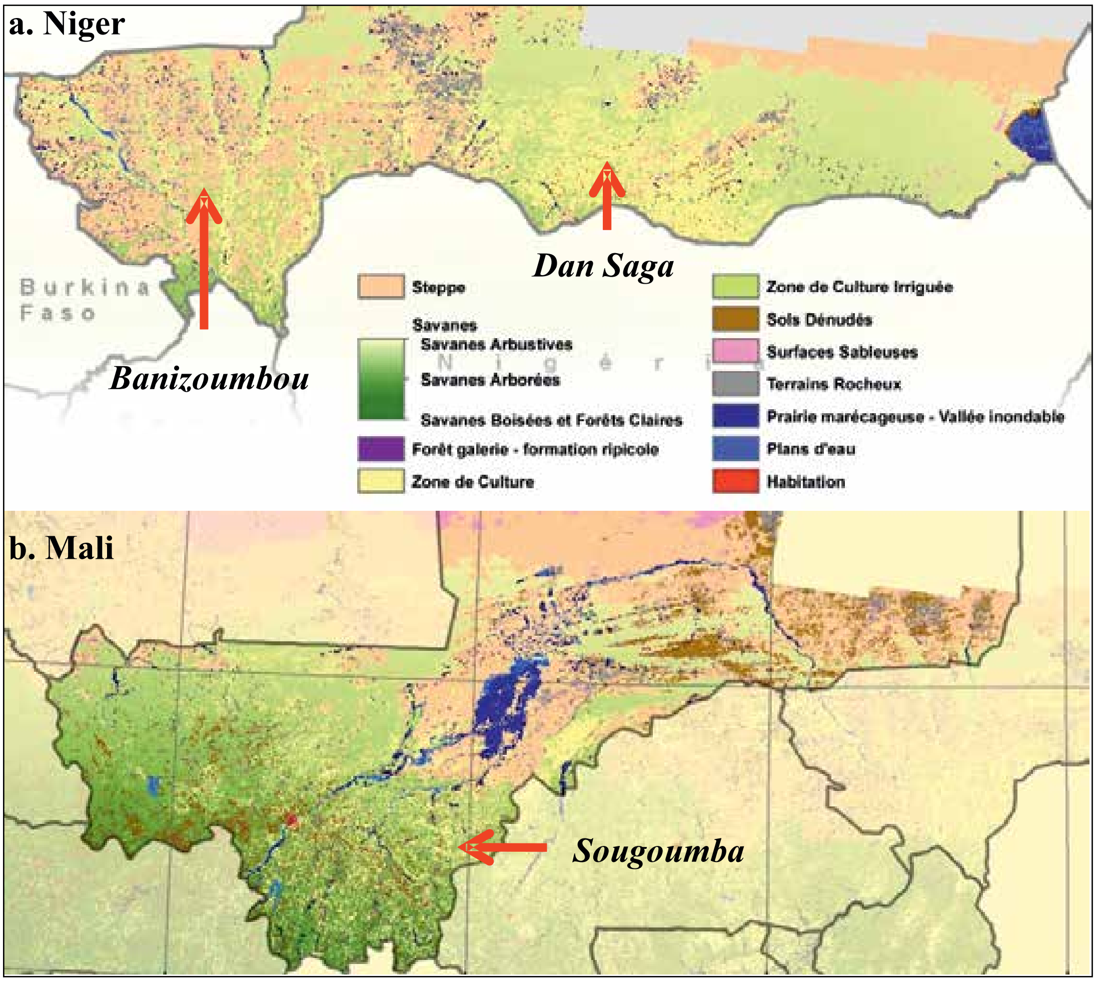


Figure 7. Land use in Niger and Mali.

Source: USGS (http://lca.usgs.gov/)

5.1.1 Dan Saga, Niger, rainfall 533 mm/year

Dan Saga is located in the Aguié department of Maradi state, in the central south of Niger. In 2010, total population in Niger was estimated at around 15.5 million, with almost 13 million people living in rural areas. The number of rural poor was estimated at 8.25 million, and gross national income was around US$ 370 per person per year. Maradi state makes up 3% of the area of Niger and houses over 20% of the population. It is the most densely populated province of the country, with over 260,000 rural households in 2007 (Rural Poverty Portal, http://www.ruralpovertyportal.org/). Aguié department covers about 2,800 km^2 and has an estimated 275,000 inhabitants, which is close to a density of 100 inhabitants per km^2 (Yayé, 2009). The town of Dan Saga is located 24 km north of Aguié, the department capital, 30 km west of Tessaoua, and 72 km east of Maradi, the state capital. A wide but un-tarred road runs from Dan Saga to Aguié, but not to Tessaoua and Maradi (Google Earth™).

Land tenure in Maradi is still arranged largely through customary laws, but the state has imposed changes in the land tenure system since independence, and is taking away powers from customary leaders, thus reducing their ability to regulate land ownership and division (Boubacar, 2000). The insecure situation has led to reduced investments in land in the past, especially where state and customary rules interfere.

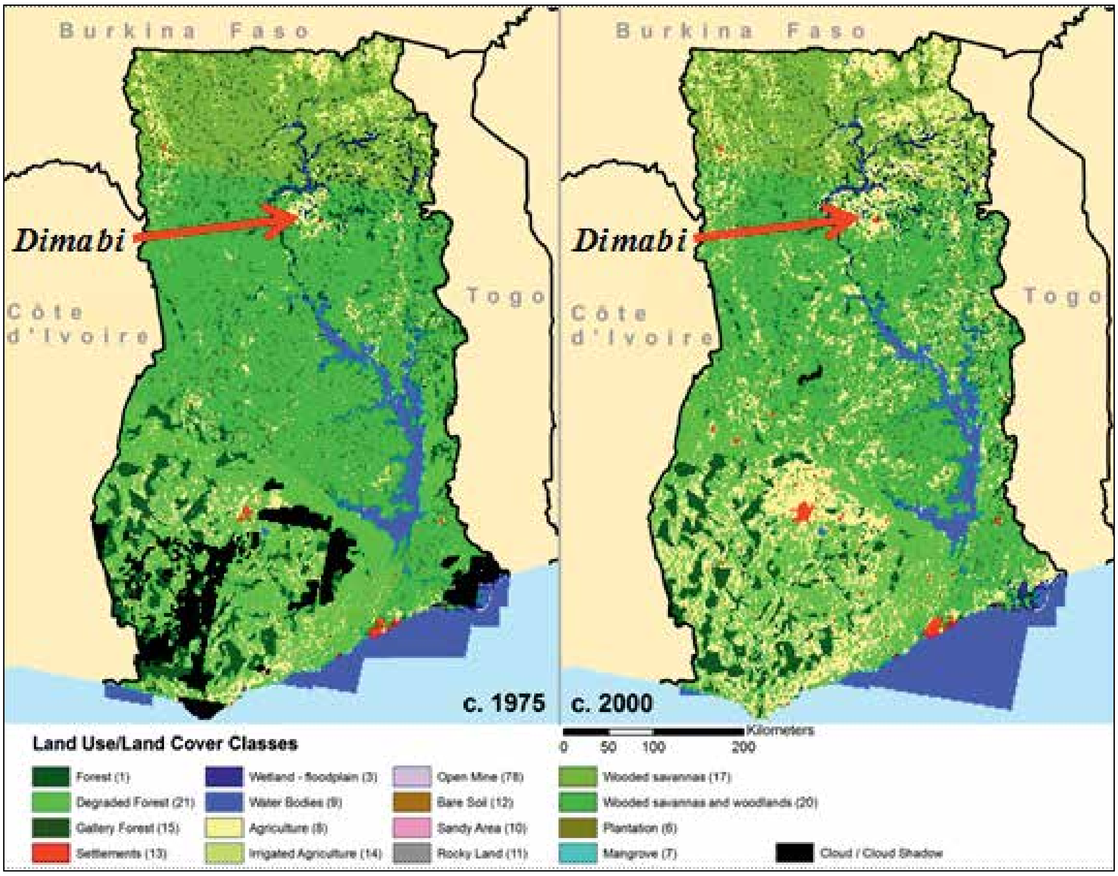


Figure 8. Land use and land use change in Ghana.

Source: USGS (http://lca.usgs.gov/).

5.1.2 Banizoumbou, Niger, rainfall 553 mm/year

Banizoumbou, in Niger, is located 15 km south of the tarred road which leads to Niamey, 60 km to the west. The population of Niamey was estimated at 774,235 in 2006 but is now expected to be much larger (Wikipedia, http://en.wikipedia.org/). Banizoumbou is located in the dry Fakara canton of the Kollo arrondissement. The landscape is hilly, with sand-filled valleys. An extensive survey of the region, with Banizoumbou as one of the research sites, was carried out by Moussa and colleagues (2011). Crop and animal production were indicated to be the main activities in the region, with 49% of the households owning cattle and 71% owning small ruminants, and with the majority of the households having access to at least 1 ha of cropping land. External input use was close to zero. Only 18.6% of the households sold grain products, but 47.9 and 66.4% sold cattle or small ruminants, respectively. Despite good market access, commercialization was found to be generally limited (note: the CRP 1.1 research site table indicates strong commercialization). More information on the Fakara region can be found in the online database of JIRCAS (JIRCAS, http://www.jircas.affrc.go.jp/).

5.1.3 Sougoumba, Mali, rainfall 935 mm/year

Sougoumba, in Mali, is located 4 km south of the main road which leads to Koutiala, 45 km to the south-west. Koutiala cercle, in Sikasso region, had approximately 575,000 inhabitants in 2009, of which almost 138,000 lived in Koutiala city (Wikipedia, http://en.wikipedia.org/). Koutiala is the cotton-production capital of Mali. The 'Cercle de Koutiala' covers about 9,100 km^2, an area of which 60% is covered by gravelly shallow soils that are unsuitable for agriculture (Lopez-Ridaura, 2005). The area is hilly, with gentle slopes (2-4%). In 1998, around 190,000 hectares in Koutiala were used for cotton and grain production, which contributed greatly to the total production in Mali (Sissoko 1998). Lopez-Ridaura indicates a natural pasture coverage of around 60% in the entire cercle, but the information assembled by CRP1.1 (2012) indicates a far lesser coverage of only 15%, and an additional 10% of rocky outcrops, in the Sougoumba area.

Strong local drivers of change in the rural parts of the region are changes in rainfall (smaller quantities and more variation), demography (population growth, urbanization, and rural migration), economy (increasing importance of cash crops, and transition from subsistence-orientated to monetary economy), technology (increased use of equipment in agriculture), and environment (soil erosion and degradation, degradation of the natural vegetation, and loss of forests) (Sissoko, 1998).

5.1.4 Dimabi, Ghana, rainfall 1095 mm/year

The village of Dimabi, in Ghana, is located along a dirt road, 3 km south of Tolon and the tarred Tolon-Daboya road, which leads directly to Tamale, 25 km to the east (Google Earth™). Tamale had a population of around 350,000 in 2000 and is the third largest city in Ghana. Population increased by 48.8% between 1984 and 2000, but nevertheless livelihoods in the urban region are still mainly dependent on agriculture (IWMI, http://ruaf.iwmi.org/). Dimabi falls outside the peri-urban region of Tamale, but increasing pressure for land and degradation of natural areas are negatively affecting the sustainability of agriculture in the village and the region.

5.2 Biophysical and socio-economic conditions in the four research sites

The biophysical and socio-economic conditions in the four research sites are represented in Table 12. The same indicators were used for the assessment of adoptability in the previous chapters. Substantial differences exist between the research sites. There are quite a number of information gaps. Some show a lack of data from a particular research site (especially Dan Saga) whereas others show a general shortage of information with regards to a particular indicator, such as labor availability and access to credit. These information gaps need to be addressed in order to create a full understanding of the local conditions, potentials and constraints.

The table is organized as the tables in Chapter 4, and includes the same indicators (enabling conditions, only). The color codes indicate the extent to which the conditions are constraining for intensification. Four qualitative classes have been defined: not at all constraining (green), a bit constraining (yellow), constraining (orange) and very constraining (red).

Table 12. Conditions in the four selected research sites.					
Category	Indicator	Dan Saga	Banizoumbou	Sougoumba	Dimabi
Land, natural resources, climate	Land area	Cropland 90-95% of area	35-45% of area under crops, extensive systems due to very poor fertility	75% crops, 15% pastures, 10% rocky outcrops	Very high population pressure
	Rainfall, AI, length of growing season	533 mm/year, 0.21, 70 days	553 mm/year, 0.20, 96 days	935 mm/year, 0.47, 130 days	1,095 mm/year, 0.58, 187 days
	Availability of water sources	Limited	Good: continental terminal aquifer all over	Substantial	Substantial
	Soil fertility/ quality	No information available	Very poor fertility, extensive systems	Acceptable, but much soil erosion and ongoing decline of soil fertility	Acceptable, but loss of SOM and ongoing decline of soil fertility
	Rangeland extent/ quality	No communal rangelands, possibility for transhumance	Woodlands and rangelands (25% of area) and long-term fallows (15-20% of area), degradation due to severe overgrazing	Pastures 15% of area, no rangelands but possibility for transhumance. Threat of poorly regulated fuel wood markets	No information available
Inputs	Internal/ re-allocated inputs	Large demand for crop residues (provide 80% of animal fodder), manure used for crop production	Much use of fodder for livestock feed, increasing use of manure for fertilization	Large demand for crop residues (98% of farmers own at least one pair of oxen), good manure availability	Crop residues for animal feed, manure for crop production
	External/ purchased inputs	No information available	Prohibitive costs of market access. Farmers' organizations and cooperatives exist but small numbers, lack of access to banks, increasing commercialization	Cooperatives, strategic fertilizer loans, regional chamber of agriculture	Available, facilitated by cooperatives and local government, but high costs are limiting factor
	Labor	No information available	Strong gender divisions, substantial migration (12% of men) to urban areas in the dry season. No use of cattle or donkeys	98% of farmers own at least one pair of oxen, additional labor information not available	No information available
	Information, skills	Very good extension services available, information about farmer education level not available	15.7% no education, 58.6% primary only. Limited availability of extension services	Extension services available, information about farmer education level not available	Extension services available, information about farmer education level not available

Continued

Table 12. *Continued*					
Category	Indicator	Dan Saga	Banizoumbou	Sougoumba	Dimabi
Economic	Availability of credit	No information available	Lack of access to banks	Strategic fertilizer loans, cooperatives	No information available
	Markets	25 km from nearest market, good access to improved varieties	Dense network of accessible markets in the region (but high travel costs), reasonable access to improved varieties	Good market access, reasonable access to improved varieties	Good market access, limited access to improved varieties
	Price level and stability	Market driven	Market driven with sometimes a transient pricing policy	Cotton price regulated, millet/ sorghum seeds subsidized	Market driven apart from in disaster situations
	Demand	Product dependent, no information available	Product-dependent but potentially large due to proximity of large urban center	Large demand for cotton (CMDB), potentially large for other products due to proximity of large urban center	Product-dependent but potentially large due to proximity of large urban center
Institutional	Policy	No national policy for food products	No national policy for food products	Cotton price regulated, millet/ sorghum seeds subsidized	No national policy for food products
	Land tenure	Customary, increasingly commercial, insecure	Family inheritance, officially a free market for cropping land is in place	Highly traditional, transferred as heritage, marginal lands allocated to returning migrants	Mainly through customary law
Social/ cultural	Culture/ tradition	Customary land tenure and free grazing of animals in the dry season	Customary land tenure and free grazing of animals in the dry season, some commercialization	Customary land tenure, high degree of commercialization	Customary land tenure, stall feeding of animals in dry season, increased commercialization

5.3 Adoptability of the example technologies in the research sites

Now that the enabling conditions of four example techniques have been determined, and the research sites were analyzed in similar terms, it becomes possible to match the sites and the technologies. In real-life, a far more in-depth survey of the target systems would be undertaken, and farmers and researchers together would steer the process of technology selection. The analysis below is an exercise to demonstrate the potential application of the indicators defined in Chapter 3, and to provide a starting point for future research.

5.3.1 Zaï cultivation

The key enabling costs for zaï cultivation are i) large labor demand, ii) need for manure or compost or, alternatively, for chemical fertilizer, and iii) requirement for secure land tenure, especially if the zaï are used for natural regeneration. The returns on labor can be quite limited, which has implications for the potential of the technology to contribute to meeting farmers' objectives. Strong drivers for zaï construction are population pressure in combination with severe soil degradation.

Agricultural intensification in the Dan Saga area is limited by biophysical as well as market constraints. However, population pressure is high, space for extensification is virtually absent, and soil fertility is declining, which means that intensification, diversification or 'stepping out' are essential strategies if farmers are to secure their livelihoods. Rural-urban connections are likely to strengthen, with labor, cash and goods flowing in both directions. In severely degraded fields, the construction of zaï would be an option for improving production, provided that labor is not in strong demand elsewhere. Manure availability could be a major constraint for the continued productivity of zaï-treated fields, as manure is already in large demand. Paradoxically, income increase and returns on labor are largest when totally unproductive soils are reclaimed (Kaboré and Reij, 2003). In Banizoumbou, severe soil degradation and crusting of the topsoil are common, and zaï construction could help to reclaim the affected areas. However, population pressure is quite low, and 10-15% of the area is under long-term fallow. Recent changes in national law have instituted a 'free market for cropping lands', but in practice traditional land rights still prevail. It is unlikely that individual farmers would willingly invest in the digging of zaï in communal areas for the purpose of natural regeneration. Additionally, labor migration in the dry season is common, which means that digging zaï is profitable only if the return on labor is larger than in off-farm employment, or if other employment opportunities are not available. Mechanization of zaï digging would relieve the labor needs but requires traction animals, and oxen are not readily available in the Banizoumbou area. In conclusion, it is unlikely that zaï cultivation will become widespread in Banizoumbou as long as population pressure remains low.

The construction of zaï pits is not considered as an option for the Sougoumba and Dimabi regions, which receive too much rainfall for the pits to function well.

5.3.2 Microdosing

For microdosing, the key enabling condition is market accessibility for purchase of fertilizers. The short-term benefits of the technology can be substantial but in the longer term, microdosing in isolation will deplete the soil nutrient pool and yields will fall. Additional measures are therefore essential, and microdosing should be considered as an initial step in the intensification process or as part of a set of technologies, rather than as an intensification option in itself.

Microdosing is a low-risk technology which requires little investment in terms of cash and labor. It fits well within the flexible livelihood strategies of farmers in poor-rainfall environments such as Banizoumbou and Dan Saga. Uptake potential in Dan Saga is large if fertilizer can be made accessible, for example through collective purchase initiatives. In Banizoumbou, several constraints are likely to limit integration of microdosing into the farming system. First of all, transport is costly due to the poor state of the roads and the lack of draught animals. Secondly, soil fertility in Banizoumbou is generally poor, which is likely to reduce yield responses to fertilizer application, especially in the first years (Tittonell and Giller 2013). Additional measures for improving fertility, such as the application of manure or compost, would be beneficial, but would not necessarily create direct responses. Thirdly, the farming systems in Banizoumbou are very extensive and even minimal cash investments could be incompatible with farmers' objectives. On the other hand, off-farm labor in urban centers is common in the dry season, which means some cash for investment is likely to be available, and fertilizer can be purchased during the off-farm period.

In the better-rainfall region of Sougoumba, production of cotton as a cash-crop is common. Sougoumba is located in the Malian 'cotton belt' and is, in fact, the main cotton-producing region in the country. There is an active group of NGOs and government bodies, and the cotton market is well established. Farm households are relatively well-endowed, with an average of 9.3 cattle per household and widespread draught ploughing activities (98% of the households own at least one pair of oxen). The degree of commercialization is high; households regularly sell cotton, sesame, cowpea, peanuts and cereals. For resource-endowed, market-orientated farmers microdosing may be of interest to boost cereal production on outfields or after a cotton rotation, especially when applied through the mixing of fertilizer with seeds so that no additional labor investment is required. The addition of fodder or dual-purpose legumes in combination with P-microdosing to the rotation could increase overall productivity and improve soil conditions. As rotation is already common practice in the region, this option does not require extra land area.

Though Dimabi has the most favorable climate in terms of rainfall, with a growing season lasting from April to October, cash crop production appears to be limited compared with Sougoumba. In a Boserupian sense, agriculture is intensifying, as continuous cropping without fallow is common. Small ruminant fattening as a market-orientated activity is widespread. But the area is poorly served by extension agencies. Access to improved seeds is limited, and fertilizers are available only at high costs. The use of external inputs is limited, and soil degradation is becoming more severe. The favorable climate and location of Dimabi (25 km from Tamale, the third largest city of Ghana) gives it a large potential for commercial crop production. From the available data, it appears that the main constraints are institutional. It is necessary to address these constraints when new technologies such as microdosing are introduced. The facilitation of a scheme for collective purchase of fertilizers may help to reduce financial risks and to circumvent the need for credit. Microdosing could be a first step in the transition from low-input to high-input crop production. As in Sougoumba, microdosing with P-fertilizer on dual-purpose legumes could benefit fodder production. This would contribute to small ruminant fattening and to the stall-feeding of cattle in the wet season, which is already common practice in the region. Fixation of nitrogen, and the production of additional manure, which is in large demand for application onto the fields, may contribute to an alleviation of soil fertility constraints.

5.3.3 Intensive legume cultivation

The introduction of legumes into the cropping system, or the increase of legume cultivation intensity in systems where legumes are already integrated, could be highly beneficial. However, several conditions must be met. Phosphorus availability must be sufficient to allow productive growth of legumes. Labor must be available for planting, weeding and harvesting activities and, in the case of intensive cowpea grain production, for the application of pesticides at flowering time. Access to markets is required for the sale of legume products and for the purchase of inputs such as P-fertilizer and improved seeds. Credit may be needed for investment in inputs, and demand for legume products is required for the investments to be profitable. Lastly, legume cultivation, especially in relay, requires regulation of free grazing by livestock during the dry season.

No information is available on current rotation practices in Dimabi, but fallow periods are known to be short or absent. Rotation with legumes would be beneficial considering the large demand for fodder and the positive effects on soil fertility and on pest and disease pressure, but it is likely that cereal production will have priority. Intercropping with legumes at high density offers a good alternative, especially as a wide range of legumes can be cultivated in the dry sub-humid climate of Dimabi. The extra labor requirement could be a major constraint, as the returns of off-farm labor in the urban center of Tamale are competitive, especially on the short term. The long growing season may allow for relay cropping with dual-purpose legumes or green manures, but free grazing of livestock in the dry season may present a serious limitation.

In Sougoumba, crop rotations with legumes are common, and groundnuts and cowpea are produced as cash crops. Legume production can be intensified through increased density of legumes in intercropping, application of insecticide on cowpea at the flowering stage, or the introduction of new legume species and varieties, such as dual-purpose cowpea. Farmers have good access to improved seeds, which is provided by a number of NGOs. Intensive legume production is a promising option in

Sougoumba, but the labor requirements and the effects on the production of especially cotton needs to be assessed. As in Dimabi, relay cropping could greatly increase productivity per unit area, but the grazing of the fields by livestock would need to be regulated.

In Dan Saga and Banizoumbou, cowpea is traditionally grown in association with millet. Improved varieties of cowpea are predominantly used in Dan Saga (76%). No information on the use of improved varieties is available for Banizoumbou, but access through NGOs in the region is good. Groundnut cultivation is widespread as a typical activity for women on small fields. Increased rotation with legumes is unlikely to be implemented in Dan Saga, as land is limited and cereal production has a priority. In Banizoumbou, rotation would be an option, especially considering the poor soil fertility. However, the poor fertility is also a constraint, along with the substantial labor migration and extremely extensive nature of farming systems in the region. Willingness to invest in legume cultivation, either in rotation or at increased density in intercropping, is likely to be limited in Banizoumbou, unless a strong market develops or land pressure increases. In Dan Saga land pressure is already intense and there are few natural pastures. The cultivation of millet in association with dual-purpose cowpea at high density is promising, as long as cereal yields do not suffer. A market for crop residues is already in place, which means the revenues of increased cowpea production are potentially large. This allows investments in P-fertilizer and improved seeds.

5.3.4 Small-scale dairy production

Small-scale dairy production can give good revenues, but there are multiple high costs and the risks can be substantial in intensified systems. Assuming that intensification implies stall feeding of most of the productive animals, the biophysical conditions must be suitable for the production of sufficient biomass. Rangelands can provide part of the feed for the non-productive animals and serve as a back-up in case of drought or crop failure, provided that they are accessible.

Dairy production requires large labor investments, and is demanding in terms of skills and knowledge. Support from extension is advantageous and access to veterinary services is necessary. The requirement for inputs is large. Good quality crop residues can be produced within the system or can be purchased. Veterinary assistance, feed supplements, housing and transport all require the availability of sufficient cash or credit. Good market access is essential, especially because dairy products are perishable. The large investments will only pay off in case of sufficient demand. Price instability increases the risks and can be a serious threat. Institutional support, such as fixed selling prices or the provision of veterinary services, is highly advantageous but uncommon in West Africa.

Whether or not intensive dairy production is possible in poor-rainfall areas, where feed production potential is inherently limited, is a topic of debate. In areas such as Dan Saga and Banizoumbou, there is a limit to the amount of biomass that can be produced, and feed shortages in the dry season are likely to occur. This makes the use of improved cattle breeds more difficult, as they are generally less well adapted to Sahelian conditions. Achieving maximum milk production with local breeds requires large labor and capital investments and is likely to be possible for the more resource-endowed farmers. Market demand is a key determinant for the economic benefits of intensification of dairy production. Especially in Banizoumbou, pastoral (extensive) systems of livestock production are widespread, and the sale of cattle for income-generation is common. It is unlikely that intensive dairy production offers a good alternative, especially because transport is costly. In Dan Saga land availability is far more limited. Cattle go on transhumance during the rainy season and feed on crop residues in the dry season. The relatively high intensity of crop production and the good market access could favor intensive dairy production, but the limited total biomass production is a serious constraint. Residues are in large demand, which could stimulate the market but also inflate prices. In conclusion, intensive dairy production could be feasible for better-off-households in Dan

Saga if demand is large and prices are stable, but for Banizoumbou it is unlikely that far-reaching intensification of dairy production will take place, as transport is costly, the systems are generally very extensive, and production of sufficient feed will be a serious problem.

Cattle ownership in Sougoumba is already widespread, and a stable market demand would probably drive increased dairy production. Production of dual-purpose or fodder legumes, especially in relay, could help to provide sufficient feed, but livestock access into the fields needs to be regulated and labor must be available. As cattle play an important role for draught purposes and also provide manure, a larger productivity could benefit the entire system. Market demand and price stability are key issues.

Dimabi, with its location close to the Tamale urban center and its good rainfall and long cropping season, has large potential in terms of dairy production. As in Sougoumba, relay cropping with dual-purpose or fodder legumes can provide feed, if labor is available for the cultivation activities and livestock grazing in cropped fields can be prevented. Market demand and price stability are again key issues. Drought risks are small, but large price fluctuations can be equally destructive. Competition from imported powdered milk is a serious limitation, especially in urban markets.

5.4 Discussion

The above analysis illustrates the use of the indicators for integration and adaptation that were defined in Chapter 3 for the purpose of matching the four example technologies with four research sites. The analysis shows the strengths and weaknesses of the four example technologies and the potential and limitations of the four research areas. There is a clear variation with regards to the 'fit' of each of the technologies in each of the sites. Where zaï cultivation has potential in Dan Saga, it is unlikely to be adopted in Banizoumbou, Sougoumba and Dimabi. Microdosing can be beneficial in all of the areas, though issues around the availability and affordability of fertilizers need to be resolved. Intensive legume cultivation is interesting in the drier as well as in the wetter regions, for the purpose of grain or fodder production or for soil fertility improvements. Small-scale dairy production can benefit from legume cultivation. Dairy production is certainly an option for farmers in Dimabi and Sougoumba, and potentially also in Dan Saga, if feed constraints can be overcome. An integration of the different technologies (P fertilizer microdosing on legumes in combination with small-scale dairy production) is likely to result in the largest impact, but may be feasible only for more resource-endowed farmers.

From the analysis it appears that large information gaps still exist, in the characterization of the farming systems and institutional context in the research areas as well as in the characterization of the intensification technologies. It is also demonstrated that none of the proposed technologies works very well in isolation. This confirms the importance of taking a systems approach.

6. Conclusions

Smallholder farmers in the West African drylands operate in a complex and high-risk environment. They have adapted by the development of diverse and flexible livelihoods, which often involve extensive crop production, rearing of cattle and small ruminants, and off-farm employment or labor exchange. As a consequence of increasing population densities, land is becoming scarcer and local practices, such as long-term fallowing and pastoralism, are under pressure. This pressure can cause 'vice and misery' (Malthus, 1798), shorter sequences of cultivation (Boserup, 1965) or innovative intensification (Boserup, 1965; Goodman 1993; Laney, 2002), and often a combination of all of these (Goodman, 1993; Laney, 2002).

In this report, we have attempted to analyze if, how and why certain agricultural technologies may fit in smallholder farming systems and contribute to the process of innovative intensification. An abundance of technologies that might fit in West African smallholder systems has been identified and listed. The diversity of the technologies illustrates the large variation of biophysical and socio-economic conditions in which smallholder farmers in West Africa are living and working, as well as the large differences between farm households. Consensus emerges that simple, silver bullet solutions for farming in Africa do not exist (Andriesse et al. 2007; Giller et al. 2011; Giller, 2012). Technologies that are highly suitable – best fits – in one community or farming system may not be well suited elsewhere. A wealth of case study reports available in scientific and grey literature, describe the different intensification technologies and illustrate their potential impact. However, as Sumberg and colleagues (2012) suggest, there is a tendency towards exaggerating impacts. In the CRP1.1 project proposal, one of the aims is "to provide the poorest and most vulnerable (...) with the means and capabilities (...) to enhance their own livelihood and that of their households" (ICARDA, 2011: p. 10). The desired impact is an actual increase in household wealth and welfare. Outcomes, in this case, are changes in farm productivity (Alene et al. 2012) whereas adoption is the integration of a new or innovative technology or activity in the farming system. The degree of technology adoption is often reported as a project result, but in fact it does not necessarily say anything about the contribution of the technology to household wealth and welfare. This report focuses on assessing the suitability (or adoptability) of technologies as a first step towards sustainable agricultural intensification. We would like to caution against confusing 'adoption' with 'impact', and against the use of the word 'adoption' without clearly defining what it is supposed to mean. Well-defined, quantifiable indicators are required to draw meaningful conclusions on the adoption of a technology. The degree of adoption can only be assessed several years after a project has ended to ensure that farmer participation, experimentation and testing is not mistaken for adoption.

Actual, long-term integration of new technologies into farming systems is sometimes widespread and long-lasting (eg, Baudron et al. 2012) but often minimal (eg, Sumberg, 2002). It is important for researchers, policy makers and donors to realize that intensification often does not fit with the objectives of farmers (Adams and Mortimore, 1999; Baudron et al. 2012). As long as risks are not reduced and land is abundant, smallholder farmers tend to extensify and diversify their livelihoods (Adams and Mortimore 1999; Drechsel and Zimmerman, 2005). Strong inducing factors, such as pressure for land, market demand, and often a combination of both, are required to drive intensification. Unless the tendency towards extensification and diversification is taken seriously, and the conditions under which intensification is induced are recognized, it is unlikely that an appropriate research agenda will be identified. If research moves in the wrong direction and offers options that do not fit centrally within the aspirations and resources of rural households, it is likely that the impacts, in other words the effects on household wealth and welfare, will be limited.

This report aims to contribute to the search for best-fit options for agricultural intensification in West Africa. Fitting options are more likely to be adopted by farmers and are more likely to lead to desired outcomes and impacts. Farmers will decide on the adoption of a technology based on the investments required and the expected returns. To assess the potential of adoption, we propose a set of 21 'adoptability indicators', based on a large body of literature (CIMMYT, 1993; Adams and Mortimore, 1999; Cassman, 1999; Inaizumi et al. 1999; Drechsel et al. 2005; Erenstein, 2006; Aune and Bationo, 2008; Baudron et al. 2012; Moritz et al. 2012; Muzari et al. 2012; and others). Adoption is *the long-term integration of a technology or part of a technology into the set of household livelihood activities, measured in terms of well-defined and quantifiable indicators*. Adoptability, then, is *a qualitative assessment of the potential of a technology to be adopted in a specific target system*. The adoptability indicators identified include 16 enabling conditions/costs and five outcomes (Table 3). Out of the enabling conditions, five are biophysical and eleven are socio-economic. This suggests that socio-economic factors are important in determining the 'fit' of a technology in a certain system. Such factors include capital, labor, market demand, cash need, information requirements and cultural factors.

With the set of indicators developed, we matched four technologies against four target research sites. A large variation in the adoptability of the technologies in each of the sites became apparent, so that we could derive recommendations on the ‘best bet’ options for each site. In a next step, other technologies may be matched to each of the sites, so as to create a large pool of ‘best bet’ options. For ‘best bet’ options to become ‘best fit’, further assessment at community and farm household level is required. Technologies may fit within a community or farming system as they are, or may be adapted through farmers’ experimentation to become ‘better fits’.

A number of frequently mentioned bottlenecks (high enabling costs with few alternatives) emerged from the analysis. Requirement for internal, re-allocated inputs such as manure or crop residues appeared as a serious bottleneck for zaï cultivation and small-scale dairy production, as competition for such resources is often intense and fertilizers or purchased feedstock are expensive or unavailable (de Ridder et al. 2004). Poor soil fertility was a key constraint for intensive legume cultivation and small-scale dairy production. Lack of available soil phosphorus will limit crop establishment and growth and thus limit N-fixation, legume grain yields and fodder production. Fertilizers may resolve this issue, but are often expensive or not accessible. The need for cash inputs was a bottleneck for fertilizer microdosing, legume cultivation and dairy production. These technologies require the purchase of fertilizers, feed, seeds, pesticides, veterinary services, etc. Informal rules and agreements indirectly affected the adoptability of all technologies through cattle grazing of legume stover, access to rangelands, land tenure issues and the division of, among others, labor, manure and seeds.

Apart from identifying bottlenecks, the set of indicators can also be used to identify information gaps. Case studies often address only a subset of the adoptability indicators. Labor constraints are often ignored, as are cultural/traditional factors and price stability. Awareness of the different aspects of adoptability may assist in development of appropriate research priorities and identification of information gaps.

The magnitude of the enabling costs and outcomes, estimated in terms of low – medium – high, are qualitative assessments of the relevance, derived from quantitative and qualitative data generated in experimental fields and case studies. Individual researchers are likely to come to different assessments of these magnitudes, based on their own background, perspectives and considerations. Alternative systems, such as ranking or the allocation of marks or percentages, could be equally functional but have similar constraints. Considering the estimated indicator magnitudes as facts rather than as best estimates would confuse communication and would miss out on their true purpose. We propose that the indicators can be used as a framework to structure analysis or discussions between experts or in project teams, so that a general consensus about the strengths and weaknesses of an intensification option can be reached and ‘best bet’ and ‘best fit’ options can be more readily identified.

Step-wise trajectories towards sustainable intensification through introduction of new technologies, and accumulation of resources, will be feasible only with long-term projects which see through the entire process of change (Wiggins et al. 2005). Drastic, rapid changes are likely to occur only if strong drivers are present locally. If the constraints to intensification are too numerous or too severe, then innovation and intensification will be inhibited (Lele and Stone, 1989). In West Africa, such constraints are often related to labor availability, market demand and infrastructure. These are typically socio-economic constraints at the community, regional or national level, rather than technical constraints at the household level. Understanding such constraints should be a first priority, as they have an overriding effect on opportunities for agricultural intensification.

Under the current unstable political and economic climate it is likely that smallholder farmers in West Africa will continue to extensify and diversify their livelihoods, using their experience to derive the most they can from their variable and unpredictable environment. Only when key constraints are resolved, or a strategy is found to circumvent them (such as the warrantage system to overcome limits in credit accessibility), will the process of agricultural intensification in West Africa take off. It is the role of science to maximize understanding of the complex array of biophysical and socio-economic factors which determine the potentials and limits of farming systems in West Africa, and to search for those best-fit options that are likely to have the greatest potential for helping farmers to achieve their objectives. The numerous constraints to intensification must be named, understood and addressed through interaction with stakeholders and policy makers on higher organizational levels. The adoptability approach helps to identify key conditions which are required for technologies to function. Thus, it helps to navigate between finding 'best fit' options on the one hand and identifying key constraints on the other, so that research can provide maximum support for farmers in the process of sustainable agricultural intensification.

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