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Use and management of biodiversity by smallholder farmers in semi-arid West Africa

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ABSTRACT

Strategies that strengthen and use biodiversity are crucial for sustained food production and livelihoods in semi-arid West Africa. The objective of this paper was to examine the role of biodiversity in sustaining diverse forms of multifunctional farming practices while at the same time providing ecological services to subsistence-oriented farming families in the region of study through mechanisms as (a) crop species diversification, (b) management of spatial heterogeneity, and (c) diversification of nutrition-sensitive landscapes. Our analysis shows that crop associations between cereals and legumes or between perennials and annuals, have overall positive effects on soil characteristics and often improve crop yields. Soil heterogeneity is produced by woody perennials and termites. Local management provides opportunities to collect a diversity of nutrition-rich species year-round and sustain household nutrition.

1. Introduction

Management of biodiversity is the cornerstone of agriculture. Historically, the perspective of 'ecology in agriculture' was introduced by Hanson (1939), underlining the need for ecologists to broaden the spectrum of study from wild native plants to domesticated, exotic, and cultivated crops. Agroecological 'theory' suggests that the strategic use of locally-available biological diversity (cultivated or wild) is key in supporting ecological functions and maintaining food cultures (Gliessman, 2011). A growing body of knowledge recognizes the importance of anchoring these designs in local food cultures and household objectives (Duru, 2013; Luckett et al., 2015; Bellon et al., 2016; Nicholls et al., 2016), and of integrating scientific and local farmer knowledge in the co-design of more sustainable farming systems (Dogliotti et al., 2014; Speelman et al., 2014; Geertsema et al., 2016; Garibaldi et al., 2017).

Rain-fed agriculture in semi-arid West Africa (SWA) is characterized by soils that are naturally poor in nutrients and organic matter content. Production indices for countries of semi-arid West Africa show increases in total staple food production yet average yields for local consumption remain alarmingly low, below 1 t ha^{-1} (www.faostat.org). While food security assessments and recommendations often focus on increasing production of staple food crops (i.e. cowpea, millet, sorghum, rice), it is unlikely that smallholder farmers in SWA sustain on grains exclusively. The strategic use of locally-available biological diversity (cultivated or autochthonous) is key in the design of agricultural management systems able to (1) produce sufficient food and ecosystem services, (2) diversify diets to meet food security and nutrition, and (3) support and sustain local food systems. In particular, woody perennial vegetation in Sahelian ecosystems provide an array of services to farming families, from the regulation of on-farm and landscape ecological processes to supporting local livelihoods (Sinare and Gordon, 2015). Despite a wide diversity of initiatives to cope with erratic environmental and market conditions (West et al., 2008; Sissoko et al., 2010), financial constraints and low institutional support rarely help in recognizing smallholders as innovators with valuable expertise to share with peers.

Farming practices that include biodiversity make use and simultaneously generate sources of spatial and temporal resource heterogeneity at various scales having consequences for soil functions, food

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production, and habitat provision for wildlife (Tittonell et al., 2015). At regional scales, several environmental characteristics may shape landscapes. These include biophysical aspects, such as heterogeneous soil types and topography (i.e. lowlands and salinization), soil fertility hotspots (i.e. termite nests or presence of woody perennials), and anthropogenic drivers such as accumulation of organic matter around household compounds (i.e. biomass transfers of woody or organic amendments and plant associations) (see Fig. 1).

Moreover, it is common in SWA to encounter different types of actors in farming territories, including pastoralists (nomadic or sedentary), market-oriented farmers (cotton, horticulture), and subsistence-oriented farmers (cereals, legumes, wild edible plants) (Diarisso et al., 2015). These actors use and manage biodiversity following food and livelihood objectives in different ways, but mainly through the combination of plant and animal species, the spatial and temporal management of fields and natural habitats, or through the direct collection of wild foods, medicinal plants and other resources from their landscape.

The objective of this paper is to examine the role of biodiversity in sustaining diverse forms of multifunctional farm and food systems and in providing ecological services. This is done through the analysis of farmer-driven (i) plant species diversification, (ii) management of spatial heterogeneity at field level and (iii) strategic use of nutritional functional diversity at landscape level. Illustrations and quantitative examples are built with own research data from semi-arid Burkina Faso.

2. Management of plant species diversification

2.1. Annual plant associations

Annual plant association or intercropping is an ancient and widespread agricultural practice in semi-arid West Africa (Mbaye et al., 2014). It consists of establishing two or more crops with overlapping development cycles simultaneously on the same plot during the same season (Zongo, 2013), with the objectives of diversifying and/or securing agricultural production and integrated fodder systems, but also for the improvement of soil fertility, weed-growth control, labour reduction, and intensive management of the available land (Essecofy, 2011; Karim et al., 2016). In traditional farming systems, the geometric arrangement of cultural associations may vary widely, from crops grown in different rows, or alternated within the same row, to distributed randomly without a specific geometric arrangement (Table 1). Associated crops can be sown in the same planting hole, as well (Zongo, 2013), or planted at different growth periods according to expected outputs or functions. The most represented combinations were cereals

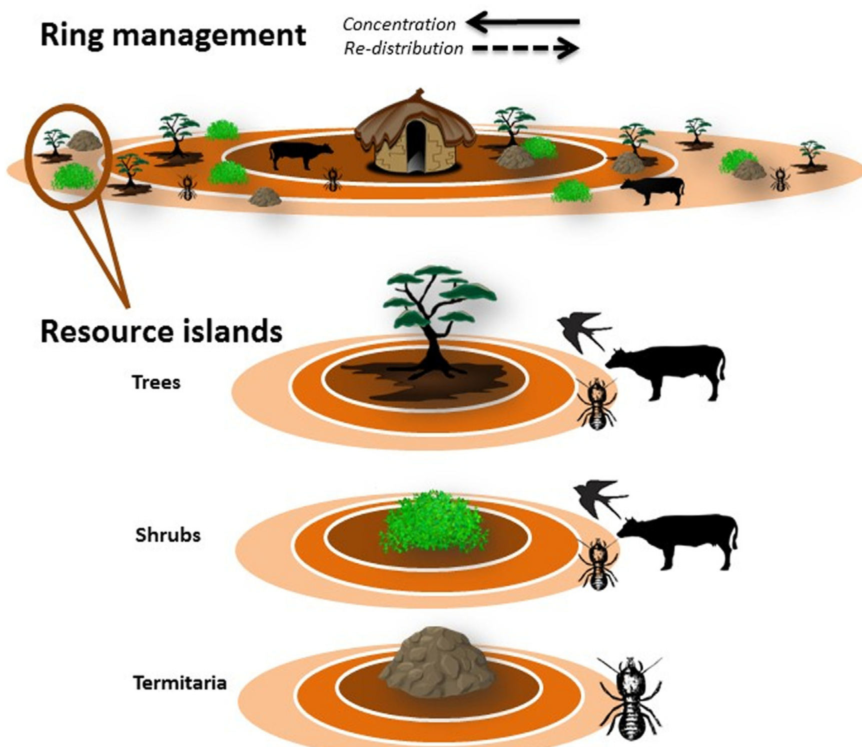

Fig. 1. Ring management results in continuous soil fertility gradients, catalysed by biodiversity management at the landscape level. Nested rings are formed by trees, shrubs, and termite nests constitute 'resource islands' that provide conditions for other organisms to thrive.

Table 1
Examples of spatio-temporal arrangements in intercropping practices of West Africa.

Location	Author	Cereal component	Associated legume component
Sub-humid Senegal	Diangar et al. (2004) ; Mbaye et al. (2014)	Millet (2 rows; 100 x 90 cm)	Cowpea (1 row; 10-15 days after; 100 x 60 cm)
Burkina Faso	Sanou et al. (2016)	Millet (1 row; 80 x 60 cm)	Cowpea (1 row; 80 x 40 cm)
Sahelian zone	Sarr et al. (2009)	Millet (1 row; 150 x 50 cm)	Cowpea (2 rows; 50 x 50 cm)
	Garba (2007)	Millet (1 row; 100 x 80 cm)	Groundnut (1 row; 100 x 30 cm)
		Sorghum (1 row; 100 x 80 cm)	Cowpea (1 row; 10 days after; 100 x 50 cm)
		Maize (2 rows; 80 x 50 cm)	Cowpea (1 row; 10 days after; 80 x 50 cm)
		Maize (2 rows; 120 x 80 cm)	Groundnut (2 rows; 10 days after; 40 x 15 cm)

(sorghum, millet, or maize) associated to legumes (cowpea, groundnuts, or Bambara nut-*voandzou)*. Some associations may also include cereals and forage legumes (cowpea, *Mucuna pruriens, Stylosanthes hamata, Pueraria phaseoloides*). Cowpea (*Vigna ungiculata*), for example, may be combined to millet to obtain grains in the outer fields (food security objective) or to obtain fodder biomass in the fields closest to the households (animal feed objective). Associations between grasses and agroforestry plants and occasionally, associations between grasses (*Panicum* sp., *Brachiaria* sp.) or tuberous plants (yam or cassava) with forage legumes have also been documented. Scientific literature reports more than 21 species tested for their forage potential or fertilizer properties in semiarid zones of Benin (Kouelo et al., 2014), Burkina Faso (Coulibaly et al., 2012) and Nigeria (Abayomi et al., 2001).

The comparative performance of crop mixtures is often assessed by calculating the land equivalent ratio (LER), or the sum of all crop yields in the mixture, weighed by their area share and divided by their respective yields when grown as monocultures (Vandermeer, 1981; Gliessman, 2002). An LER value equal to 1 means that the crop mixture performs as well as the monoculture, and values greater than 1 denote enhanced productivity of the mixture. Trail et al. (2016) showed in Senegal that millet associated with cowpea yielded 20–55% more grain than millet grown as sole crop (1500 kg ha^{-1}). They found LER values in Senegal ranging from 1.34 to 1.95 for combinations of millet and cowpea, an overall favourable outcome. Partial LER values (i.e., the ratio of each crop in the mixture to its monoculture) calculated with data from on-farm experiments during four consecutive years in Yilou, Burkina Faso (Félix et al., 2016), showed that sorghum-cowpea mixtures allow for improved LER index as compared to sole crop cultivation (Fig. 2). Average monoculture yields were 470 kg ha^{-1} for cowpea and 1000 kg ha^{-1} for sorghum. LER values greater than 1 were observed in 50% of the cases throughout the experiment (2013–2016), indicating that the performance of plant associations varies greatly, and could be influenced by date and density of sowing, soil preparation or nutrient additions. High LER values could indicate higher workload requirements yet Kermah et al. (2017) showed that grain-legume intercrops not only improve productivity per area but also make a better use of labour inputs than sole crop cultivation, especially on marginal fields.

Numerous studies in West Africa have shown that it is possible to significantly improve the yield of cereals associated with legumes by choosing methods of tillage or fertilization adapted to this type of associations (Cissé, 2013; Sarri et al., 2013; Zongo, 2013; Kouelo et al., 2014; Mbaye et al., 2014; Karim et al., 2016).

Legume-crop rotations are another means to take advantage of agricultural diversity in time. A recent review by Mason et al. (2014) compiles data from several studies in semiarid West Africa where millet- or sorghum-cowpea rotations were tested, following conservation agriculture principles (i.e. zero or minimum tillage, crop rotations or associations, and permanent soil cover). This review showed that millet grain yields increased by 10–50% in rotations with cowpea, while sorghum yields increased up to 100%, especially when environmental conditions were not favourable (i.e. control yields < 1 t ha^{-1}), and up to 20% when conditions were more favourable (i.e. control yields > 1 t ha^{-1}).

2.2. Woody perennials in cropping systems

Integration of trees within croplands is a widespread and well documented practice in West Africa (Bayala et al., 2014; Sinare and Gordon, 2015). Based on data retrieved in Bayala et al. (2014), the relative crop yield difference (in %), in presence of 9 woody species of SWA, was plotted against the relative crop yield without the influence of trees or shrubs (Fig. 3). Beneficial effects (positive values) of woody perennials on crop growth appear above the dotted line while depressive effects (negative values) are below this line.

Faidherbia albida is a well-known native species that has an inverted phenology (Vandenbeldt, 1992). Leaves grow during the dry season, providing shade and additional fodder for livestock when rainfall and grasses are scarce. Inversely, the trees remain leafless during the rainy season, allowing sufficient sunlight for crops to grow successfully nearby its trunk (Fig. 3C). Other trees such as *Parkia biglobosa* (Fig. 3E) and *Vitellaria paradoxa* (Fig. 3I), may have depressive effects on crop growth, but are kept in agroforestry parklands for their economic importance to farming families (i.e. commercial and highly-nutritious seeds/fruits). Trees and shrubs function as 'resource islands' in dry savannah ecosystems (Hernandez et al., 2015). The processes involved include above- and below-ground biomass production, which improve carbon and nutrient cycling in the vicinity of trees through organic matter transfers and in-situ decomposition of leaf litter and root material (Buerkert and Schlecht, 2013). Deep root systems pump water and nutrients from the deeper soil layers, making these available for crop plant uptake in the upper soil layers. The process known as 'hydraulic lift' increases soil moisture and promotes soil microbial communities in situ (Bayala et al., 2008; Kizito et al., 2012; Diedhiou-Sall et al., 2013; Diakhaté et al., 2016). Moreover, higher infiltration rates around perennials are likely to contribute in maximizing groundwater recharge (Bargués Tobella et al., 2014; Ilstedt et al., 2016).

Shrubs in cropping systems in SWA accumulate organic residues and nutrients around their base (i.e. organic C, total N, and total P). A series of 16 *Piliostigma* shrubs monitored in Yilou, Burkina Faso during the dry season of 2015 (Cheriere, 2015) confirmed that shrubs form a 'fertility hotspot' at their base (Fig. 4). Shrubs however did not significantly modify soil pH.

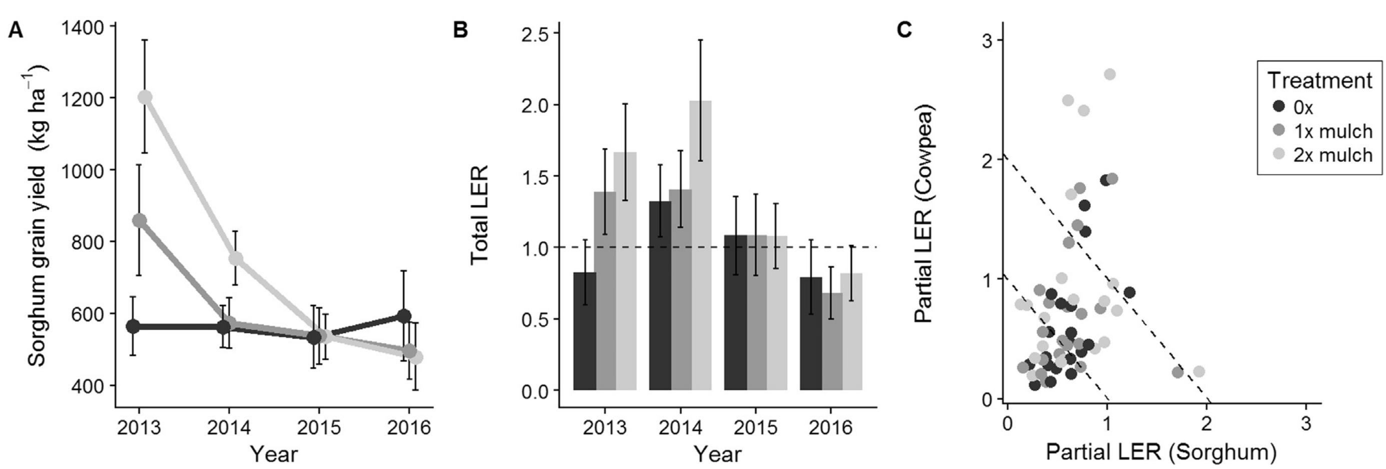

Fig. 2. On-farm experiment with varying amounts of ramial wood (RW) amendments on sorghum-cowpea intercrops (panel A). Total land equivalent ratio (LER, panel B) and partial LER for sorghum and cowpea intercropping systems (panel C). Yilou, Burkina Faso. Data adapted from Félix et al. (2016).

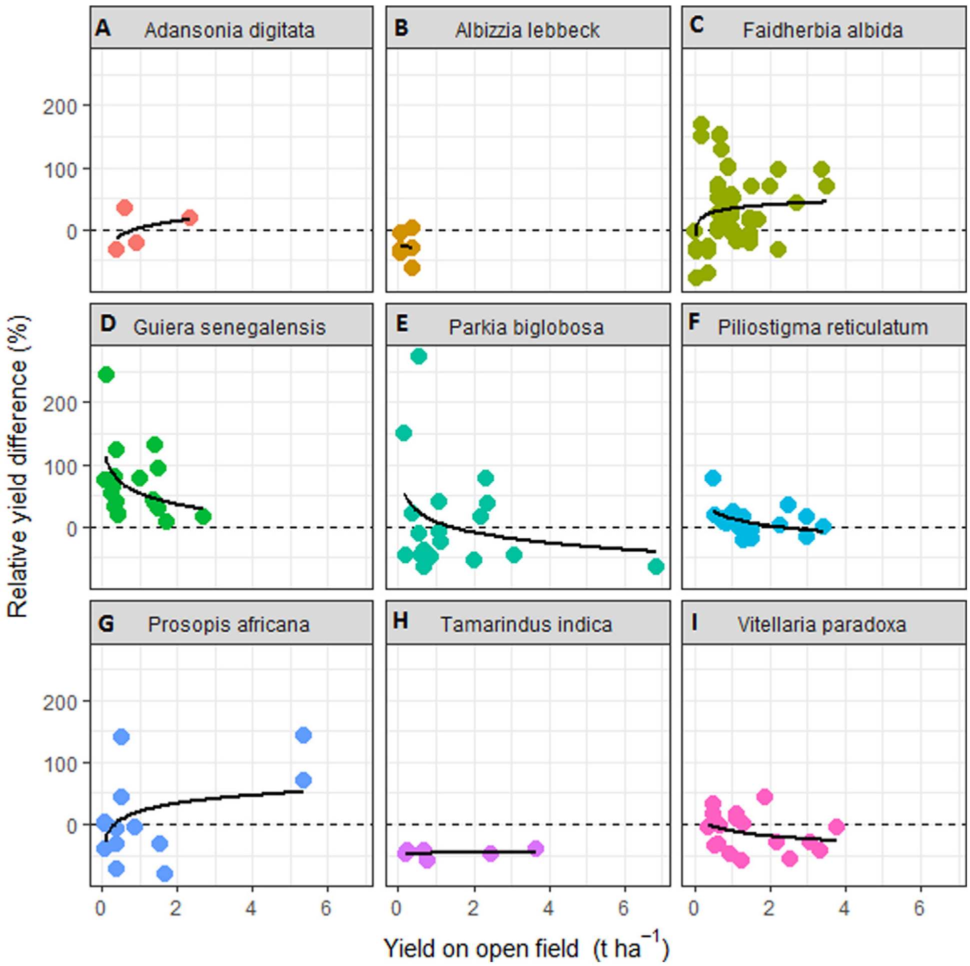

Fig. 3. Relative yield difference in the vicinity of trees or shrubs as a function of yields outside the area of influence of 9 woody species of semi-arid West Africa. Data points were fitted to exponential model to show trends for each species. Data adapted from supplementary material found in Bayala et al. (2014).

Studies conducted in Niger support the promotion of farmer-managed natural regeneration with trees as a cost-effective way of enhancing rural livelihoods, more attractive than classical reforestation efforts that tend to rely on investments in planting and seeding of native and/or exotic trees (Haglund et al., 2011). Although agroforestry systems can contribute to sustainable land use only when they are maintained over time (van Noordwijk et al., 2014), farmers in West Africa will rarely invest in planting trees but rather take advantage of the existing vegetation in novel or ancestral ways.

Much has been written on the benefits of trees for cropping systems (Bayala et al., 2014, 2015; Sinare and Gordon, 2015), but studies on the contribution of shrubs to agroecosystem productivity and sustainability have been less common. Native shrubs such as *Guiera senegalensis* (Fig. 3D) and *Piliostigma reticulatum* (Fig. 3F) are an important component of biodiversity and of spatial heterogeneity in West African agroecosystems. In an experiment of 11 years in Senegal, Bright et al. (2017) found that groundnut and millet rotations performed better in presence of *P. reticulatum* shrubs than in absence of these perennial shrubs. Relative yield differences were greater when environmental conditions were more limiting and yields without shrubs lower. Overall differences between shrub and no-shrub systems were smaller with increasing fertilizer doses.

Areas of land left uncultivated during a certain number of years, or fallows, allow for native vegetation re-growth following a succession of herbaceous, shrub and tree strata (Bonetti and Jouve, 1999). In this sense, setting land as fallow is also a plant species diversification practice that operates at landscape level. Fallows are common in shifting agriculture around the world and are key in restoring soil fertility on extensive systems (Wezel and Haigis, 2002). In West Africa, the traditional fallow system is a biodiversity-based soil management practice that is becoming rarer and shorter due to the shortage of land caused by population growth, soil deterioration and desertification (Bonetti and Jouve, 1999; Diarisso et al., 2015). In Loukoura, Burkina Faso, fallows account for 53% of the village territory while cultivated lands only occupy 16% (Cabral, 2011). In other places like Yilou, Burkina Faso (Sudano-Sahelian region), fallows will last no more than two to three years (Lahmar and Yacouba, 2012b). Such short periods of rest may seem far from ideal to restore soil productivity (Kintché et al., 2015) or to maintain soil functions or habitats for biodiversity. Nevertheless, remnant trees and shrubs are ever-present on continuously cultivated cropping systems in the region (Hiernaux et al., 2016), contributing also to create spatial heterogeneity.

3. Managing spatial heterogeneity

3.1. Nutrient and water concentration

Contour stone-bunds are barriers placed along the contour lines of farmer fields to reduce erosion, increase soil water retention and the accumulation of sediments, organic matter and nutrients (Critchley et al., 1994). As a complement, or a substitute to stone rows, farmers sometimes sow seeds and/or allow the regeneration of *Andropogon gayanus* grass as erosion control barriers (Zougmoré et al., 2009). These grass strips have similar benefits for soil and water conservation as

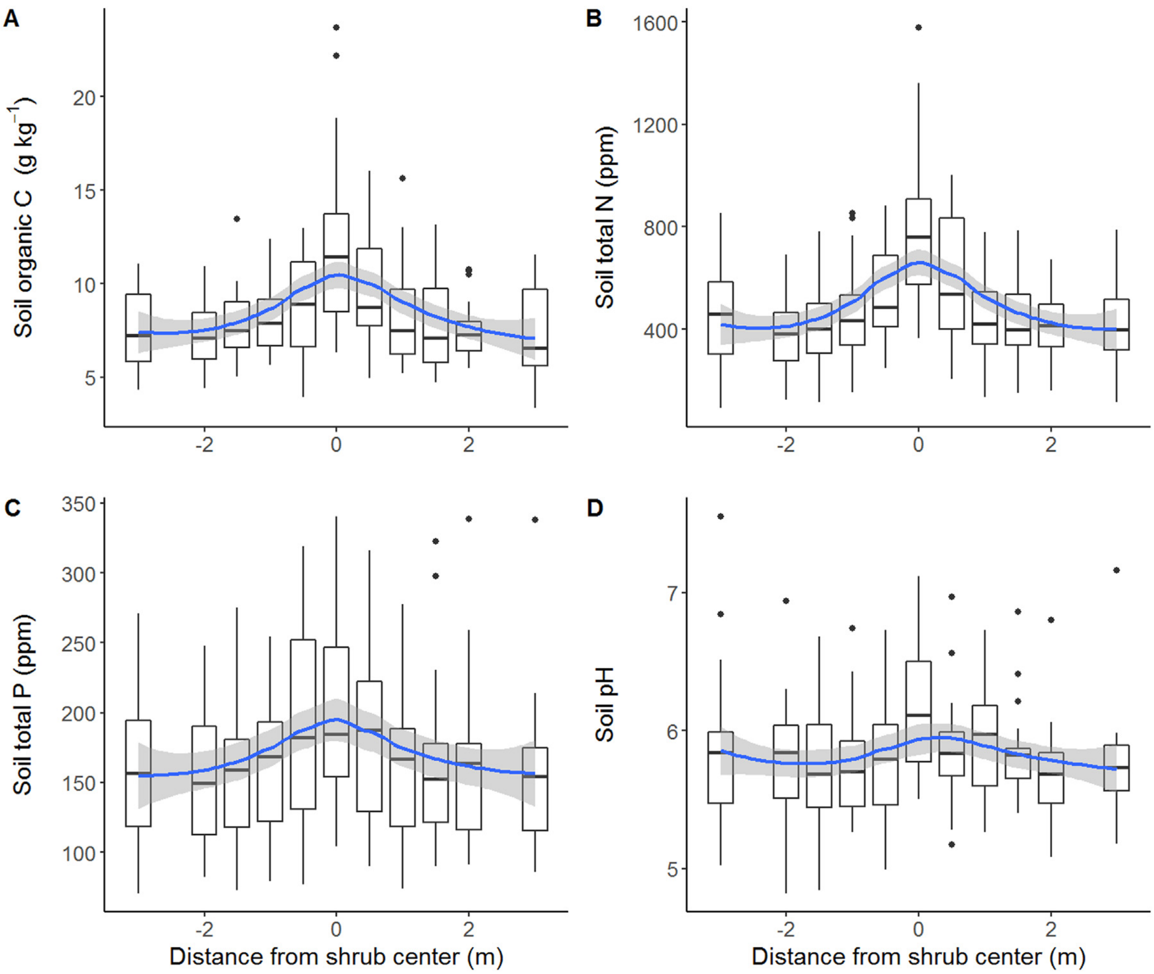

Fig. 4. Soil fertility in the vicinity of *Piliostigma reticulatum* shrubs (n = 21), Yilou, Burkina Faso. Analysis of soil organic C (panel A), soil total N (panel B), soil available P (panel C), and soil pH (panel D) across 6-m transects, from direction North-East (-3 m to shrub center) towards direction South-West (shrub center to +3 m). This coincides with Harmattan winds orientation occurring during the dry season. Data adapted from Cheriere (2015).

stone-bunds (Spaan, 2003). *Andropogon* also provides construction material, since the stalks may be used to build some types of silo where harvests are kept year-long. With time, small trees and shrubs tend to settle in these contours, consequently increasing ecosystem services supporting food and cropping systems.

A traditional way of sustaining soil productivity is the addition of organic inputs (i.e. animal manure, crop residues, woody amendments). Animal manure is a soil amendment commonly used in SWA (Zorom et al., 2013), but its supply is too limited to sustain soil fertility at landscape scale, and is directly linked to livestock production (Dongmo et al., 2012). Resource concentration occurs in SWA either (a) *actively* by grazing animals (macro) or termites (micro) or (b) *passively* through accumulation around heterogeneities in the landscape (trees, shrubs, termite nests) after movement by wind or water.

Livestock typically roams around the landscape freely during the dry season (Dongmo et al., 2012; Diarisso et al., 2015). During the rainy season, organic matter and manure depositions are concentrated around homesteads, leading to fertility gradients, described by Prudencio (1993) as ´ring management´(see Fig. 1). This practice has largely shaped the landscape and biodiversity distribution structure of the Mossi Plateau of Burkina Faso. But spatial heterogeneity is also important at field and plant-scales. Nested rings of 'fertility' such as in the vicinity of semi-perennial landscape structures like tall grasses, trees, shrubs and termite nests often act as ´resource islands´ that concentrate water and nutrients (see Fig. 1). Farmers recognize and manage this diversity intensively in West Africa by integrating crop-livestock systems in time (Ramisch, 2005) and by maintaining complex tree-shrub-crop systems such as parklands in space (Lahmar et al., 2012a).

Manure collection and re-distribution may eventually lead to increased diversity of plants present during the dry season, both through enhanced fertility locally by nutrient addition, but also by a seeds contained in manure after livestock has digested pods of locally-available and palatable perennial species and their distribution through animal movement at landscape level. *Zaï* pits or micro-basins dug by farmers to establish their crops in semiarid West Africa typically provide excellent conditions for seeds contained in manure to germinate and produce additional biomass that can be recycled into the system, including perennial grasses, shrubs or trees (Sawadogo, 2011). Building zaï and half-moons are well known techniques for soil restoration and nutrient concentration in cropping systems of W-Africa, and they are dug during the dry season particularly on crusted soils (Hien et al., 2010; Tsozué et al., 2014). Perspectives for optimizing this technique have been explored, especially in combination with other management practices like crop residue or woody mulch to further increase soil organic matter decomposition locally (Lahmar and Yacouba, 2012b).

Taking into account the multiple services provided by woody perennials in the semi-arid regions of West Africa (Bayala et al., 2014; Sinare and Gordon, 2015), at low input levels cropping systems supported by interactions with integrated shrubs can both have higher productivity and provide more products and functions than monocultures. Wezel (2000) observed two-fold millet productivity improvements in Niger when crops were grown in the vicinity of shrubs of *Guiera senegalensis* (i.e. 0.6–0.9 t ha^{-1}) as compared to millet plants growing more than 2 m away from the shrub (i.e. 0.3–0.4 t ha^{-1}). The authors attributed these differences to improved soil fertility due to sediment siltation and entrapment.

3.2. Biomass transfers

Re-locating carbon-rich plant material to rehabilitate patches of crusted soils is a technique practiced by smallholder farmers in West Africa (CSFD, 2015). This allows the restoration of degraded lands (Mando and Stroosnijder, 2006), often resulting in an increase of crop yields (Félix et al., 2015). Prior to the cropping season, farmers prune the shrubs on the fields and use the biomass of both leaves and branches as soil amendment, usually in the surroundings of the shrub (Lahmar et al., 2012a; Bright et al., 2017). These biomass amendments can improve soil water content and organic matter cycling via reduced erosion, increased sediment trapping, increased rainfall infiltration, and enhanced nutrient retention (Buerkert et al., 2000; Mason et al., 2014). Other mechanisms involved in soil aggradation (as opposed to *degradation*) processes via crop residue and ramial wood application include the reduction of soil organic matter losses due to the reduction of soil temperature and enhancement of soil biological activity, including the development of termite-mediated processes (Ouédraogo et al., 2006). Research conducted for seven years at Gampéla Research Station in Burkina Faso (Barthès et al., 2015; Félix et al., 2018) showed that although sorghum yields are lower than 1 t ha^{-1}, increasing doses of ramial wood (RW) improved crop yields significantly as compared to no RW application (Fig. 5A and C). Enhanced sorghum grain yields were attained with increasing soil organic C content (Fig. 5B). This effect was independent from treatments. Greater termite activity (Fig. 5D) was observed where high doses of RW were applied.

3.3. Termite nests

Termites play an important role in nutrient cycling and soil dynamics in SWA (Mando, 1998; Sileshi et al., 2010), through their metabolic activity and the creation of termite nests. On the one hand, termites contribute to nutrient transfers through foraging carbon-rich materials from their surroundings (Ouédraogo et al., 2004). Concentrating organic resources on degraded or crusted surfaces has proven that termites improved soil structure (Mando, 1998; Laguemvare, 2003; Ouédraogo et al., 2004).

The termite nests or *termitarium* building activities contribute to the modification of the soil micro-topography, porosity, and water infiltration capacity (Sileshi et al., 2010). A series of 12 termitaria on farmer fields (i.e. deserted termite nests) were monitored from May through November 2015 at Kindi, Burkina Faso. Soil organic C, available P, and pH, were significantly higher towards the middle (¼ and ¾ radius from center) of the termite nest as compared to the conditions of the open field (Fig. 6A through C).

Sorghum grain yields were in average twice as large on the termite mound area as compared to the open field (Fig. 6D, i.e. 2 vs. 1 t ha^{-1}). This boosting effect on termite mounds was quite noticeable on low-yielding fields (Fig. 6E) and corresponds to differences in soil pH (Fig. 6E). In cases where open fields yield low (~ 0.1 t ha^{-1}), sorghum

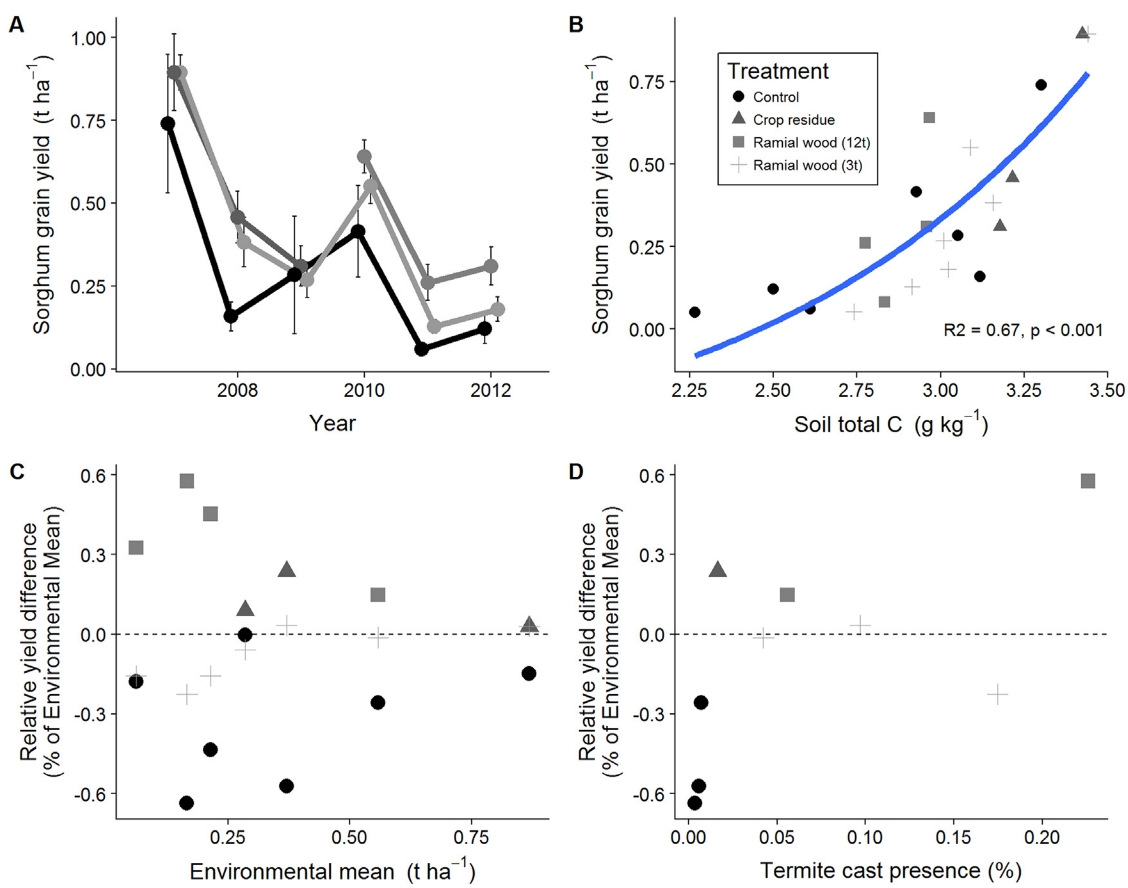

Fig. 5. Sorghum yields on continuously cultivated plots decreased over a six-year period (2007–2012) at Gampéla, Burkina Faso (panel A), with or without soil amendments. Soil total C increased sorghum yields (panel B). Use of ramial wood (RW) or crop residue amendments improved yields as compared to environmental mean (panel C). When environmental conditions were favourable (e.g. high environmental mean), the differences between treatments were less noticeable than when environmental conditions were low. Termite activity (measured in 2009, 2010, and 2011) was enhanced in presence of high rates of RW application (panel D). Data adapted from Barthès et al. (2015); Félix et al. (2018).

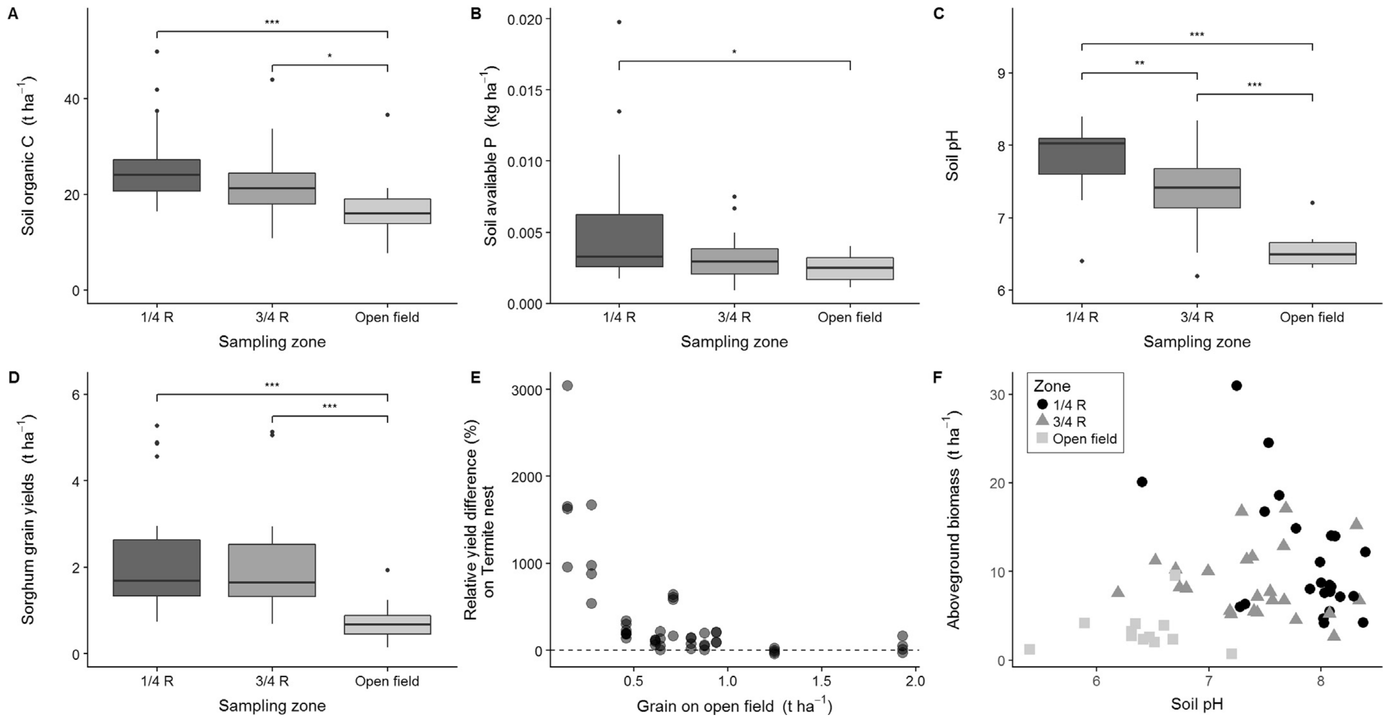

Fig. 6. Soil properties and crop performance of sorghum crop on termite nests present on 16 farmer fields in Kindi, Burkina Faso. 1/4R is the sampling zone that corresponds to 25% of the radius (from center of each termitaria), 3/4R corresponds to 75% of that radius, and open field were samples taken outside the zone of influence of the termitaria. Soil organic C (panel A), soil total P (panel B), and soil pH (panel C), at 0–20 cm depth, show fertility gradients, with higher nutrient stocks and increased yields towards the center of the nest (panel D). Relative yield differences between on termite nests were more important when yields on the open field were low (panel E). Soil pH was close to 6 on open field and close to 8 in the termite nest center, also showing highest yields in aboveground biomass (panel F). Significant differences: * < 0.05, ** < 0.01, *** < 0.001. Original data, with contributions from Patrick Winterhoff.

grown on neighbouring termite mounds (properly mulched with straw or woody debris) could yield up to 1 t ha^{-1}. Occasionally, grain harvested on these 'fertile spots' are kept as seed material for next cropping season.

4. Biodiversity contribution to household nutrition

Diets are mainly determined by local food availability and diversity (i.e. cultivated crops and animals, wild edible plants collected from the surrounding landscape, or products exchanged and bought at the market). Food diversity is a relevant indicator for nutrient adequacy and health, positively correlated to micronutrient intake (Foote et al., 2004; Allen et al., 2014), and is an indicator for ecologically and socially sustainable diets (Remans et al., 2014). In particular, the nutritional functional diversity (NFD) indicator is useful to link the effect of biodiversity in natural and managed systems with human nutrition, and considers nutrient trait diversity in the intake of families within a given social-ecological system (Luckett et al., 2015). The diversity of food items consumed over the year was monitored in a study in 12 households at Yilou, Burkina Faso (see Le Garff, 2016).

Total diversity inventoried among these 12 families ranged between 64 and 88 food items per household during the year considered. Markets accounted for 50% of food item diversity, farm-produced items constituted 30%, and food items collected from the landscape accounted for 20% (Fig. 7). On-farm sources of food diversity were slightly more important during food abundance (FA) and food shortage (FS). A list of woody perennials contributing to household nutrition may be found in Table 2. The proportion of NFD collected from the landscape was more important during FS than during FA (39% of total food items compared to 33%). Contribution of market and farm produce was similar between FS and FA (81% compared to 84%, and 38% compared to 39%, respectively). In the case of vitamin A, households derived about one third of their intake from wild foods collected from

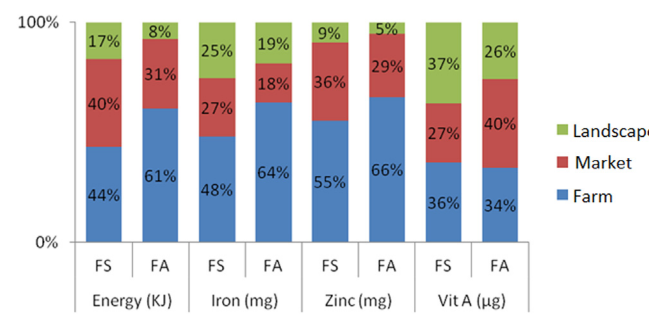

Fig. 7. Landscape, market and farm contribution to household nutrition, Yilou, Burkina Faso (FS = food shortage, FA = food abundance). Data adapted from LeGarff (2016).

the surrounding landscape, both during food shortage or abundance periods. Wild food contribution to energy intake was less significant at both periods.

While food availability may be in short-supply at times, local ecological knowledge of wild edible plants (trees, shrubs) allows for accessibility to nutritious food items. Moreover, in times of FS, nutrient-rich food items for household use may be collected from landscape elements such as leaves of *Adansonia digitata* (baobab). According to Lamien et al. (2009), the contribution of local fruit snacks plays a fundamental role in sustaining nutritional intake of rural populations drylands of Burkina Faso. Yet the selection of available local fruits varies throughout the seasons. From October through December, *Diospyros mespiliformis, Ziziphus mauritiana,* and *Balanites aegyptiaca* were most consumed per person. From January to March, *Z. mauritiana* and *D. mespiliformis* are collected along with *Gardenia erubescens* and *Detarium microcarpum.* During the wet season (April through June), the selection of fruits available includes species featured in parkland

Table 2
Calendar of collected fruit and vegetables from landscape species and accessibility in time. Green indicates produce harvested from the landscape, blue denotes dried spices from wild trees that are available throughout the year, and red denotes seasonal availability at local market. Data is adapted from a case study in Yilou, Burkina Faso (Le Garff, 2016).

Food item	Species	June 2015	July 2015	Aug. 2015	Sept. 2015	Oct. 2015	Nov. 2015	Dec. 2015	Jan. 2016	Feb. 2016	Mar. 2016	Apr. 2016	May 2016
Vegetable	*Adansonia digitata*	green	green	green	green	green	green	green	green	green	green	green	green
	Bombax costatum	green	green	green	green	green	green	green	green	green	green	green	green
	Ipomoea aquatica	green	green	green	green	green	green	green	green	green	green	green	green
	Cassia obtusifolia	green	green	green	green	green	green	green	green	green	green	green	green
	Tamarindus indica	green	green	green	green	green	green	green	green	green	green	green	green
	Leptadenia hastata						green	green	green	green	green	green	
	Cratevia religiosa										green	green	green
	Balanites aegyptiaca										green	green	
	Acacia macrostacchya	blue	blue	blue	blue	blue	blue	blue	blue	blue	blue	blue	blue
Fruit	*Tamarindus indica*	red	red	red	red	red	red	red	red	red	red	red	red
	Mangifera indica	red									red	red	red
	Sclerocarya birrea	red	red	red								red	red
	Acacia sp. ('gumvine')	red	red	red	red								red
	Vitex doniana	red	red	red									red
	Ximenia americana	red	red	red	red	red	red						
	Vitellaria paradoxa	red	red	red	red								
	Lannea microcarpa	red	red	red									
	Adansonia digitata				red	red	red	red	red	red	red		
	Diospyros mespiliformis						red	red	red	red	red	red	
	Ziziphus mauritiana						red	red	red	red	red	red	
	Annona senegalensis						red	red					

systems such as *Lannea microcarpa*, *Saba senegalensis*, *Ximenia americana*, *V. paradoxa*, and *P. biglobosa*.

Biodiversity sustains an array of ecological functions for farming families on their territories (Culman et al., 2010; Altieri et al., 2011; Blanco et al., 2013; Sinare and Gordon, 2015; Garibaldi et al., 2017; Wilson et al., 2017). The examples illustrated show that the development of appropriate strategies to reduce vulnerability of resource-poor farmers and move biodiversity-based approaches forward, is a process that emerges from a variety of contextualized 'options,' and not, from silver-bullet 'solutions' (Mortimore and Adams, 2001; Isgren, 2016).

5. Conclusion

The underlying functional hypothesis "the more complex the structure, then the more services are obtained from the system" was challenged in this paper, with examples from SWA. We analyzed three levels at which farmers manage biological diversity: crop mixtures, resource islands, and household nutritional diversity. Particularly, we focused on effective resource extraction (i.e. crop yields) in heterogeneous environments by showing (a) how multiple species explore different niches, and (b) how temporal fluctuations of resource availability are managed.

Most common associated annual crops in SWA feature cereals and legumes, and the available evidence suggests that their intercropping can improve field-level productivity by concentrating nutrients, biomass, and water at the plant roots. Crop associations not only represent a risk-aversion strategy in case of crop failure, but their implementation requires tacit knowledge on synergetic (or antagonistic) relations between plants (i.e. system components). In presence of woody perennials soils are improved and crops may perform better. Tree-crop or shrub-crop combinations are based on perceived benefits and trade-offs by farmers. Managing spatial heterogeneity includes termite nests that have been abandoned and weathered. Indeed, termite activity leads to a concentration of soil nutrients (C, N, P) and a clear difference between the center of the termite nests and the open field. Our analysis shows that yields are systematically improved in presence of termite nests.

Wild plants (i.e. grasses, shrubs, vines, and trees) collected from surrounding landscape play an important role in sustaining micronutrient accessibility at the household level. On-farm diversity contributes mainly to household nutrition, and this diversity comes from the capacity of farming families to combine crops in smart ways. Local ecological knowledge is very valuable to extension and rural development services since in revisiting past practices, then new skills or methods can be developed in their own areas. This would thus make clear that farmer creativity is a valid form of knowledge acquisition and application to co-innovate on the use of biodiversity and its role in multifunctional farming systems.

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Conflict of interest

The authors declare no conflict of interests.

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