Shea tree (*Vitellaria paradoxa* Gaertn. f.): from local constraints to multi-scale improvement of economic, agronomic and environmental performance in an endemic Sudanian multipurpose agroforestry species

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Abstract

Shea trees (*Vitellaria paradoxa* Gaertn. f.) have been for perhaps as long as 3,000 years probably the most economically and culturally important tree species in Sudanian agroforestry systems. The existing studies show that the specific magnitude and limits of shea tree presence and shea products' advantages are highly variable. This synthesis paper gathers and updates most of the scattered knowledge on shea trees and parklands, reported by category of knowledge: socio-economic potential of shea production, tree impacts on environmental resources and associated crop production, current means of enhancing shea domestication. It concludes with a proposal for a systemic and participative bio-economic modelling approach in order to simulate intensification of shea parklands' production using process-based research results on their agronomic and environmental performance.

Keywords: Africa, agroforestry, nut processing, socio-economic issues, tree functioning, tree impacts, product properties.

Introduction

Agroforestry parklands are the oldest and most widespread agricultural systems in West Africa. They consist in multipurpose woody species scattered in crop fields that regenerate in subsequent fallows (Boffa 1999, Faye et al. 2011, Garrity et al. 2010). Among the woody species concerned, shea (*Vitellaria paradoxa* Gaertn. f.) has been for almost 3,000 years probably the most economically and culturally important endemic species in Sudanian agroforestry parklands and fallows (Maranz 2009). The distribution area of shea parklands is a continuous strip 6,000 km long and 500 km wide on average, crossing 21 countries and receiving 600 to 1,400 mm of average annual rainfall (Allal et al. 2011, Hall et al. 1996, Hatskevich et al. 2011). The original biotope of shea is open savanna woodland (Serpantié et al. 1996). In fallows and agroforestry parklands, shea dominates the woody covers, most often in conjunction with *Parkia biglobosa* (néré) but also with other species (*Acacia senegal*, *Annona senegalensis*, *Terminalia avicennioides*) (Boffa 1999, 2015, Hall et al. 1996). In the context of slash-and-burn cropping and fallow farming systems, shea parklands dominate wherever population densities have been high enough to support nearly sedentary farming, but low enough to allow fallows of 15 years minimum for regeneration of trees (Ræbild et al. 2012, Serpantié 2000). At each clearing stage of this clearing-fallow cycle, farmers select and spare a small number of the “best” shea trees, a practice that gradually leads, after several cycles, to a more or less homogeneous and highly productive shea parkland, producing for family consumption or sale on local, national or sub-regional markets (Lovett and Haq 2000a). Trees to be spared are selected intuitively and visually. They are generally tall and in good health, with the least irregular year-to-year fruit yields, sweet fruit pulp and high fat content in nuts (Maranz et al. 2004a). Moreover, tree density and canopy size and shape are such that associated crops do not suffer much from tree competition for light or soil resources (Bayala et al. 2013, 2015). Neither planted nor cultivated, this “semi-domesticated” species is present in a wide variety of environments. Successive droughts combined with high demographic growth in Africa (2.5% per year) have had strong contrasting impacts on shea parklands: a general extension of parklands but local declines and worrying decreases in shea supply, mainly due to the lack of favourable conditions for natural tree regeneration following the disappearance of forests and fallows (Aleza et al. 2015, Diarrassouba et al. 2009, Djossa et al. 2008, Kaboré et al. 2012, Ky et al. 2009). The growing demand for shea on international markets offers an increasing source of foreign earnings to producer countries as well as an opportunity for agricultural development and the empowerment of their rural societies, especially women (Ingram et al. 2015), although this last assertion remains questionable (Saussey 2011). In addition, agroforestry is one of the options currently being explored for sustainable intensification of crop production (Van Noordwijk et al. 2014): trees improve soil fertility while helping to mitigate climate change effects at both the local and global scales by increasing carbon sequestration, regulating water flows (decreased runoff, increased rainfall recycling to the atmosphere) and buffering variations in microclimate parameters (radiation, temperature, hygrometry). Shea trees have recently been estimated to be good performers in green belt development, according to an index based on pollution tolerance, morphological traits and socio-economic characteristics (Ogunkunle et al. 2015). However, knowledge of the functioning of shea trees and shea agroforestry parklands, especially tree-crop interactions, remains fragmented (Bayala et al. 2013, 2015). This review updates most of the existing knowledge on the current social and economic potential of shea products, shea’s impacts on environmental resources and associated crops, and methods currently being explored to improve domestication practices. In conclusion, this synthesis leads to identification of a useful systemic approach for improving local evidence-based parkland management that would enhance the role of shea in food security, poverty alleviation, and agronomic and environmental performance in the context of global changes. I have chosen not to address the expansion and improvement of shea markets and trade, but to stick to the upstream mainstay issue: agroforestry production. This may be justified by the fact that, despite the boom in the shea trade and the arrival of leading foreign firms, the shea value chain is a counter-example to the trend towards more buyer-driven value chains, owing to the inherent constraints on shea nut supply (Rousseau et al. 2015) combined with the current lack of knowledge on the agronomic and environmental potential of shea parklands.

Socio-economic potential of shea production

The oldest benefits of shea production are local and regional. For centuries, shea has provided rural communities in Sudanian Africa, which represents today more than 80 million people (Naughton et al. 2014), with shea butter or oil, contributing to their nutritional health, livelihoods and well-being (Boffa 2015). Shea trees grow in Sub-Saharan African countries that have not the same potentials for shea nut production per year (Bup et al. 2014): high production concerns Benin, Burkina Faso, Ivory Coast, Ghana, Mali, Nigeria, Sudan and Uganda (70 000–300 000 tons/year); average production concerns Cameroon, Chad, Central African Republic, Guinea Conakry, Senegal and Togo (10 000–70 000 tons/year) and low production concerns the Democratic Republic of Congo, Ethiopia, Gambia, Guinea Bissau, Niger and Sierra Leone (less than 10 000 metric tons). Traditionally, men manage the land and own the woody species, which were strong markers of land tenure rights when planted (Pélissier 1980). Women control shea production, the income from which contributes to food security and other household needs, notably child care and feeding (Boffa 2015, Ingram et al. 2015, Pouliot 2012). The case of shea suggests, however, that intra-household knowledge sharing and collaboration may hold greater significance for achieving resilient resource management strategies, as Elias (2015) has noted concerning African agroforestry. All shea nuts are collected by women and children, who enjoy priority harvesting rights on land currently farmed by their family members. They gather fallen mature fruits from beneath the trees and carry the harvest back to the homestead (Boffa 2015, Lovett 2004, Picasso 1984). Collection of shea nuts and processing into shea butter now would provide 16 million women with income in producer countries after the Global Shea Alliance (https://globalshea.com). This vegetable fat is, after palm oil, the second most important staple fat source for cooking in Africa. As shea grows in areas unsuitable for oil palms, the two are not in trade competition (Hall et al. 1996). Shea fat is also used as a cosmetic, medicinal and ceremonial ointment. Shea fruit is appreciated as food. It provides an important source of protein, sugar, calcium and potassium from the end of the dry season to the outset of the rainy season, the period known as the “hunger gap”, despite considerable tree-to-tree variation in its nutritional value (Hall et al. 1996, Maranz et al. 2004a, Teklehaimanot 2004). Honfo et al. (2014) reviewed the literature over the last ten years on the quantitative nutritional value of shea products (pulp, kernels and butter) and the qualitative properties of the butter. Shea products also include honey; edible caterpillars; husks used as compost; cakes as a source of fuel; wood for charcoal, construction, furniture and mortars; bark for traditional medicines, and latex for glue. Although collection occurs at the same time as the heavy work of tilling and sowing, shea has been found in western Benin (Donga department) to account for at least 12% of poorer households’ income during the hunger gap (Droy et al.

2014). Shea is a small but essential contribution to food security although very low-paying (Bidou et al. in press). In Benin, the poorest smallholder women farmers and those who live in the most isolated villages and have no more profitable alternative, such as sale of vegetables, livestock products and food crops or working as pickers, depend the most on shea for their cash income (Bidou et al. in press, Droy et al. 2014). These dependance vary according to the farm type (Droy et al. 2014) but also to the evolution of gender inequalities, to the international market prices and to the relative interest of the men farmers for this resource (Bidou et al. in press).

The economic potential of shea products is enhanced by the fact that Sudanian belt is the sole region supplying the increasing international demand for shea nuts and butter, because shea does not grow anywhere else. Around 1920, international trade in shea products was nil. From that date, however, increasing amounts were exported towards Europe and international demand began to rise strongly (Terpend 1982). Based on 5 kg of dry kernel per tree (Boffa 1999), the potential production would be currently about 2.5 million t year^{-1} of dry kernels (Lovett 2004, Place et al. 2016). Between 11% (Place et al. 2016) and 52% (Lovett 2004) are estimated to remain uncollected because many shea stands are far from the villages, while women lack availability and means of transport, and collection varies from one year to the next according to annual production, women’s willingness and the profitability of collection for women relative to other activities and other demands on their time (Lovett 2004). Household characteristics governing management strategies also impact the total yield of shea parklands (Aleza et al. 2018). Such estimates vary widely, however, since the total amount of shea nuts collected annually in Africa was estimated in 2000 at around 650,000 t, of which 33-58% are thought to be exported, although domestic consumption has not yet been precisely estimated (Boffa 2015, Reynold 2010). Between 75% (Lovett 2004) and 90% (Maranz et al. 2004a) of the nuts harvested are sold in Africa, an estimated 55% of which is consumed by domestic markets and 45% exported (150,000 t kernel, Lovett 2004). However, these estimates have yet to be carefully checked. Although shea nut yields have not increased (1.96 t ha^{-1} on average over 1961-2016), and have even trended downwards since 2007, total nut production rose four-fold between 1961 and 2016 due to the extension of shea parkland areas from 85,000 ha in 1961 to more than 604,000 ha in 2016 (Figure 1). Production increased from 169,000 t in 1961 to a maximum of 777,000 t in 2007 before decreasing slightly until 2016 (604,000 t) with the yield decrease (FAOSTAT food and agriculture data 2016). During this period, international trade in shea experienced a boom (Rousseau et al. 2015). Indeed, between 2001 and 2005, sub-Saharan Africa’s total exports of shea nuts and butter increased by 35% in nut weight equivalent, with an exceptional increase of 660 percent in volume for shea butter, which accounted for 26% of total shea exports in 2005 compared to only 5% in 2001 (Yinug and Fetzer 2008).

This international boom in shea is due to the properties imparted by the structures of the nuts’ triacylglycerol components (Akihisa et al. 2011). Shea butter is one of the main cocoa butter substitutes in the chocolate and confectionery industries, which account for more than 90% of world imports and whose demand for nuts and kernels is increasing. These products are exported in bulk at low prices, mainly to Europe, North America and Asia (Elias and Carney 2004). The prices of shea nuts from West Africa are closely related to cocoa prices: higher cocoa prices generally raise demand for and consequently the prices of shea nuts as well, although the latter are cheaper than cocoa butter (Teklehaimanot 2004).

Shea butter also benefits from the increasing popularity of “natural” components, exotic plants, herbal remedies and fair trade among customers of Western artisanal, manufactured or industrial cosmetics companies (Maranz et al. 2004b). Cosmetics factories, which account for 10% of world imports and are growing explosively, use shea butter as an ingredient partially because of its unusually high level of non-saponifiable lipid compounds (Akihisa et al. 2011). This emphasis led to an export increase estimated at 26% between 1994 (200 t) and 2004 (Lovett 2004). As these companies generally require high standards of butter quality, they are currently the only outlets for certified organic shea butter resulting from investment in fair trade practices that are supposed to benefit and empower women producers (Elias and Saussey 2013, Maranz et al. 2003). In these new configurations, however, local know-how is supplanted by standardised know-how, which covers all operations from fruit collection to the logic of marketing imposed by development stakeholders and Western “natural” products companies. The upgrading of shea butter to meet the requirements of international, standardised quality standards is not always an alternative model that enables women to obtain more power and control over the resources and tools needed. In the end, the production of butter, however standardised, may only reinforce the unequal and hierarchical relations between men and women without the expected empowerment (Saussey 2011).

Shea butter is also used for preventive treatments against several diseases (Akihisa et al. 2010a,b).

Shea production is still temporally volatile and spatially heterogeneous. In many places of its distribution area, it currently seems to be experiencing difficulties to meet the increasing international demand despite years of good production may occur. Very few producer countries (Burkina Faso and Ghana, among others) have taken full ownership of and responsibility for this opportunity.

Constraints on shea production intensification and solutions currently explored

Biological obstacles

Several intraspecific biological constraints to intensification of shea production remain unsolved. Shea trees can live more than 200 years (Picasso 1984) and display very slow growth, probably linked to their long lifetime, with trunk diameters increasing by 1-6 mm year^{-1} depending on tree age and soil fertility (Delolme 1947, Picasso 1984, Ruyssen 1957, Serpantié 1996). Trees do not start to flower until they are 15-20 years old at the earliest (Picasso 1984, Serpantié 1996), the first flowers being sterile, and attain full fruit production between 40 and 100 years of age, which makes shea regeneration increasingly difficult in view of the strong reduction of fallowing area and duration although the flowering age should be corrected as there are indications of much early flowering depending on the ecological and management conditions (for instance planted individuals). Nowadays, the grafting methods and the *in vitro* technology are promising ways to over-come the long juvenile phase of shea although a perfection of the techniques and investigations on the management of the grafting environment are required (Tom-Dery et al. 2018). However, the reluctance among farmers to plant shea trees, owned not only to its lengthy juvenile phase but also to taboos against planting shea trees and to the difficulty in growing them due to the recalcitrant seed, emphasizes the need for dissemination of improved materials and adequate management practices (Azela et al. 2018). In addition, shea phenology and production are subject to wide intra- and inter-population variations. Various factors (climate, land use, ecological and soil conditions, agricultural practices such as ploughing, tree density, fertilisation and pesticide application on associated crops, weeding, etc.) have been identified as influencing them, but no general pattern among these factors has yet emerged (Jurisch et al. 2012, Kelly et al. 2007, Lamien et al. 2007, Nouvellet et al. 2006, Okullo et al. 2004). Furthermore, household socio-economic characteristics such as road accessibility, landholding size, and gross annual income influence shea fruit yield (Aleza et al. 2018). The length of time during which farmers have been selecting trees with high productivity of specific local fruit traits also contributes to the high variation observed in shea fruit quality and quantity (Boffa 2015, Lovett and Haq 2000a). Furthermore, fruiting may be limited by low pollination (bees are a major pollinator), inbreeding, insect oviposition, fruit abortion and fruit fall because of weather factors (Teklehaimanot 2004). Seed dispersal occurs during the rainy season, generally around the seasonal rainfall peak. This is the least risky period for survival of desiccation-sensitive shea seeds as well as for the establishment of seedlings (Okullo et al. 2004), since shea seeds are highly recalcitrant, i.e. desiccation-sensitive, dying at water contents as high as 20-30% (Pritchard et al. 2004, Ruyssen 1957). Early wet season seed dispersal and immediate germination would indicate the species' adaptation to the seasonal aridity of the upper soil layers (Serpantié et al. 1996). However, Ræbild et al. (2012) found that the number of seedlings starts to increase before the first fruits mature on trees (March-April). The authors attribute these seedlings to root suckers that emerge from seedlings dieback during the previous rainy season. Sprouting vigorously during the following rainy season, juveniles survive repeated removal of their above-ground parts by burning, grazing or cutting by plough or machete (Bellefontaine 2005, Hall et al. 1996, Ky-Dembélé et al. 2007). Their vigour must be related to seedling age and the degree of leaf removal after defoliation, a topic unexplored until now (Ugese et al. 2011).

Bayala et al. (2008b) recommend total pruning to rejuvenate old trees in parklands because fruiting recovers faster than crown. In Burkina Faso since 2012, the Forest and Environment Department (DEF) of Burkina Faso's Institut de l'Environnement et Recherches Agricoles (INERA) assists women producer groups in implementing rejuvenating pruning, Assisted Natural Regeneration (ANR), nurseries, while testing cutting beds, grafting, etc. The stakes are high in Burkina Faso, which is the main or only supplier of shea butter to a number of large cosmetics firms (Yves Rocher, Body Shop, OLVEA, L'Occitane en Provence, etc.). The World Agroforestry Centre (ICRAF) made the innovative choice of focusing on the use of *Vitellaria paradoxa* germplasms. Germplasms are living tissues – a seed or other plant part, such as a leaf, a piece of stem, pollen or even just a few cells – from which new, genetically identical plants can be grown. Germplasm selection is based on variations in fat composition across the shea distribution area. Taking into account the huge variability observed in morphological and chemical traits of shea products (wood, leaves, fruits, nuts), combined with a lack of knowledge about genetic and environmental factors impacting them (Jahurul et al. 2013, Lovett and Haq 2000a, Maranz and Wiesman 2003, Sanou et al. 2006, Ugese et al. 2010), this is a long-term bet on the benefits of uniformity, which is expected to ensure consistent yields and make management easier (Lovett and Haq 2000b, Sanou et al. 2004). Gene flow and seed dispersal are much higher today than 100-150 years ago because of the increase in parkland area (Kelly et al. 2004). Genetic variation of agronomic, chemical and morphological traits has been estimated at 70-85% within shea populations (Maranz et al. 2004b, Sanou et al. 2006), highlighting the high variability in the quantity and quality of harvests (Lovett and Haq 2000a). On the other hand, this wide range of genetic diversity offers many opportunities for varietal selection to preserve desirable traits and thus improve shea products, depending on ecological locations, traditional management practices and target products. Scientists should draw on local knowledge to identify and characterise desirable traits to be selected since local people have a strong knowledge of shea morphotypes that are significant in the quality and quantity of the different shea products (Sandwidi et al. 2018).

While the difficulties noted above stem from the trees' late maturity, slow growth and high variability in traits and output, there is also a lack of knowledge on the impacts of environmental factors, especially climate change, and of plot and tree management on shea tree functioning and products, as well as on the species' ability to resist or adapt to these two pressures. According to Maranz (2009), the northern limit of the shea tree's distribution area is 13.4° N, which is 130 km south of documented occurrence 1,000 years ago (15°N). The sharp drop in rainfall since the 1960s in West Africa (Mahé and Paturel 2009, Nash et al. 2016) has stranded anthropogenically distributed species beyond their rainfall tolerance limits (Maranz 2009). However, as shea trees avoid regularly flooded areas, excessive moisture would not be favourable to the species' growth (Serpantié et al. 1996). At the regional scale, a land-use suitability map was developed by Naughton et al. (2015) from the following eight parameters: land use, temperature, precipitation, elevation, fire, Normalized Difference Vegetation Index (NDVI), soil type and soil drainage. It could be used as a first regional estimate of the most suitable areas to plant shea or maintain existing trees. However, most of the required studies on the species' functioning and its adaptative traits remain to be conducted.

Constraints due to social and cultural features

Shea products are still exploited at a small scale in a traditional way, and shea parkland management remains neither controlled nor sustainable (Ky et al. 2009). The key drivers of farmers' interest in intensification of shea production are their perceptions of the benefits that would arise from the low cost and minimal cash required to establish the trees. Currently, in West African parklands, tree density depends on balancing crop-yield decline due to competition for light, water and nutrients against the multipurpose products and other services provided by trees. However, density also varies according to the degree of social, economic and environmental priority that farmers and rural communities give to the products and other services provided by shea parklands (Kiptot et al. 2014, Mbosso et al. 2015). Consequently, previously to any intensification forecast, it is increasingly apparent that farmers' priorities, attitudes, skills and assets need to be analysed (Bandura 1977, Faye et al. 2011, Sanogo 2014, Sanogo et al. 2017). Appropriate economic models, such as the one-year planning horizon farm household model called ANDERS (Agricultural aNd Development Economics model for the gRoundnut basin in Senegal), should simulate the impacts of scenarios on farm and household incomes to identify those that maximise income and as such are more likely to be implemented by farmers (Sanfo and Gérard 2012).

At the social level, a crucial issue for shea production is that although women are often responsible for managing trees at the early stages of establishment and control shea collection, nut processing, and nut and butter trade, in many contexts they have less access than men to productive resources and opportunities such as land, labour, education, extension services, financial services and technology. Although productivity, spacing and shading effects remain the main factors influencing the decision to conserve, improve or plant shea trees in fields, planted – and probably also improved – trees have a crucial tenure security value. Women are rarely as likely to own land as men, and female-headed households often have less land than male-headed households (Sanogo et al. accepted). As regards tree tenure, men and women have separate rights to different parts of the tree. Women's rights are mostly confined to "byproducts" considered secondary with less significant economic importance. When "byproducts" become valuable, they are usually taken over by men (Kiptot et al. 2014). Moreover, in the traditional system land cannot be sold. This is why migrant land rights are also increasingly precarious, while migratory movements intensify with population increase as a short-term survival strategy. Consequently, in order to obtain maximum harvests on marginal and limited lands, isolated migrants tend to destroy shea parklands (Serpantié 1996, Serpantié et al. 1996). Farmers may, or may not, share their fruit harvest with land borrowers from the more recent migrant ethnic groups. In addition, land is generally borrowed only for a limited time, leaving the borrowers with little right to the trees, which means that trees on borrowed land are given less protection (Ræbild et al. 2007). Ethnicity and host/migrant status also confer different levels of tenure security on farming households (Elias 2013).

Regeneration of shea populations and new planting are thus limited by uncertainty about current tree and land tenure (Faye et al. 2011). More generally, land is a key determinant of Africa's agricultural and economic sustainable development, which is rarely studied and almost never taken into account in shea intensification plans. The characterisation of the governance frameworks (laws and customary rights combined), institutional arrangements and policies impacting shea parkland management at territory scale is also an indispensable step in co-building realistic governance and land tenure arrangements with a focus on resolution of land and resource tenure conflicts (Ostrom 2003). The fact is that current policies do not always facilitate change. For instance, shea is listed as an endangered and protected species, so pruning is often forbidden by forestry laws, while removal of trees from crop fields is encouraged by most ministries of agriculture in order to allow mechanised cropping (Lovett and Haq 2000b). Official and customary rights of access to – and use of – land and renewable resources (agricultural, tree, etc.) are negotiated and controlled at the territory scale (Le Bris et al. 1991). Sociological surveys, focus groups and a participative livelihood approach at territory scale should help to encourage the adoption of scientific and local evidence-based intensification scenarios developed with – and selected by – stakeholders, including local governance arrangements providing a favourable economic environment to farmers who want to get involved in shea intensification.

Shea tree agronomic and environmental performance

In addition to the numerous provisioning services noted above (income, nutrition, medicine, construction and tool timber, energy, etc.), shea trees, like other agroforestry species, provide crucial agronomic and environmental services that are linked together and that only recently have started to be quantified. The reason is that mineral fertilisers are expensive, beyond the means of most smallholder farmers, and unsustainable. Yet the area under trees constitute "fertility islands" that enhance soil fertility and water infiltration. In addition, perennial cover reduces erosion, enhances biodiversity, buffers climate variations and sequesters more carbon than crops alone, thus helping to mitigate the effects of climate change and contributing to the adaptation of agriculture. At the scale of crop field plots, however, there is an upper threshold of tree density at which the system switches from being a state of facilitation, which ensures higher and/or more stable performance of the system, to being a state of competition for resources, which makes crop performance start to decrease (Bayala et al. 2013, 2015, Ong and Leakey 1999). This threshold needs to be quantified by experimental field data recording the levels and the direction (increase/decrease) of shea tree impacts on resources at the tree and plot scales, according to the very diversified situations occurring within the shea distribution area. Moreover, from the perspective of climate change, shea parklands' contribution to the environment at the plot to landscape scales is far from fully investigated (Bayala et al. 2015). In the present context of environmental consciousness and ecological sustainability, the role of shea agroforestry intensification as an environment-friendly alternative to conventional intensification for achieving sustainable food security needs to be properly addressed and explored. In addition, many of the environmental impacts that are enjoyed by society at the regional or global scales derive from plot management at the farm scale, to reap agronomic benefits, and from land use at the landscape scale (Shibu 2009).

Impact of shea trees on light resources

In terms of environmental performance, the filtration of sun radiation by shea tree canopies provides an understorey microclimate that significantly buffers temperature variations expected from climate change. However, in terms of agronomic performance, shea canopy has been indicated in most of the studies as causing a decrease in understorey crop yield. Photosynthetically active radiation (PAR) was found on average to be 25-47% less under the canopies of shea trees than outside the canopies (Bayala et al. 2002, Bazié et al. 2012, Boffa et al. 2000, Rao et al. 1998), with highly variable impacts observed on associated crops. A decrease of 35-50% was observed in millet and sorghum yields within three metres from the trunk (Bagnoud et al. 1995, Serpantié et al. 1996), and of 15-65% in underneath sorghum and pearl millet yields (Boffa et al. 2000, Gnanglé et al. 2013, Kater et al. 1992, Kessler 1992), while sorghum plants were 10% shorter (Gnanglé et al. 2013). The grain yield of maize was estimated to be reduced by 45% and its straw yield by 30% (Saïdou et al. 2012). No reduction was observed in cotton yield by Kater et al. (1992), while other authors observed cotton plants 6% shorter, with bud production down 13% and fresh biomass down 36% (Gnanglé et al. 2013). Reductions of 28% in number of cotton bolls plant^{-1}, of 27% in number of branches bearing cotton bolls plant^{-1} and of 24% in number of plants m^{-2} were estimated by Gbemavo et al. (2010). As a corollary to the reduction of light by shea canopy that leads to reductions in associated crop yields, shea crown pruning increases grain and straw yields by 520% and the height of sorghum plants by 348%, improving this crop's performance two- to five-fold (Saïdou et al. 2012). At the plot scale, sorghum grain production was found to be higher in parklands with mean shea canopy radii of 225 to 275 cm and average densities of 12 and 31 trees ha^{-1} than in crop fields without trees (Boffa et al. 2000). Canopy pruning also reduces tree demand for water (significantly lower transpiration) and nutrients, and may increase the supply of nutrients to the crop root zone by inducing fine root turnover in the trees, while lowering underground competition (Bayala et al. 2002, 2004).

Parkland management should aim at optimising shea density at plot scale and canopy size at tree scale according to farmers' current priorities regarding the trade-off between the additional income provided by shea products and yield loss.

Impact of shea trees on water resources

In terms of agronomic performance, the results are paradoxical. Macroporosity coming from the tree roots' growth, litterfall and dripping along trunks and stems improves infiltration, while canopy shadow decreases topsoil temperature, albedo, wind speed and thus vapour pressure deficit, which limits evaporation and underneath crops' water demand, but consequently curbs their photosynthetic activity, and hence their height and yield as well (Boffa et al. 2000, Rao et al. 1998, Saïdou et al. 2012, Serpantié et al. 1996). In the laboratory, Ibrahima et al. (2008) found that the maximum imbibition capacity of shea litter was reached after three days, and its variation was highly significantly (R^2=0.95) fitted to an exponential model illustrating relatively slow absorption. However, the maintenance of too much humidity may also reduce biomass production and yields of associated crops, especially under the wettest climates (Coulibaly et al. 2014).

In terms of environmental performance, such as reacting to weather conditions, trees contribute to surface water balance through evapotranspiration, the photosynthetic process playing an important role in the regulation of water uptake from the soil and its release into the atmosphere (Tia 2008). According to Ong and Leakey (1999), a properly managed agroforestry system could recycle up to 30-45% of rainfall by vegetation transpiration. Such levels of rain use efficiency (RUE) are rarely achieved in African agroforestry parklands because of extensive (low-productivity) farming practices. Consequently, there are broad opportunities for raising RUE by increasing tree densities in parklands, as shea trees occur generally in low densities of 5-10 trees ha^{-1} (Kessler 1992). However, tree transpiration is difficult to estimate and highly variable according to climate, season, tree size and land use. Awessou et al. (2017) estimated the range of daily transpiration of a shea tree (DBH 8-38 cm) to be 4.4-26.8 l day^{-1}, and 15% lower in the dry than in the rainy season, in a fallow receiving 1,200 mm $year^{-1}$ of average annual rainfall. Upscaled to the transpiration of the shea cover in the same fallow, Awessou et al. (accepted) found a very low value (0.03 mm/day), corresponding to 0.42-1.32% of the atmospheric demand estimated by reference evapotranspiration Eto and only 1.15% of annual rainfall. Compaoré (2006) estimated this value at about 79 l and 32 l day^{-1} at the beginning and end of the dry season respectively, in a fallow receiving 700-1,100 mm $year^{-1}$ of rainfall, and Bayala et al. (2008a) at 121 l day^{-1} in trees with

DBH of 64 cm in a parkland receiving 700 mm year^{-1}. Smaller leaf size observed in more arid conditions is a probable adaptation that limits tree water loss while decreasing soil moisture consumption (Lovett and Haq 2000a).

Lastly, “hydraulic redistribution” is nocturnal water flow from the deep, wetter soil layers along the tree roots and its redistribution in the drier upper layers. It is thought to occur in most woody species in dry tropical areas as an adaptation to drought (Caldwell et al. 1998, Ludwig et al 2003, Ryel et al. 2003). Bayala et al. (2008a) estimated that the amount of redistributed water would be approximately 73.0 l day^{-1} for one shea tree (DBH 64 cm), which would represent 60% of the transpired amount. However, further knowledge is required on the extent of such transfers and specific conditions suggesting tree facilitation of associated crops’ access to resources below the crops’ rooting zone.

Impact of shea trees on carbon and nutrients

The carbon (C) sequestration potential of agroforestry systems has attracted worldwide attention since the Kyoto Protocol recognised such systems as an efficient strategy for greenhouse gas mitigation. In terms of environmental performance, available results vary according to shea stand characteristics and to which C compartments are considered. Takimoto et al. (2008) estimated the total C stock (biomass C + soil C in the layer 0-100 cm) in shea parklands at 50 t ha^{-1} of which the percentage of soil C stock alone corresponds to 55%. Including root and soil C, a maximum of 7.5 t of C ha^{-1} was estimated by Peltier et al. (2007) in parklands of 30 trees ha^{-1} on average. In denser shea parklands (50-100 trees ha^{-1}), Dayamba et al. (2016) estimated that the C stock did not differ from the community-managed forests (56-67 Mg ha^{-1}, 1Mg=1.10 t), and that more C was sequestered in parklands than in four- to six-year-old fallow lands (5-9 g kg^{-1} of soil). In the same way, Sanogo et al. (2016) found that aboveground sequestered C was higher in parklands than in fallows and protected areas (0.07-0.11, 0.05-0.07 and 0.06 Mg ha^{-1} yr^{-1} respectively). These results support the idea that shea parklands may be a good alternative to deforestation for greenhouse gas mitigation.

In terms of agronomic performance, shea tree impacts on soil fertility, across spatial and temporal scales, result mainly from litterfall production and fine root decay, which can potentially be optimised within shea agroforestry systems (Bayala et al. 2003, 2005, Dayamba et al. 2016, Gnankambary et al. 2008a, Rhoades 1997). The chemical and physical nature of the litter alters decomposition and nutrient availability via controls on soil water and the physiology of soil fauna involved in litter decomposition. Redistribution beneath tree canopies occurs through extensive lateral roots (Rhoades 1997) and litter transport by the wind. Thus, litter with low N content like that of shea trees, which may contain higher recalcitrant carbon, decomposes less rapidly than litter with high N content (low C:N ratio) such as that of *Faidherbia albida* (Gnankambary et al. 2008a) or *Parkia biglobosa* (Bayala et al. 2005). Nevertheless, the results of most studies indicate that shea litterfall improves soil fertility by increasing organic matter, total and available nitrogen, total and available potassium, total and available phosphorus, and pH (Clermont-Dauphin et al. accepted, Gnankambary et al. 2008b, Saïdou et al. 2012, Traore et al. 2004, Verbree et al. 2015). In laboratory conditions, loss of half of the shea litter mass occurred within three days (72 hrs) of leaching incubation, while the initial water-soluble sugar content (12.63%) – a relatively high proportion compared to some other Sudanian agroforestry species – dropped to 2.46% after 15 days. Cellulose, 1.46% initially, increased to 7.16% after 15 days, while lignin, 1.05% initially, increased to 4.69% (Ibrahima et al. 2008). Allelopathic effects observed by Bayala et al. (2003) are thought to be due to shea's high concentration in phenolics. However, sequestration of organic carbon depends also on climate and soil conditions that impact the speed of organic C decomposition (Takimoto et al. 2009). Finally, mixing lower-quality organic residue (high C:N ratio) with labile tree leaf material is a promising option that can contribute to better synchrony between nutrient release and crop demand by shunting nutrients into microbial biomass (Gnankambary et al. 2008a). Nutrient release would thus be gradual rather than pulsed by the first rains of the rainy season (Bayala et al. 2005, Rhoades 1997).

Proposal of a multidisciplinary research-development approach

The dense canopy of shea trees generally limits light resources for associated crops, thus decreasing associated crop production; however, soil fertility (water, organic carbon, nutrients) increases around shea trees, which is favourable to crop production if trees are pruned to eliminate the constraint on light resources (Figure 2). In addition, tree pruning reduces belowground competition linked to associated fine root reductions. However, the strength of this trend, i.e. the intensity of the processes involved, depends on many local to global drivers, which are social and economic as much as environmental and biological in nature. Modelling seems the only tool able to simulate the processes and mechanisms involved in shea parkland agronomic and environmental performance according to its drivers (environment, management) from data collected in the field (trials, observations, measurements, experiments) from only a few environmental situations. In this respect, devices used to study other parklands or agronomic systems in dry tropical Africa or in other tropical areas should be useful in studying shea's contribution to the resource budget and yields in shea parklands, but also in estimating its environmental performance under different climate and management scenarios. Most biophysical and agronomic studies currently place the emphasis on the plot scale to predict the effect of changes in tree density and distribution pattern, mix and tree size, species mix, or that of plot management on parkland production drivers (soil, microclimate) and on environmental performance (carbon sequestration, energy and water balances).

In terms of agronomic performance, the WaNuLCAS model (Water, Nutrient, and Light Capture in Agroforestry

Systems) has recently been used in Burkina Faso to identify the most limiting factors in the association of trees with annual crops by comparing various management options simulated under different climate scenarios (Coulibaly et al. 2014). Agronomic diagnoses (Clermont-Dauphin et al. 2016) that compare yields under different tree and plot management practices, along with different tree densities, would help to parameterise and validate crop growth models such as CELSIUS (CEreal and Legume crops SImulator Under changing Sahelian environment, Ricome et al. 2017), APSIM, SARRA-H (Guan et al. 2017, Sultan et al. 2013) or simple ad hoc PYE (Potential Yield Estimator) crop simulation models (Affholder et al. 2013).

In terms of environmental performance, future investigators are invited to build devices combining observations and measurements of the functioning of the various components of shea parklands; to use eddy covariance (micro-meteorological tower) to measure exchanges of carbon dioxide, water vapour and energy between the terrestrial surface and the atmosphere at the plot scale; and to use SVAT modelling (Soil Vegetation Atmosphere Transfers) to quantify processes and flux in other situations (environment, management). However, eddy-covariance flux towers are very scarce in Africa compared to other continents (Falge et al. 2017). These multi-scale devices are currently in use in West Africa, but in agrosystems other than shea parklands: the Sahelian agro-pastoral system in south-west Niger (Boulain et al. 2009, Issoufou et al. 2013, accepted, Velluet et al. 2014), the system in Sudano-Guinean (northern) Benin (Ago et al. 2016, Awessou et al. 2017, Mamadou et al. 2014, Seghieri et al. 2009), and two systems in pastoral Sahelian sites in Senegal (Tagesson et al. 2015, 2016) and in Mali (Mougin et al. 2009, Seghieri et al. 2009, 2012). Examples of SVAT models that may be used are SiSPAT (1D) modelling (Simple Soil–Plant–Atmosphere Transfers) already used in millet-*Guiera senegalensis* agroforests (annual crop) in Niger (Velluet et al. 2014) or MAESPA (3D) already used in coffea agroforests (perennial crop) in Costa Rica. These two models couple radiative transfer, photosynthesis, and energy and water balances at the plot scale. MAESPA is able to simulate the partitioning of evapotranspiration in heterogeneous multi-species, multi-strata agroforestry systems with diverse spatial scales and management schemes (Charbonnier et al. 2017, Vezy et al. 2018). Remote sensing makes it possible to upscale results obtained at the plot scale (Leroux et al. 2016) since such devices will probably be widely deployed within the shea parklands distribution area, unless their cost is prohibitive.

In addition, biophysical models are now coupled with economic models in order to integrate the complex human-mediated processes (Ricome et al. 2017, Sanfo et al. 2017). This bio-economic modelling may be used to assess the economic, agronomic and environmental performance of shea and other parklands according to various driver trajectories (climate, demography, policies, markets).

Despite the multiple benefits shea trees provide, and even if the environmental carrying capacity would support more trees in crop fields, this knowledge alone will not convince small farmers to plant and protect trees if they face heavy constraints (such as insecure land tenure) and/or if they have other, often short-term food and income priorities. As seen above, access to resources from shea parklands also depends on how parklands and trees are governed by political, cultural, economic and social systems. For sustainable intensification of crop production as well as increased farm income and better environmental performance of shea parklands, intensification scenarios must give weight not only to ecological processes that enhance environmental and agronomic performance but also to existing contextual adaptive practices across the diversity of ecological, technical and socio-economic conditions, knowledge and agricultural systems in the shea distribution area. To maximise and sustain their adoption, innovative scenarios for managing sustainable intensification of shea parklands must be co-built with stakeholders through a participative approach (Cabot 2017, Sanogo 2014, Sanogo et al. 2017), with scientists providing the elements needed to simulate (model) them, with impacts on economic, agronomic and environmental performance as outputs.

To summarize, we propose the following multidisciplinary approach (Figure 3), which combines field experiments, measurements, observations, surveys and participative modelling of economic, agronomic and environmental performance of shea parklands according to their drivers, in a innovation platform including two scales:

1) The farm scale, with farmers, through participative bio-economic modelling based on process-driven agronomic, environmental, economic and social diagnosis and performance from the plant to the farm scale, combined with contextual local knowledge. Bio-economic models allow simulations of parkland intensification scenarios (densification, new tree management techniques, introduction of new species, etc.) proposed by farmers, thus estimating the impacts on farm incomes and environmental performance. Biophysical and agronomic studies will provide parameters for the “bio” part of the model, while social and economic studies will provide its economic part, according to shea parklands’ drivers and the short- and long-term trade-offs between provisioning services (food security) and other socio-ecosystem services. In addition, wherever the economic data are insufficient to drive economic models, participative livelihood approaches can investigate scenario feasibility (Adger 2006, Turner et al. 2003), assessing the impacts of shocks (climate, volatility of commodities prices, population growth, soil degradation) on livelihoods, as well as farmers’ capacity to change their current practices.

2) The territory scale, with relevant stakeholders – local and national government and customary authorities, harvesters and producer groups, “social cadets” (e.g. women, youth, migrants), value chain businesses, NGOs, etc. – in a participative approach to co-build realistic governance and land tenure arrangements supporting intensification initiatives by motivated farmers.

This approach can be used not only for shea but for all other tropical agroforestry parklands in small-farmer production systems. It will be tested in the project Leap-Agri ERA-NET Cofund (http://www.leap-agri.com/) on the Roles of Agroforestry in sustainable intensification of small farMs and food SEcurity for SocIetIes in West Africa (RAMSESII 2018-2021).

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Figure captions

Figure 1: Change in shea parkland area (black line) and shea nut yield (grey histogram), 1961-2016, after FAOSTAT food and agriculture data http://www.fao.org/faostat/en/#data/QC accessed 23 April 2018.

Area (black line) refers to the area of cultivated parklands. Area under cultivation corresponds to the total shea production area, but after the harvest it excludes ruined areas (e.g. due to natural disasters). Some countries provide data in terms of number of trees instead of area. This number is then converted to an area estimate using typical planting density conversions.

Yield (black histogram) illustrates the harvested production per ha for the area under cultivation.

Figure 2: Schematic of the shea tree impacts on resources and associated crops most often reported in the scientific literature. When a shea tree is pruned, crop production benefits from the “fertility island” effect of the tree.

Figure 3: Systemic and participative modelling approach proposed for further studies on shea parklands with a view to intensification of production.

Figure 1

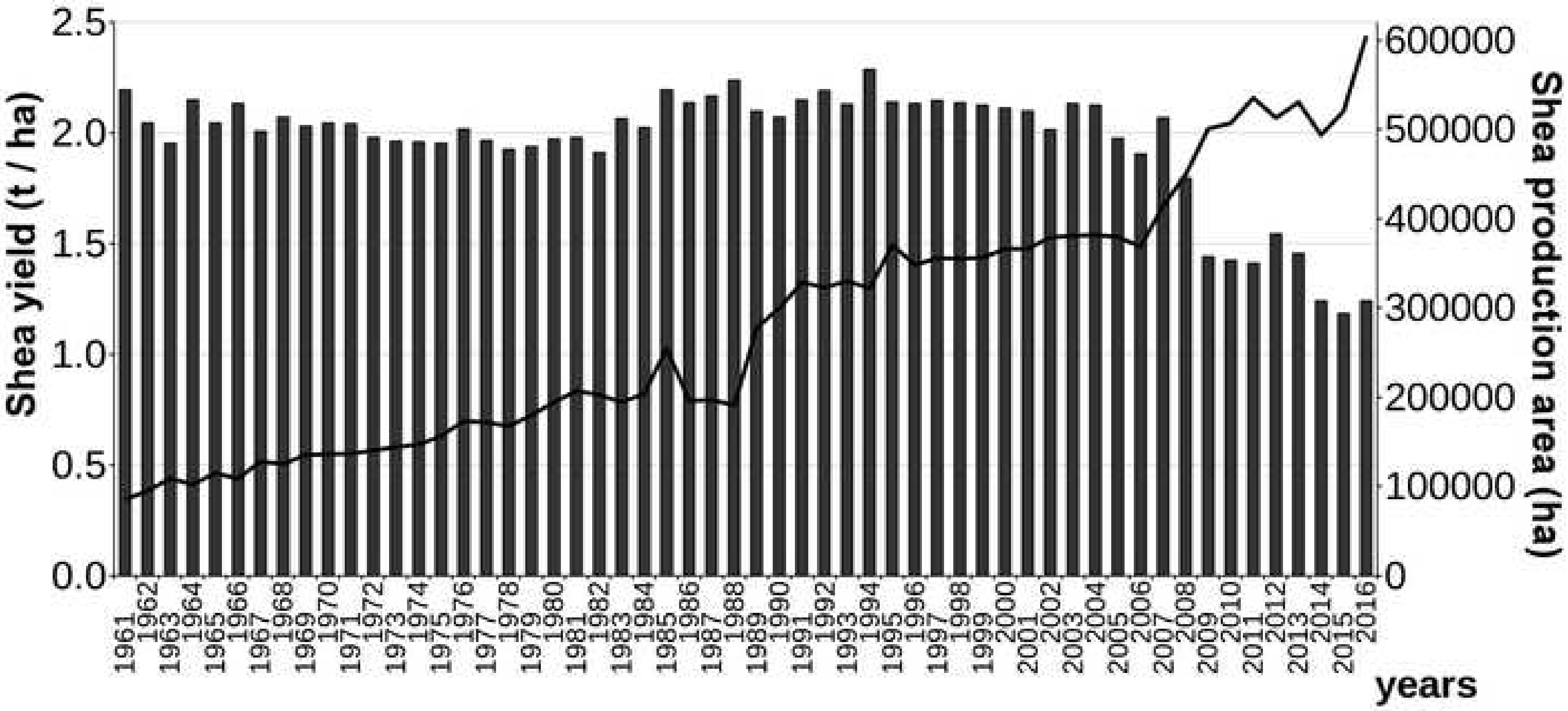
Shea yield (t / ha)
2.5
2.0
1.5
1.0
0.5
0.0
Shea production area (ha)
600000
500000
400000
300000
200000
100000
0
years
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Figure 2

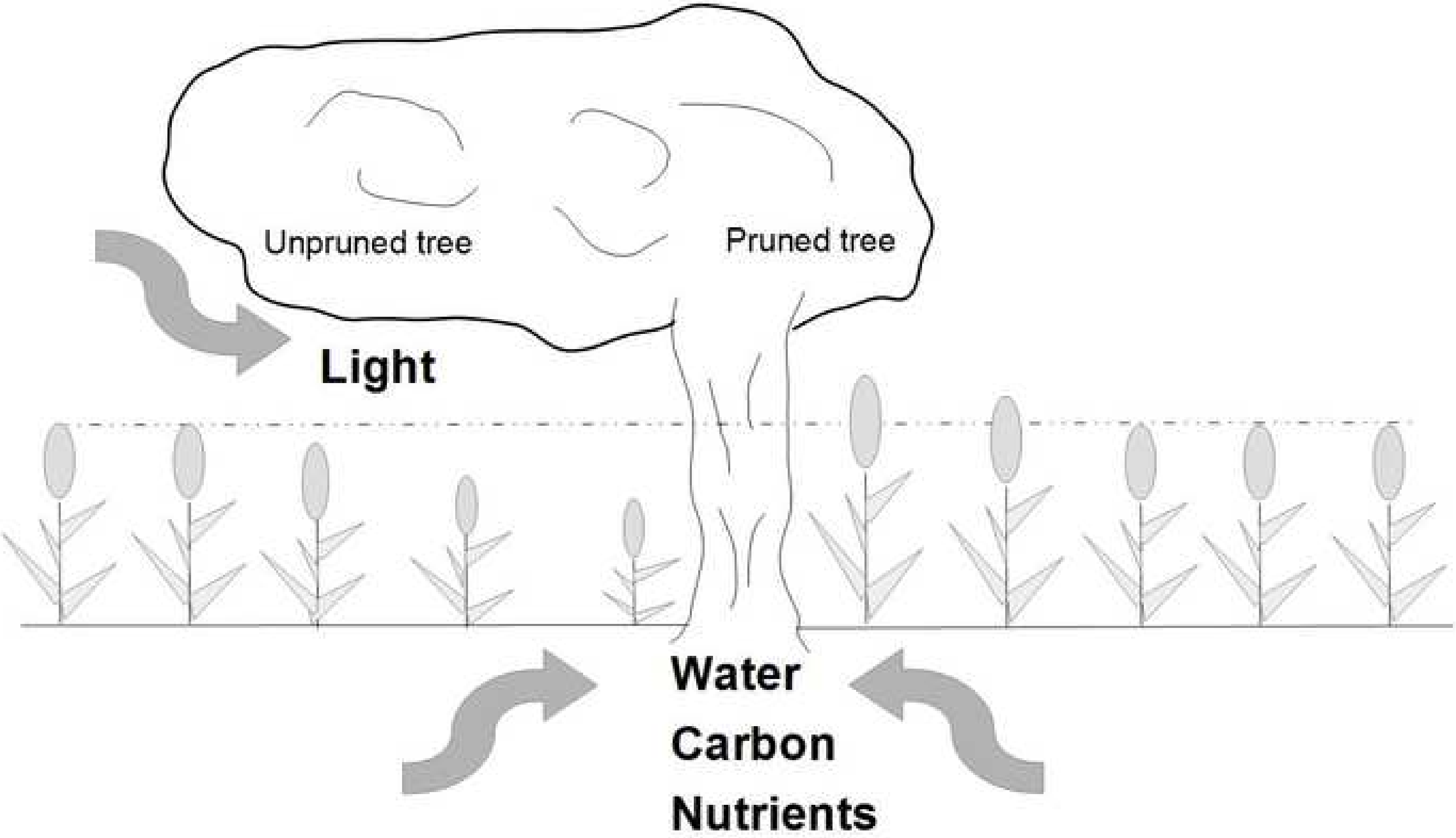
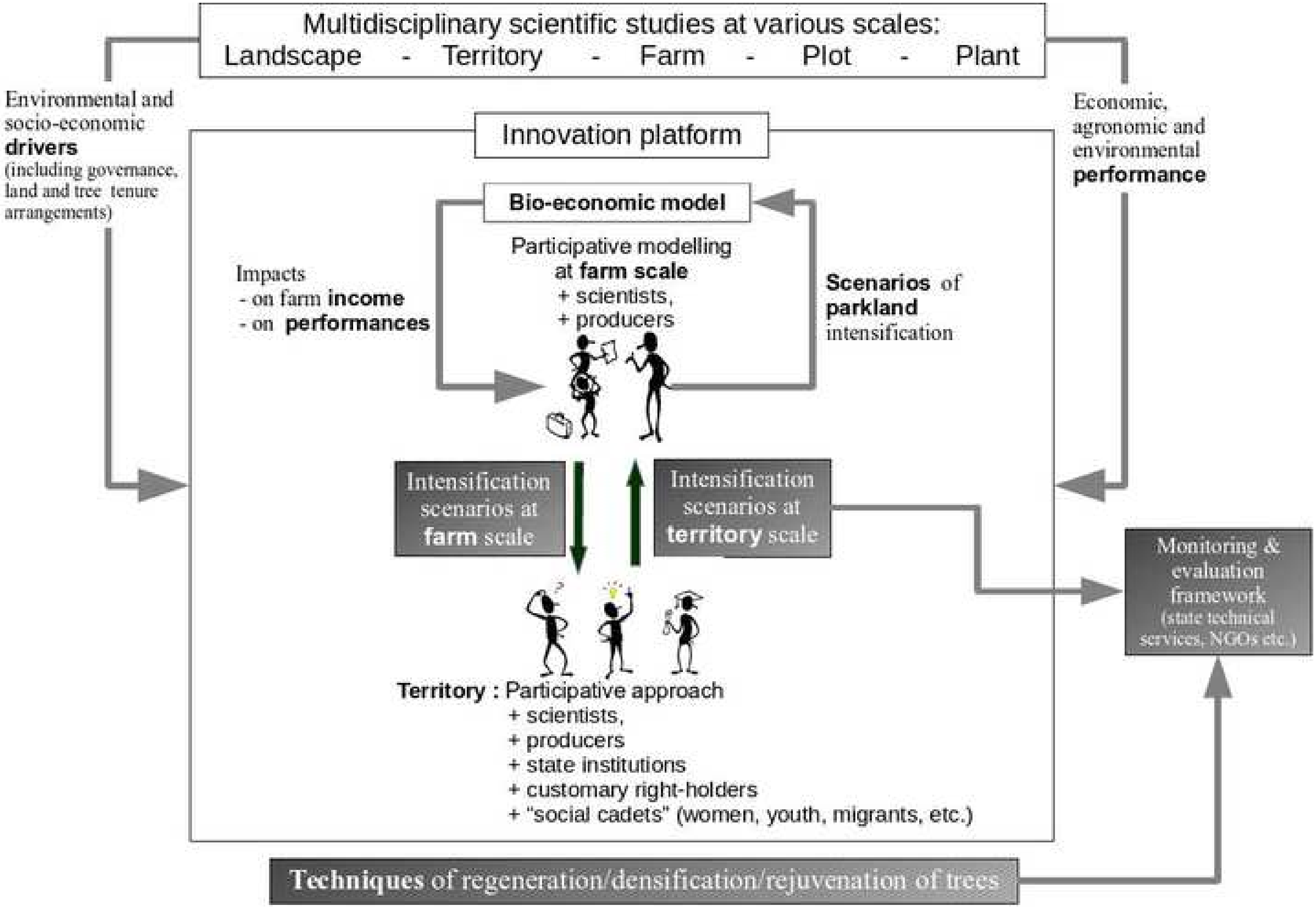


Figure 3


Multidisciplinary scientific studies at various scales:
Landscape - Territory - Farm - Plot - Plant
Environmental and socio-economic **drivers** (including governance, land and tree tenure arrangements)
Economic, agronomic and environmental **performance**
Innovation platform
Bio-economic model
Participative modelling at **farm scale**
+ scientists,
+ producers
Impacts
- on farm **income**
- on **performances**
Scenarios of **parkland** intensification
Intensification scenarios at **farm** scale
Intensification scenarios at **territory** scale
Monitoring & evaluation framework (state technical services, NGOs etc.)
Territory : Participative approach
+ scientists,
+ producers
+ state institutions
+ customary right-holders
+ "social cadets" (women, youth, migrants, etc.)
Techniques of regeneration/densification/rejuvenation of trees