Environ Dev Sustain
https://doi.org/10.1007/s10668-018-0107-1

Ecological sustainability and environmental risks of agricultural intensification in inland valleys in Benin

Justin F. Djagba[1,2] · **Sander J. Zwart**[3] · **Christophe S. Houssou**[4] · **Brice H. A. Tenté**[5] · **Paul Kiepe**[6]

Received: 20 April 2017 / Accepted: 12 February 2018

Abstract To meet food demand after the failure of irrigation system developments, agricultural intensification is occurring in inland valley agro-ecosystems in sub-Saharan Africa. Agricultural enhancement in inland valleys, which undermines environmental sustainability, was assessed using 'Driving Force–Pressure–State–Impact–Response' approach in four agro-ecological zones of Benin. The survey revealed that inland valleys are largely devoid of ligneous species. Crop residues are mainly transferred from inland valley fields to feed cattle, burnt in situ by the farmers themselves or abandoned to wildfires or to pasture—not mulched. Crop diversification is not universal and is limited to rice and vegetables crops. Monocropping of rice, practised by 83.3% of inland valley farmers, requires large chemical fertilizer application despite their impacts on environment including land degradation and water contamination. A major challenge is to determine means of characterizing entire agro-ecosystems of inland valleys in a way that is simple enough to be effectively and efficiently monitored. Inland valley agricultural development projects might include backstopping activities and policies that enable monitoring of chemical inputs and farming practices in inland valleys to reduce negative impacts on the environment and human health.

✉ Justin F. Djagba
j.djagba@cgiar.org

1 Africa Rice Center (AfricaRice), 01 BP 2031 Cotonou, Benin

2 International Chair in Mathematical Physics and Applications (ICMPA-UNESCO Chair), University of Abomey-Calavi, 072 BP 50 Cotonou, Benin

3 Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217, 7500 AE Enschede, Netherlands

4 Laboratory Pierre Pagney 'Climate, Water, Ecosystems and Development' (LACEEDE), University of Abomey-Calavi, BP 922 Abomey-Calavi, Benin

5 Biogeography and Environmental Expertise Laboratory (LABEE), University of Abomey-Calavi, BP 677, Abomey-Calavi, Benin

6 Africa Rice Center (AfricaRice), 01 BP 2551 Bouaké 01, Côte d'Ivoire

Published online: 23 February 2018

Keywords Agricultural intensification · Inland valley · Sustainable development · DPSIR model · West Africa

1 Introduction

Lowland growing environments, particularly inland valleys, are considered the future food baskets of West Africa (Rodenburg et al. 2014). They are believed to have large potential for agricultural intensification and diversification (Djagba et al. 2014; Sakurai 2006; Maméri et al. 2008), and they are resilient to the impacts of climate change (Zorom et al. 2013). Inland valleys have favourable hydrological conditions compared with the surrounding uplands, and water availability is higher as a result of ground and surface water flows (Rodenburg et al. 2014; McCartney and Houghton-Carr 2009). Soils in the inland valleys have higher fertility levels than those in upland agro-systems (Ogban and Babalola 2003; Wakatsuki and Masunaga 2005). Dossou-Yovo et al. (2017) find that soil properties and hydrological regime determine inland valley land use. Inland valley exploitation is an economically viable activity since cultivated crops are profitable and returns on investment of the factors of production such as the capital (material, human, financial, land) and labour are greater than in other agro-ecologies (Erenstein et al. 2006; Rodenburg et al. 2014; Schuyt 2005; Singbo and Lansink 2010). Inland valleys provide jobs and substantial incomes for many working in the agricultural sector, including smallholder farmers. Agricultural activities in inland valleys allow farmers to diversify not only the crops, but also their sources of income (Singbo and Lansink 2010; Erenstein et al. 2006). They also provide urban centres with vegetables and staple crops such as rice (Erenstein et al. 2006; Drechsel and Dongus 2010). Thus, inland valley landscapes contribute significantly to food security in Africa.

During the 1990s, the Inland Valley Consortium (IVC), hosted by the Africa Rice Center (AfricaRice), promoted the sustainable development of inland valleys in West Africa, addressing appropriate water management, weed control, human diseases associated with lowland environments, land-tenure arrangements and access to input and output markets. Inland valley development projects focus on agricultural intensification through measures targeting productivity increase, expansion of cultivated area, introduction of dry season crops and agricultural diversification by introducing cash crops or aquaculture. Improved land and water management provides the basis for further investments, and infrastructural projects for irrigation water supply and water control are common (Johansson et al. 2002; Dinar and Mody 2004; Hussain et al. 2007), though often unsuccessful (Djagba et al. 2014; Inocencio et al. 2007).

As in many sub-Saharan African countries, population pressure in Benin is increasing sharply. The population is expected to double from 6.77 million in 2002 to 11.50 million inhabitants in 2018 (according to General Census of Population and Habitation in 2013). To feed the growing population and to be less dependent on international markets, the country's food production must be augmented through intensification and expansion of agriculture (Amissah-Arthur and Miller 2002; Verburg et al. 1999; Place and Otsuka 2000; Pender et al. 2004; Sakurai 2006). However, arable land has become scarce and land degradation is increasing because of reduced fallow periods (Franke et al. 2008; de Ridder et al. 2004; Giertz et al. 2012). Climate change and variability put extra pressure on the agricultural production that is largely rainfall dependent.

Agricultural land-use intensification is one of the most significant forms of land cover modification (Lambin et al. 2000; Sayer and Cassman 2013) and undermines agro-ecosystem sustainability (Palm et al. 2014). Increasing demand for food by growing populations increases the competition for land, water and other inputs for food production (Garnett et al. 2013; Tilman et al. 2002). There has also been a significant increase in area under commercial non-food crops such as cotton, sugarcane, tobacco and areca and under horticultural crops such as coconut and grape (Purushothaman et al. 2013). These cropping patterns have implications on the types and quantities of fertilizers and pesticides applied. Modern agriculture is successful in increasing food production but can cause extensive environmental damage due to the pressures on the environment. Increasing fertilizer use, for example, leads to the degradation of water quality in many regions of the world; anthropogenic nutrient inputs to the biosphere (fertilizers and atmospheric pollutants) exceed natural sources and have widespread effects on water quality in coastal and freshwater ecosystems (Rasul and Thapa 2004; Foley et al. 2005). Likewise, traditional cropping practices—such as mixed cropping, crop rotation and intercropping—are gradually being replaced by monocropping and higher dependency on external inputs (chemical fertilizers and pesticides). Such agricultural intensification for increased production affects land quality and ecosystem services (Pretty 1999). Regulating and supporting ecosystem services, nutrient cycling, climate regulation, regulation of water quality and quantity, pollination services, and pest control are sometimes disrupted (Palm et al. 2014; Rasul and Thapa 2004).

The Government of Benin aims to become self-sufficient in, and an exporter of, staple food crops by 2018. The National Rice Development Strategy for Benin (Direction de la Programmation et de la Prospective 2011) forecasts a boost in paddy rice production by improving productivity in inland valleys (from 3.5 to 5.5 tonnes ha^{-1}), while expanding rice-producing areas (from 33,000 ha in 2008 to 138,000 ha in 2018). The Government of Benin and international organizations are heavily involved in the rice sector development by inland valley rice intensification and provide inland valley farmers with immense support. This support is in the form of free improved rice seeds, subsidized fertilizers, development of inland valleys, rice mills, land preparation machinery (e.g. tractors and power tillers), development of the rice value chain, agricultural credit and purchase of paddy. However, the environmental impact of intensification of rice production and agriculture in general in the inland valleys is under-researched.

The aim of this study was to assess the effects of agricultural intensification on environmental sustainability in inland valleys in Benin. We investigated the pressures on this agro-ecosystem that may have environmental impacts (Pender et al. 2004; Amissah-Arthur and Miller 2002). More specifically, we analysed farmers' use of natural resources in inland valley agro-ecosystems and the practices that may potentially affect these resources. We further investigated the risks that inland valleys are confronted with and actions taken to help maintain a healthy environment. We finally propose corrective measures which may be advocated. It is in this light that further analysis of the nature and impacts of intensive cropping systems in inland valleys is warranted. Our analysis is based on a holistic approach, 'Driving Force–Pressure–State–Impact–Response' (DPSIR), used to deepen the environmental assessment across the agro-ecological zones (AEZs) present in Benin.

2 Materials and methods

2.1 Study area

This study was carried out in Benin, which is located in West Africa, bordered by Togo to the west, by Nigeria to the east and by Burkina Faso and Niger to the north (see Fig. 1).

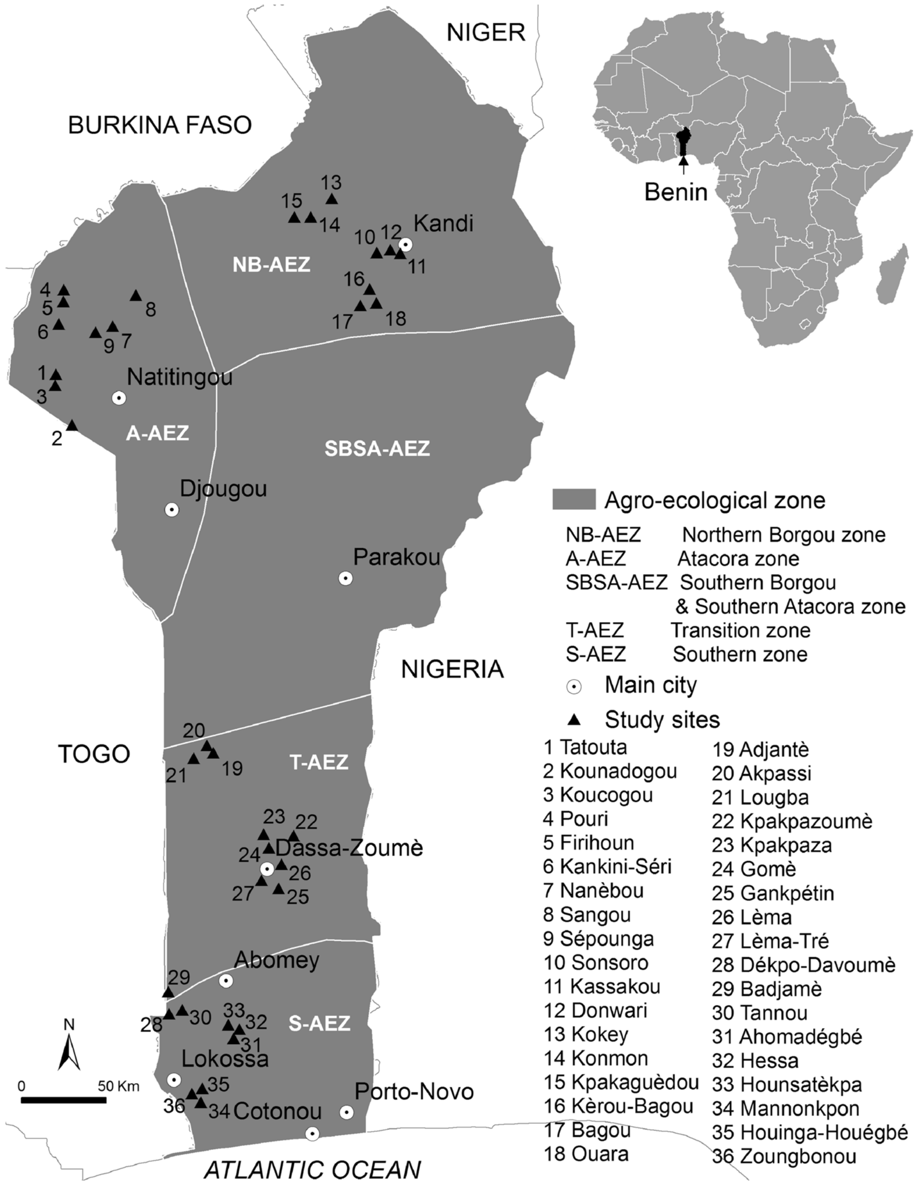

Fig. 1 Location of sampled inland valley sites in the five agro-ecological zones in Benin

According to Windmeijer and Andriesse (1993), AEZs are defined on the basis of the mean annual rainfall, the duration of the growing period and of the potential of vegetation and agriculture. In Benin, five AEZs are defined from north to south (Vissoh et al. 2004) (Table 1; Fig. 1): (1) Northern Borgou zone (NB-AEZ), (2) Atacora zone (A-AEZ), (3) Southern Borgou and Southern Atacora zone (SBSA-AEZ), (4) Transition zone (T-AEZ) and (5) Southern zone (S-AEZ). The climate is determined by the interaction of two air masses: humid maritime air from the Atlantic Ocean associated with south-westerly winds, and dry continental air from the African continent associated with north-easterly winds from the Sahara (Yabi and Afouda 2012). Rainfall across Benin ranges between 850 and 1500 mm per year. The climates from south to north are: (1) subequatorial, with two rainy and two dry seasons; (2) Soudano-Guinean, without clear distinction between the two rainy seasons; (3) Soudanian, with one rainy and one dry season; and (4) Soudano-Sahelian, with one rainy and one dry (Adam and Boko 1993). Four major groups of soils may be distinguished (Adomou 2005): (1) ferralitic soils covered by semi-deciduous forests; (2) ferruginous soils covered by dry forest, woodland and savannah; (3) vertisol in the depression of Lama, covered by a particular dry type of semi-deciduous forest; and (4) hydromorphic soils covered by swamp and riparian forests (Table 1). The vegetation in all climatic zones is highly modified by human activity.

2.2 Survey design and sampling strategy

For field data collection, we used direct field observations, key informant interviews and individual farmer surveys. Field observations and key informant interviews for each targeted inland valley were conducted from December 2014 to January 2015 and farm surveys from July to September 2015. Using direct observations, we collected information on environmental components (on-site presence of ligneous resources, crop residues and visible erosion effects), presence and state of infrastructure for water control and iron toxicity [which is a syndrome of large concentrations of reduced iron (Fe^{2+}) in soil solution which occurs in flooded soils and hence affects primarily the production of inland valley rice and the typical visual effect is the 'bronzing' of the rice leaves and substantial yield losses which can also reach the complete crop failure (Becker and Asch 2005)]. Direct observations were carried out by measuring modalities previously defined for each studied environmental parameter. Respectively, 'frequent, infrequent and no ligneous', 'transferred, forsaken and burnt', 'land alteration or no of inland valley fringe' and 'iron toxicity symptoms observed or no in concerned inland valley' were considered to evaluate ligneous resources, crop residues, erosion and iron toxicity. Open questions were addressed to key informants to collect general and historical information on the inland valleys, and about the state of the inland valleys with respect to major environmental problems that are consequences of mismanagement of farmland resources, namely erosion and iron toxicity. Additional information was obtained from the farmers via a questionnaire. The questionnaire was designed around three principal themes related to sustainability and risks of agricultural intensification in inland valleys: (1) farming practices, (2) agricultural diversification and (3) use of chemical fertilizers and pesticides.

We selected 36 inland valleys distributed in 12 districts in four AEZs (see Fig. 1) while considering the following selection criteria. Selected districts had high density of inland valleys developed for agriculture. The selection criteria for the inland valleys were that the area of each inland valley was at least 10 ha and that they were exploited for agriculture. We also selected on the basis of a variety of projects and donors that intervened in the inland valleys, such as international organizations, NGOs and bilateral and public-funded

Table 1 Characteristics of the five agro-ecological zones of Benin. Reproduced with permission from (Vissoh et al. 2004)

Agro-ecological zone (AEZ)	Annual rainfall[a] (mm)	Climate[a]	Major soil types	Natural vegetation	Main crops
Northern Borgou zone (NB-AEZ)	850–1000	Soudano-Sahelian, with one rainy and one dry season	Tropical ferruginous	Shrubby savannah	Cotton, maize, millet and sorghum
Atacora zone (A-AEZ)	850–1200	Soudanian, with one rainy and one dry season	Tropical ferruginous	Arboreous savannah	Sorghum, cowpea, maize and millet
Southern Borgou Southern Atacora zone (SBSA-AEZ)	1100–1500	Soudanian, with one rainy and one dry season	Tropical ferruginous	Arboreous savannah	Sorghum, cotton, maize and yam
Transition zone (T-AEZ)	1100–1200	Soudano-Guinean, without clear distinction between the two rainy seasons	Tropical ferruginous	Arboreous savannah	Maize, cashew, cassava, cotton, groundnut and yam
Southern zone (S-AEZ)	850–1500	Subequatorial, with two rainy and two dry seasons	Ferralitic, hydromorph and vertisol	Relics of forest	Maize, cassava, cowpea, oil palm and vegetables

[a]Update of climate data (Adam and Boko 1993)

agricultural development projects (see Table 2) because inland valley development approaches used varied according to the project and could impact differently the inland valley environment. This information was obtained from interviewed farmers and from the Inland Valley Development Unit of the Ministry of Agriculture in Benin. In each AEZ, we selected three districts in which we sampled three inland valleys to provide sufficient spatial variation and variety for the analysis. Consequently, inland valleys of the SBSA-AEZ did not sampled because scarce inland valleys in that AEZ respected to the selection criteria. Let us add that SBSA-AEZ was cotton zone and dominated by many classified forests (more than dozen) and cashew trees plantations (Adomou 2005).

We interviewed 10 individual farmers in of each of the 36 selected inland valleys; a total of 360 farmers were interviewed. Direct field observations and key informant interviews were made in all 36 inland valleys. Key informants consisted of older farmers and decentralized authorities at local level.

2.3 Data analysis and Driving Force–Pressure–State–Impact–Response (DPSIR) model

The Driving Force–Pressure–State–Impact–Response (DPSIR) model is an approach developed by the Organization for Economic Cooperation and Development (OECD) in the 1990s (Pirrone et al. 2005). It is used to highlight relationships between human activity and environmental change. Based on a concept of causality, DPSIR provides a comprehensive mechanism for analysing environmental problems (Ranaivomanana 2006; Pirrone et al. 2005; Karageorgis et al. 2005). Economic and social development such as demands of rising populations, expectations of food security and water security exerts 'pressures' on the environment and alters the quality and quantity of natural resources ('state') (Schulze 2004; Jennings 2005). This results in 'impacts' on human health, ecosystems and natural resources, which elicit an environmental, economic or sectoral 'response' from the society (Bonierbale 2004).

The model takes into account each indicator in detail. Thus, DPSIR has been adopted as a policy tool to identify management options for a range of environmental problems. As developed in the framework of many environmental issue projects, the DPSIR approach can be summarized as:

- 'Driving forces' are processes and anthropogenic activities (agricultural intensification in inland valley agro-systems in this study) able to cause pressures;
- 'Pressures' are the direct stresses, derived from the agricultural system, affecting the natural environment, e.g. excessive agrochemical use, natural resources destruction and management;
- 'State' reflects the environmental conditions of natural systems (vegetation, soil, wildlife, air and water quality);
- 'Impact' is the measure of effects due to changes in the state of the system;
- 'Response' is the evaluation of actions to solve environmental problems in terms of management strategies stakeholders and authorities.

The objective of the use of the DPSIR model in this study was to establish links between inland valley agro-ecosystems use/intensification and the management of its resources. The structure of the present work follows the DPSIR scheme, analysing concurrently each environmental component that can be affected. Thus, socio-economic drivers, environmental

Table 2 Study sites and selected characteristics

Agro-ecological zone (AEZ)	District	Village	Inland valley name	Exploited area (ha)	Major crops	Funding source(s)[a]
Northern Borgou zone (NB-AEZ)	Banikoara	Kommon	Kommondarou	10	Rice and fruits	Gov. project
		Kpakaguedou	Botôdô	10	Rice and vegetables	Gov. project
		Kokey	Kokey[b]	25	Rice	Gov. project
	Kandi	Kassakou	Gargo	30	Rice	UNDP/FAO
		Donwari	Donwari	18	Rice	Gov. project
		Sonsoro	Bokossi	15	Rice	SNV
	Gogounou	Bagou	Bagou	20	Rice and fruits	UNDP/FAO
		Kérou-Bagou	Kérou-Bagou[c]	12	Rice and vegetables	–
		Ouara	Sinari N'bia[c]	15	Rice and vegetables	–
Atacora zone (A-AEZ)	Tanguiéta	Sangou	Gnanfa	18	Rice	GIZ
		Sépounga	Moutoukou	20	Rice and vegetables	Gov. project
		Nanèbou	Timporé	15	Rice	GIZ
	Matéri	Kankéni-Séri	Montchanhoun	10	Rice	Gov. project
		Pouri	Labouni-Pah	10	Rice	UNDP/FAO
		Firihoun	Lassag-Pah	23	Rice	UNDP/FAO
	Boucoumbé	Tatouta	Koupou	45	Rice and sorghum	UNDP/FAO
		Kounadogou	Koubirgou	17	Rice	Gov. project
		Koucôgou	Dicôpouri	16	Rice and soya bean	Gov. project

Table 2 (continued)

Agro-ecological zone (AEZ)	District	Village	Inland valley name	Exploited area (ha)	Major crops	Funding source(s)[a]
Transition zone (T-AEZ)	Dassa-Zoumè	Gankpétin	Kpolé	8	Rice and vegetables	IVC
		Lèma	Kpatikoa	24	Rice and cowpea	UNDP/FAO
		Lèma-Tré	Lèma-Tré[d]	10	Rice	–
	Glazoué	Gomé	Kotobo	10	Rice	IVC
		Kpakpaza	Katchéfè Toga	8.32	Rice and vegetables	UNDP/FAO
		Kpakpazoumè	Eriyindjan[d]	10	Rice	–
	Bantè	Lougba	Kafédékpo[d]	17	Rice	–
		Adjantè	Vèrôkpé[d]	15	Rice	–
		Akpassi	Ararômi[d]	10	Rice	–
Southern zone (S-AEZ)	Aplahoué	Dékpo	Davoumè[b]	6	Vegetables and maize	Protos
		Badjamè	Laougba[b]	9	Vegetables, maize and cowpea	Protos
		Tannou	Tanmè[b]	9.5	Vegetables, maize and soya bean	Protos
	Lalo	Ahomadégbé	Ahomadégbé	75	Rice	Gov. project
		Zounhomè	Hessa[b]	13	Rice	BTC
		Tandji	Hounsatèkpa	8	Rice and vegetables	BTC
	Houéyogbé	Mannonkpon	Mannonkpon	12	Rice and vegetables	UNDP/FAO
		Hoinga-Houégbé	Sissiotan	20	Rice, vegetables, maize and cowpea	BTC
		Zoungbonou	Hontoyégba[b]	12	Vegetables and maize	Protos

Gov. Government, *UNDP* United Nations Development Programme, *FAO* Food and Agriculture Organization of the United Nations, *SNV* Dutch development NGO, *GIZ* Deutsche Gesellschaft für Internationale Zusammenarbeit, *IVC* Inland Valley Consortium, *Protos* Belgian development NGO, *BTC* Belgian Development Agency

[a]Funding sources for water control implementation (development) of inland valleys

[b]Inland valley development for water control not achieved or very superficial

[c]Undeveloped inland valley benefiting from dam or well

[d]Undeveloped inland valley

pressures, the state of agricultural lands and downstream water are addressed, and the consequential impacts on human welfare and the environment are discussed, along with policy response options (Karageorgis et al. 2005). Survey data collected in the framework of this study were integrated into the DPSIR model to analyse the effects of agricultural intensification in inland valleys on environmental resources.

3 Results

3.1 Crops cultivated in the inland valleys

The number of crops per year that can be cultivated in an inland valley depends on the duration of rainy season and the specific hydrological and soil characteristics of the inland valley. Thus, the association and rotation of crops vary according to the prevailing conditions and the agricultural background and knowledge of the farmers. The principal crops encountered were: rice (*Oryza* spp.), Jew's mallow (*Corchorus olitorius*), tomato (*Solanum lycopersicum*), okra (*Abelmoschus esculentus*), chilli pepper (*Capsicum annuum*) and maize (*Zea mays*. Most farmers (95.8%) cultivated cereals—rice (83.3%), maize or sorghum (*Sorghum bicolor*) (9.4%) and rice and millet (*Panicum miliaceum*) (3.1%)—in the inland valleys. On average, 30.3% of farmers cultivated vegetable crops, and only 4.4% cultivated leguminous crops (either cowpea (*Vigna* spp.) or soya bean (*Glycine max*)). The spatial distribution within the country showed much variation: vegetables crops were more often found in S-AEZ (cultivated by 73.3% of farmers), less in NB-AEZ (24.4%) and T-AEZ (21.1%) and they were absent in A-AEZ. Leguminous crops (cowpea and soya bean) were weakly cultivated in S-AEZ (12.2%) and in T-AEZ (4.4%), with almost none in the other AEZs. All respondents in A-AEZ and almost all those in T-AEZ (99%) and NB-AEZ (90%) cultivated rice, and more than half (56.7%) cultivated rice in S-AEZ (see Fig. 2).

In 50% of studied inland valleys, crop diversification was observed: either a crop rotation (in 30.5% of inland valleys) or an association of many crops at the same time (19.4%). Crop diversification was most common in the southern regions of Benin (with 19% in S-AEZ and 14% in T-AEZ; cf. 11% in NB-AEZ and 6% in A-AEZ). This is mainly explained by the length of the growing season, which is longer in the south due to the occurrence of two rainy seasons. Rainfall permits only one rainfed crop in the north, where a second crop requires irrigation. Double cropping is mostly limited to the rice–vegetable

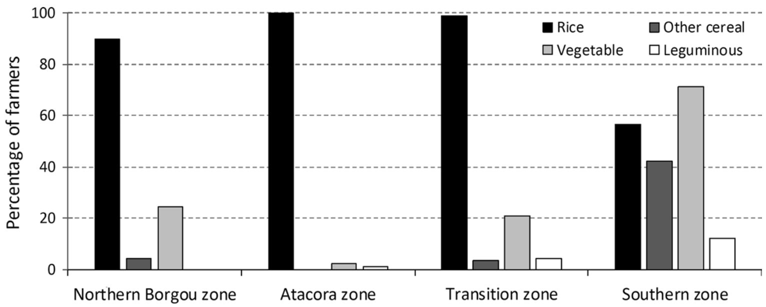

Fig. 2 Major crops cultivated in inland valleys by agro-ecological zone, Benin

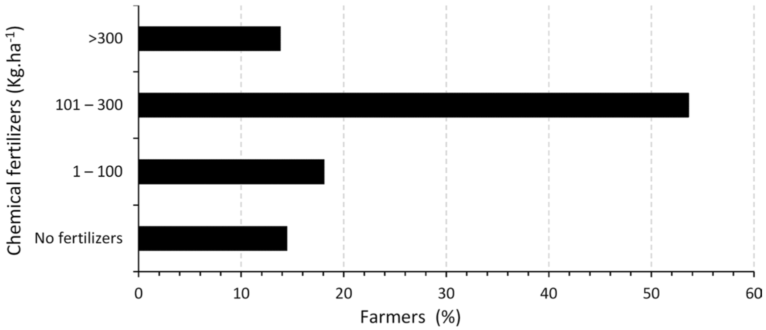

Fig. 3 Chemical fertilizer doses applied in inland valleys across agro-ecological zones in Benin

Table 3 Dose of chemical fertilizers applied by inland valley farmers (%) per agro-ecological zone in Benin

Agro-ecological zone (AEZ)	Fertilizer rate (kg ha^{-1})			
	0	1–100	101–300	>300
Northern Borgou zone (NB-AEZ)	11	23	60	6
Atacora zone (A-AEZ)	24	16	54	6
Transition zone (T-AEZ)	9	11	64	16
Southern zone (S-AEZ)	12	22	38	28

system (12 of 18 inland valleys with a double-cropping system). Some farmers believe that inland valleys are not suitable for legume or tree production.

3.2 Use of chemical fertilizer and pesticides

The chemical inputs used in inland valleys are nitrogenous fertilizers (such as urea and composite nitrogen–phosphorus–potassium [NPK]), herbicides and chemical insecticides. Chemical insecticides are often applied on vegetables to prevent attacks of insects and other pests, and on young rice plants in nurseries.

Across all AEZs, 76–90% of inland valley farmers used fertilizer. Overall, 85.6% of respondents applied chemical fertilizers: urea only (10.3%), NPK only (4.17%) or both (71.1%); only 14.4% did not use any fertilizer. Chemical fertilizers were applied in different doses. Figure 3 shows the doses applied to crops across all AEZs. As recommended by agricultural advisers and agricultural engineers in Benin, the majority of inland valley farmers (54%) applied between 100 and 300 kg ha^{-1}. The survey also revealed that 18% of farmers applied a maximum of 100 kg ha^{-1} to inland valley crops, and that 14% applied more than 300 kg ha^{-1}.

These doses of fertilizers used varied at AEZ level. Table 3 shows the fertilizer doses that farmers applied in each AEZ. Most producers (60%) in NB-AEZ stayed within the recommended norms (i.e. 100–300 kg ha^{-1}), either no fertilizer (11%) or the maximum of 300 kg ha^{-1} (83%). The situation was similar in A-AEZ, but more producers (24%) did not use chemical fertilizers. More farmers applied in excess of recommended rates of chemical fertilizers (more than 300 kg ha^{-1}) in S-AEZ (28%), as did a few in T-AEZ (16%).

Across AEZs, only 16.9% of the farmers used insecticides, while 34.4% used herbicides. More than two-thirds of insecticide users applied it to vegetable crops and the rest to rice

Table 4 Dose of herbicides applied by inland valley farmers (%) per agro-ecological zone in Benin

Agro-ecological zone (AEZ)	Herbicide application rate (litres ha^{-1})			
	0	1–2	2–5	>5
Northern Borgou zone (NB-AEZ)	45.6	7.78	43.3	18.9
Atacora zone (A-AEZ)	98.9	1.1	0	0
Transition zone (T-AEZ)	88.9	4.4	5.6	1.11
Southern zone (S-AEZ)	28.9	2.2	10.0	55.6
Average	65.6	3.9	14.8	18.9

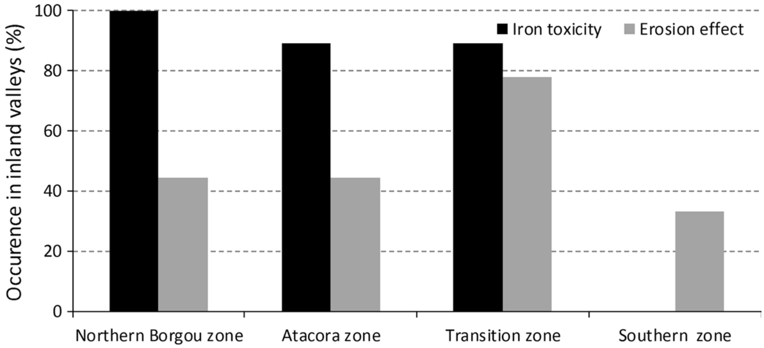

Fig. 4 Prevalence of iron toxicity and erosion in inland valleys of different agro-ecological zones in Benin

plants. Furthermore, 18% of the surveyed farmers applied herbicides on small areas within their fields. The use of chemical insecticides was most common in S-AEZ, with approximately a third (34%) of the farmers using them.

Herbicides were used most by farmers in NB-AEZ and S-AEZ (54.4 and 71.1%, respectively). Table 4 shows the doses of herbicides applied in inland valleys across and per AEZ. Herbicide dosage also varied according to the active ingredients of the product. In the inland valleys of the District of Lalo in S-AEZ, for example, producers applied herbicides twice in the same area in the same season: they used 'total weed-killers' for land preparation and 'selective weed-killers' for weeding. This use was found in intensive rice cultivation areas with full water control in the fields.

3.3 Iron toxicity and erosion in inland valleys

During the explorative phase of the study, some farmers identified the presence of iron in rice fields. Although not knowing the name of the phenomenon, they described by its characteristics or pointed it out in the affected fields. Observations revealed that iron toxicity was present in almost all inland valleys of the three northernmost AEZs. In S-AEZ, however, none of the inland valleys showed symptoms of iron toxicity (Fig. 4), which was confirmed by the farmers. Some farmers did not like to work in inland valleys due to the presence of iron toxicity. Almost all respondents had no knowledge about how to reduce iron toxicity or to manage it to mitigate its effects. They were also not aware of rice varieties that are tolerant to iron toxicity.

In terms of physical degradation of the land, we observed advanced gullying in inland valleys and their fringes. In T-AEZ, 78% of the inland valleys were affected by erosion, while in the other zones between 33 and 44% of the inland valleys showed erosion (Fig. 4). This loss of land leads to a sandbank or silting up at another place in the inland valley. Erosion also contributes to the reduction in cultivation area of these agro-ecosystems. Generally, farmers are aware of the dangers of erosion and certain farmers said that they take measures to control erosion, such as filling in and embanking ravines upstream of fields. However, this was reported in only a few cases.

3.4 Ligneous natural resources and crop residue management in inland valleys

The destruction of natural vegetation cover through the cutting of trees in studied developed inland valleys was commonly mentioned in the survey. Figure 5a shows the percentage of inland valleys with trees in the different AEZs studied. In S-AEZ, lowlands were almost devoid of ligneous species. Essentially, the inland valley agro-ecosystems of this zone are constituted of herbaceous vegetation, except in a third of cases where there are

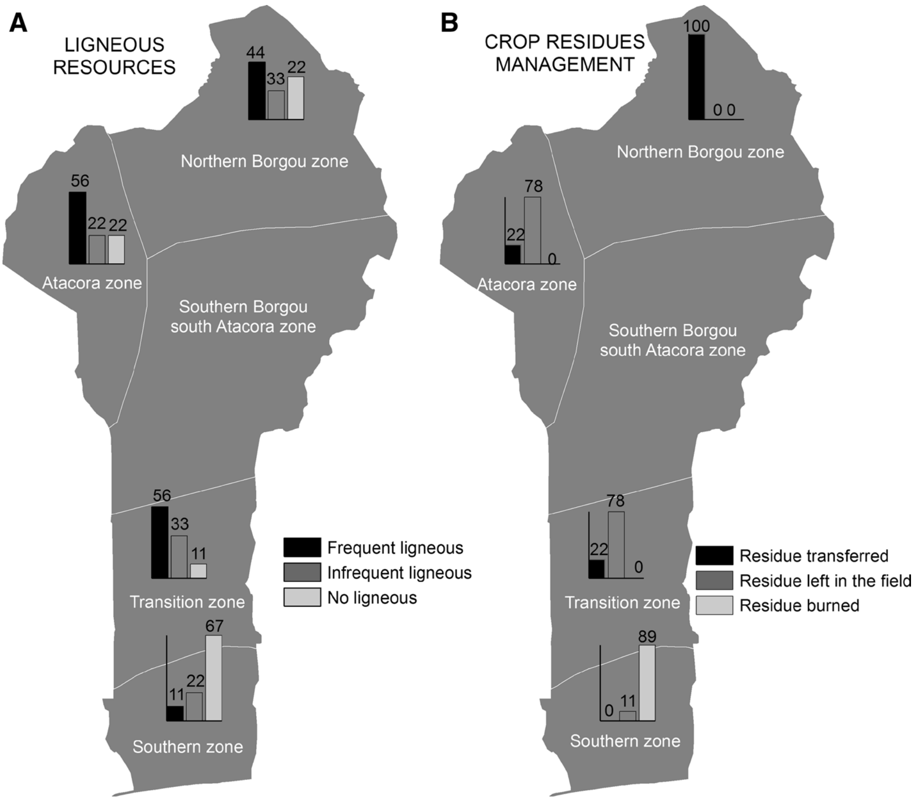

Fig. 5 Ligneous resources and crop residues management in inland valleys per agro-ecological zone in Benin

some trees. Trees and shrubs were also absent from more than 22% of inland valleys in NB-AEZ. The situation is relatively better in two other zones, where on average in 56% of the inland valleys have trees. However, in all zones many inland valleys are completely devoid of ligneous species. In some cases, the farmers proceed to use inland valley trees for charcoal production. According to farmers, the presence of trees in inland valleys reduces crop productivity. Farmers who use power tillers or tractors in land preparation remove all ligneous species from their fields, since they may delay the work and damage the machines. Farmers also reported that the presence of trees in inland valleys increases the number of granivorous birds that eat the rice grains and cause significant rice yield losses.

About the management of crop residues, crop residues from rice cultivation in inland valley agro-ecosystems are mainly burnt by the farmer in the field, transferred from the cultivation area to feed cattle or left behind in the field. This last option means that the crop residues are subject to decomposition and/or wildfires or eaten by the cattle of nomadic pastoralists. Some farmers move crop residues to their homes to feed their animals in the dry season, whereas other farmers burn all residues from their cultivation areas for soil fertility purposes and to facilitate land preparation of the new cropping campaign. The practices of farmers varied strongly across AEZs. In NB-AEZ, 100% of residues were removed from inland valleys. This zone is the region per excellence for livestock where farmers need forage for their livestock. In A-AEZ and T-AEZ, rice is harvested at the end of the rainy season, so farmers do not need to prepare the land quickly and so they abandon residues in the fields. In S-AEZ, where water is abundant and more than one crop can be cultivated during the agricultural season, farmers generally burn the residues in the inland valleys to prepare the fields for the second crop.

3.5 Causality analysis: correlation of results with agricultural intensification

National government, agricultural development agencies and donors promote agricultural intensification in inland valleys to support food security and rice self-sufficiency. This results in many cases in the removal of trees from the inland valleys. Also, residues which would potentially slow down land preparation are removed or used as cattle feed. Crop intensification in inland valleys may, therefore, lead to negative impacts on the environment and humans. We investigated stakeholders' feedbacks regarding natural resources management current states and analysed the driving forces, pressures and impacts using the DPSIR model. We further evaluated more environmentally sustainable practices and defined perspectives and responses to mitigate the negative impacts.

Figure 6 represents an adaptation of the DPSIR model for the framework and specific parameters of the conducted study in inland valleys in Benin. Agricultural intensification (the driving force) is manifested by three main aspects, i.e. the clearing of ligneous species, crop residue management and excessive usage of agrochemicals (the pressures). In the face of these pressures, inland valleys show an affected state, an environment exposed to hazards, which impacts on natural resources and humans. This new state of inland valleys leads to reduction in biodiversity, soil depletion, yield decreases and the use of high fertilizer doses, which has several negative effects on the environment, such as eutrophication, human health risks, loss of biodiversity and soil erosion. Corrective or mitigating measures must be proposed to serve as responses to these impacts. Our surveys revealed that there are no responses to mitigate or correct the negative impacts of agricultural practices on the environment. Faced with this absence of responses, actions such as crop diversification, planting of fruit trees and keeping cattle in inland valleys are suggested (perspectives) for

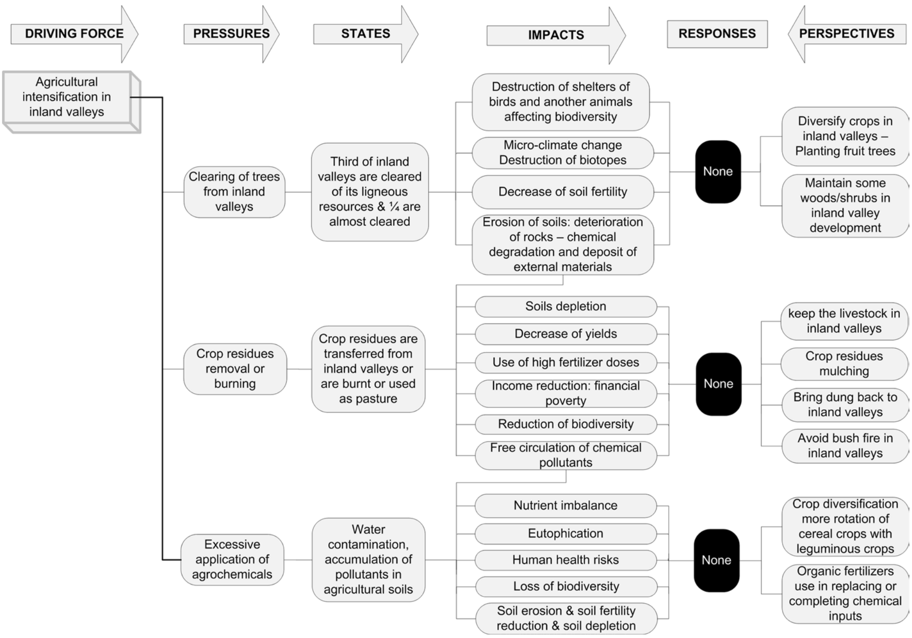

Fig. 6 Productive and sustainable agriculture in inland valleys: integration of study results in DPSIR framework

ecologically sustainable development. However, other measures may be taken to protect these agro-ecosystems and the environment, such as crop residue mulching, bringing livestock dung back to farmlands and avoiding bush fires.

4 Discussion

4.1 Crop residue management practices in inland valleys

Crop residues in inland valleys in Benin are mainly rice straw, sometimes maize cobs, or residues from cowpea and vegetables. These crop residues are either (1) removed from the farmland, (2) abandoned in the fields and burnt in wildfires or eaten by cattle or (3) burned in situ by farmers. These are also practised in other countries in Africa and Asia (Giller et al. 2009; Wang et al. 2007; Blanco-Canqui and Lal 2009). Crop residues are a potential source of renewable feed stocks for cellulosic ethanol production because of their high cellulose content (Blanco-Canqui and Lal 2009; Lemke et al. 2010). Crop residues are an important source of organic matter that can be returned to the soil for nutrient recycling to improve soil physical, chemical and biological properties and, hence, to improve soil carbon and nitrogen mineralization rates (Raiesi 2006; Dossou-Yovo et al. 2016; Edem and Ndaeyo 2009; Kulawardhana et al. 2007). Whatever the destination of removed crop residues, removal has an adverse impact on the soil, the environment and crop production (Malhi and Lemke 2007). The impact of fires on the soil can be significant: they may affect soil structure, physical, chemical and microbial properties, as well as water infiltration and run-off. Fire may thus lead to soil erosion and degradation, either by the loss of nutrients or by the removal of the mineral components (Bento-Gonçalves et al. 2012). In agricultural intensification, land is prepared to create a clean, uniform seedbed that facilitates crop establishment. So, many farmers in developing countries still rely on pre-plant burning of vegetative debris (Erenstein 2002), as is the case with crop residue management in almost all inland valley agro-ecosystems in Benin. Crop residues eaten by cattle may be equated with removal, because the animals do not leave a significant quantity of manure in the same field.

Therefore, a good practice would be to mulch the crop residues in the inland valley fields. Mulching offers great agro-ecological potential—helping to conserve the soil, improve the soil ecology, stabilize and enhance crop yield, manage weed constraints and provide various environmental services such as significant reduction in the loss of carbon from organic matter decomposition (Erenstein 2003; Blanco-Canqui and Lal 2009; Dossou-Yovo et al. 2016). Mulching would also limit water contamination by agrochemicals used in inland valleys. Other studies confirm that mulching has other beneficial effects, such as reducing soil evaporation, improving water infiltration, reducing maximum temperatures in the soil surface layers and increasing aggregate stability and soil porosity. Mulching also increases carbon sequestration through the transfer of the carbon of crops and temporary immobilization in soil, and is typically water conserving (Erenstein 2002, 2003).

Blanco-Canqui and Lal (2009) propose that, for lands from which residues are removed, best management practices must be adopted to minimize the adverse impacts of residue removal. Moderate inputs of organic matter through tillage (Wang et al. 2007) or rice straw mulching (Dossou-Yovo et al. 2016) conserve and contribute to building up soil organic carbon content through the reduction in soil CO_2 emission by increasing the soil carbon budget. The retention of crop residue mulch is increasingly recognized as essential for sustainable agriculture in India (Erenstein 2011).

The causal relationship presented in Fig. 6 lacks dynamism due to the absence of observed responses from inland valley users. In the DPSIR model, we introduced perspectives that are potential responses to mitigate the negative impact of agricultural intensification. Significant efforts by development organizations and further investigation and analysis are required, however, to introduce locally adapted solutions for sustainable inland valley development. Stakeholders must focus on awareness for inland valley farmers on the potential negative impacts and train farmers in good agriculture practices that help mitigate such impacts, such as promoted for example by scientists and NGOs in Latin America two decades ago (Altieri 1999). Examples are crop residue management such as mulching; and agricultural diversification such as rotation of cereal crops, integration of leguminous crops and maintaining or reintroducing tree crops in inland valleys. Such actions or a combination of several of them will favour the sequestration of atmospheric carbon and nitrate into the soil and reduce soil degradation. It will ultimately improve the soil organic carbon content, soil fertility and lead to sustainable crop production (Giller et al. 2009).

Corrective measures should be introduced to farmers to mitigate the negative impacts of agricultural intensification on natural resources and the environment (Malley et al. 2009). A legislative framework should support the introduction of such corrective measures and the sustainable development of natural resources in inland valleys.

4.2 Monoculture and crop diversification in inland valley agro-ecosystems

Agricultural intensification creates a tendency towards monoculture (Aragona and Orr 2011). Approximately 83% of inland valley farmers in this study cultivated only rice during the rainy season. Other studies confirm that most agricultural developments in lowlands are destined to intensive monoculture of rice (Djagba et al. 2014; Inocencio et al. 2007). Rice monoculture in inland valleys in Benin has led to high chemical fertilizer use by most farmers (Table 3; Fig. 3), which would have many negative impacts on the environment. This practice of monoculture in inland valleys leads to ecological degradation and risks such as reduced soil fertility, erosion, water pollution by nitrates and pesticides and loss of biodiversity (Malézieux and Moustier 2005) and also leads to an increased reliance on capital-intensive inputs (Aragona and Orr 2011). Soils in monoculture systems show lower values of microbiological and biochemical properties than native soils (Pascual et al. 2001). With many years of monoculture, the indiscriminate use of agrochemical inputs (especially fertilizers) will negatively affect human health and the environment. Examples are degradation of biophysical and chemical soil properties, increased risk of pests and diseases, loss of biodiversity and water contamination (Reynolds et al. 2015; Aragona and Orr 2011).

As opposite practice to intensification, crop diversification is a principle component of conservation agriculture and enhances biological processes above and below the ground (Giller et al. 2009). Diversification strategies assure adequate utilization of farmland and satisfy the food security and income generation objectives of the households (Lawal et al. 2010). Crop diversification allows reduction in the use of chemical inputs widely used in intensive monocultures and is a promising alternative for many rural societies (Malézieux and Moustier 2005). However, our survey data showed that crop diversification is little practised in inland valleys in Benin. Indeed, diversification was sometimes simply through the cultivation of a second crop in the same season, or through change of crop choice in the following year. The former was mostly a cereal followed by a vegetable crop, while the latter was the two main cereal crops, rice and maize. Although a sustainable option, leguminous crops are rarely found in crop rotations. Crop diversification during one year was almost absent in all AEZs in Benin except in S-AEZ (Fig. 2). This is largely due to the limited availability of water, although there are opportunities to cultivate cowpea before rice within the same rainy season. Studies have demonstrated the role of crop diversification and the importance of introducing a leguminous crop. Leguminous cropping may increase long-term agro-ecosystem resilience and sustainability (Edem and Ndaeyo 2009) by (1) increasing the available N supply (26–50%) compared to cereal only systems, thereby reducing the need for N fertilizer for subsequent crops; and (2) by potentially mitigating negative effects of soil organic matter loss from summer fallow (O'Dea et al. 2015). Others confirm that the crop rotation of cereal–legume forms a central pillar of conservation agriculture in the farming systems of sub-Saharan Africa (Giller et al. 2009), and that mixed cropping ensures stability of yield, income and sustainability of farmland (Lawal et al. 2010).

4.3 Environmental pollution from agrochemicals

In the past, farmers did not apply chemical fertilizer to crops in inland valleys, as they were considered as fertile farmlands. However, as a result of agricultural intensification and population pressure the practices are changing. Crop residues are removed from inland valleys, and land is rarely left fallow for soils to regain fertility (Dossou-Yovo et al. 2017). The survey revealed that only 2.5% of the inland valley farmers applied organic fertilizer to their crops. Some producers in NB-AEZ explained that the use of organic matter from animal dung brings ants and nematodes, which affect vegetables. Surveys in the framework of this study also revealed that high doses of fertilizers are now applied in inland valley agro-ecosystems in Benin: 68% of the surveyed farmers applied more than 100 kg ha^{-1} of chemical fertilizers which have nitrogen (N) as their main component. Among the farmers who did not use chemical fertilizers, 38.5% of them said that there was no fertilizer market available while 36.5% said that their financial capacity was a major limitation to buying fertilizer, and 7.7% thought that soil fertility was not a limitation for crop production. Thus, the dose of fertilizer applied varied according to the financial capacity of the farmer or to the availability of fertilizers. The survey further revealed that the highest application rates of chemical fertilizers were in horticulture; fertilizers were applied to vegetable crops almost every 2 weeks.

In S-AEZ, inland valley users applied very high doses of inputs (Tables 3, 4), especially in vegetable cultivation which is dominant in this area. The literature confirms that the agricultural sector is mainly responsible for nitrate, phosphorus, pesticide, soil sediment, salt and pathogen pollution of water from crop activities (Parris 2011; Pretty 1999; Mengistie et al. 2017). Nevertheless, experiments show that no significant differences were observed in rice yield under N fertilizer application rates of 135–270 kg N ha^{-1} (Qiao et al. 2012). Reduction in fertilizer application and enhancing N use efficiency in lowland areas is feasible through locally validated recommendations for fertilizer use (Malley et al. 2009) using new tools such as RiceAdvice (AfricaRice 2016) because the education plays a relevant role in changing farmers' lifestyles (Mengistie et al. 2017). This can increase farmer's profitability and reduce the environmental impact of agricultural intensification in inland valley landscapes.

Lowlands are generally humid areas and the transportation of dissolved chemicals though surface run-off, water streams and infiltration leads to pollution of groundwater and surface water in lakes, streams and rivers (Zedler 2003). Polluted water resources may lead to the disappearance of animals and plants, and a general reduction in biodiversity (Aktar et al. 2009; Sekovski et al. 2012). Indeed, farmers surveyed testified to the scarceness of fish in inland valleys compared to past times. Moreover, the hydrological system (streams, rivers, lakes and lagoons) will be affected by pollution and eutrophication (Karageorgis et al. 2005; Zhu and Chen 2002; Parris 2011; Sekovski et al. 2012; Smith et al. 1999; Fenn et al. 2003). The Ouémé, Mono and Couffo rivers drain into a wide and complex lagoon and delta system in southern Benin, which is important for fisheries and on which major cities depend for drinking water (Pazou et al. 2006; Agbohessi et al. 2012).

Agricultural extension and training programmes and projects initiated by the national government, NGOs or international donors as well as the Regional Agricultural Centres for Rural Development (named CARDER) contribute to higher value of crop production in lowlands (Pender et al. 2004). Our study revealed that the highest doses of chemical fertilizers are applied in inland valleys in which farmers do not receive assistance from extension agents. This confirms that continued support to inland valley farmers is required to implement sustainable agricultural development while minimizing the use of chemical inputs that damage the environment and harm the human health (Pretty 1999; Mengistie et al. 2017).

5 Conclusions

Through this study, the impacts of agricultural intensification of inland valley landscapes were analysed using field surveys and observations, and the DPSIR model. Agricultural development activities in inland valleys, which consist mainly of clearing of vegetation and establishment of water management structures, contribute to the removal of trees leading to soil degradation and reduction in biodiversity. Farm practices, including the removal of crop residues and shortening of the fallow period, lead to reduced soil fertility. Almost all crop residues are removed from the fields and consequently high doses of chemical fertilizers are required to sustain agricultural productivity. This potentially leads to the pollution of surface and ground water resources and may affect human health, biodiversity and environmental degradation in general.

Our study furthermore revealed that farmers do nothing to mitigate the impacts of agricultural intensification. Farmers are usually unaware of the potential negative effects on the environment or their own health. Through the DPSIR model, we have provided perspectives or possible solutions that support sustainable agricultural intensification. Concrete examples are crop diversification and integration of fruit trees, mulching of crop residues, avoiding bush fires in inland valleys and rotations with leguminous crops. Such practices must be further validated and adapted to local conditions in participatory on-field experiments before they can be introduced to farmers. Researchers, donors and the government play a key role in developing sustainable agricultural policies and implementing them in the framework of agricultural intensification projects and programmes.

Acknowledgements This work was supported by the European Commission through the International Fund for Agricultural Development (IFAD) under Grant C-ECG-65-WARDA; and the CGIAR Consortium Research Program (CRP) on rice, the Global Rice Science Partnership (GRiSP). The authors would like to thank Elliott Dossou-Yovo and Guy Manners for helpful comments on the manuscript. We are also grateful to the two anonymous reviewers for their constructive comments on the manuscript.

References

Adam, K. S., & Boko, M. (Eds.) (1993). Le Bénin. Les Editions du Flambloyant, EDICEF, Cotonou.

Adomou, A. C. (2005).*Vegetation patterns and environmental gradients in Benin: Implications for biogeography and conservation*. Wageningen University, Department of Plant Sciences vol. PhD thesis 150, Wageningen, The Netherlands.

AfricaRice. (2016). Japan and AfricaRice promote 'RiceAdvice' app to bolster rice yield and youth employment in Nigeria and Mali. News Release, 19 April 2016—Abidjan, Cote d'Ivoire. Available on http://www.africarice.org/warda/newsrel-RiceAdvice-apr16.asp consulted on January 5th, 2017.

Agbohessi, T. P., Toko, I. I., & Kestemont, P. (2012). État des lieux de la contamination des écosystèmes aquatiques par les pesticides organochlorés dans le Bassin cotonnier béninois. *Cahiers Agricultures, 21*(1), 46–56.

Aktar, M. W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: Their benefits and hazards. *Interdisciplinary Toxicology, 2*(1), 1–12.

Altieri, M. A. (1999). Applying agroecology to enhance the productivity of peasant farming systems in Latin America. *Environment, Development and Sustainability, 1*(3), 197–217.

Amissah-Arthur, A., & Miller, R. B. (2002). Remote sensing applications in African agriculture and natural resources: Highlighting and managing the stress of increasing population pressure. *Advances in Space Research, 30*(11), 2411–2421.

Aragona, F. B., & Orr, B. (2011). Agricultural intensification, monocultures, and economic failure: The case of onion production in the Tipajara Watershed on the Eastern Slope of the Bolivian Andes. *Journal of Sustainable Agriculture, 35*(5), 467–492.

Becker, M., & Asch, F. (2005). Iron toxicity in rice: Conditions and management concepts. *Journal of Plant Nutrition and Soil Science, 168*(4), 558–573.

Bento-Gonçalves, A., Vieira, A., Úbeda, X., & Martin, D. (2012). Fire and soils: Key concepts and recent advances. *Geoderma, 191,* 3–13.

Blanco-Canqui, H., & Lal, R. (2009). Crop residue removal impacts on soil productivity and environmental quality. *Critical Reviews in Plant Sciences, 28*(3), 139–163.

Bonierbale, T. (2004). *Eléments pour l'évaluation de la qualité environnementale des systèmes d'assainissement urbains*. Université de Marne-la-Vallée, Ingénierie de l'Environnement, vol. Thèse de Doctorat, 271 France.

de Ridder, N., Breman, H., van Keulen, H., & Stomph, T. J. (2004). Revisiting a 'cure against land hunger': Soil fertility management and farming systems dynamics in the West African Sahel. *Agricultural Systems, 80*(2), 109–131.

Dinar, A., & Mody, J. (2004). Irrigation water management policies: Allocation and pricing principles and implementation experience. *Natural Resources Forum, 28*(2), 112–122.

Direction de la Programmation et de la Prospective. (2011). Stratégie nationale pour le développement de la riziculture au Bénin. 30 Bénin: Ministère de l'Agriculture, de l'Elevage et de la Pêche (MAEP).

Djagba, J. F., Rodenburg, J., Zwart, S. J., Houndagba, C. J., & Kiepe, P. (2014). Failure and success factors of irrigation system developments: Case study from the Ouémé and Zou valleys in Benin. *Irrigation and Drainage, 63,* 328–339.

Dossou-Yovo, E. R., Baggie, I., Djagba, J. F., & Zwart, S. J. (2017). Diversity of inland valleys and opportunities for agricultural development in Sierra Leone. *PLoS ONE, 12*(6), e0180059. https://doi.org/10.1371/journal.pone.0180059.

Dossou-Yovo, E. R., Brüggemann, N., Ampofo, E., Igue, A. M., Jesse, N., Huat, J., et al. (2016). Combining no-tillage, rice straw mulch and nitrogen fertilizer application to increase the soil carbon balance of upland rice field in northern Benin. *Soil & Tillage Research, 163,* 152–159.

Drechsel, P., & Dongus, S. (2010). Dynamics and sustainability of urban agriculture: Examples from sub-Saharan Africa. *Sustainability Science, 5,* 69–78.

Edem, S. O., & Ndaeyo, N. U. (2009). Fertility status and management implications of wetland soils for sustainable crop production in Akwa Ibom State, Nigeria. *Environment, Development and Sustainability, 11*(2), 393–406.

Erenstein, O. (2002). Crop residue mulching in tropical and semi-tropical countries: An evaluation of residue availability and other technological implications. *Soil & Tillage Research, 67,* 115–133.

Erenstein, O. (2003). Smallholder conservation farming in the tropics and sub-tropics: A guide to the development and dissemination of mulching with crop residues and cover crops. *Agriculture, Ecosystems & Environment, 100,* 17–37.

Erenstein, O. (2011). Cropping systems and crop residue management in the trans-gangetic plains: Issues and challenges for conservation agriculture from village surveys. *Agricultural Systems, 104,* 54–62.

Erenstein, O., Oswald, A., & Mahaman, M. (2006). Determinants of lowland use close to urban markets along an agro-ecological gradient in West Africa. *Agriculture, Ecosystems & Environment, 117*(2), 205–217.

Fenn, M. E., Baron, J. S., Allen, E. B., Rueth, H. M., Nydick, K. R., Geiser, L., et al. (2003). Ecological effects of nitrogen deposition in the western United States. *BioScience, 53*(4), 404–420.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., et al. (2005). Global consequences of land use. *Science, 309,* 570–574.

Franke, A. C., Laberge, G., Oyewole, B. D., & Schulz, S. (2008). A comparison between legume technologies and fallow, and their effects on maize and soil traits, in two distinct environments of the West African savannah. *Nutrient Cycling in Agroecosystems, 82,* 117–135.

Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., et al. (2013). Sustainable intensification in agriculture: Premises and policies. *Science, 341,* 33–34.

Giertz, S., Steup, G., & Schonbrödt, S. (2012). Use and constraints on the use of inland valley ecosystems in Central Benin: Results from an inland valley survey. *ERDKUNDE, 66*(3), 239–253.

Giller, K. E., Witter, E., Corbeels, M., & Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research, 114,* 23–34.

Hussain, I., Gichuki, F., Louw, M. A., Andah, W., & Moustafa, M. (2007). Agricultural water management pathways to breaking the poverty trap: Case studies of the Limpopo, Nile and Volta River Basins. *Irrigation and Drainage, 56,* 277–288.

Inocencio, A., Kikuchi, M., Tonosaki, M., Maruyama, A., Merrey, D., Sally, H. &de Jong, I. (2007). Costs and performance of irrigation projects: A comparison of sub-Saharan Africa and other developing regions. 81 Colombo, Sri Lanka: International Water Management Institute, Research Report 109.

Jennings, S. (2005). Indicators to support an ecosystem approach to fisheries. *Fish and Fisheries, 6,* 212–232.

Johansson, R. C., Tsur, Y., Roe, T. L., Doukkali, R., & Dinar, A. (2002). Pricing irrigation water: A review of theory and practice. *Water Policy, 4,* 173–199.

Karageorgis, A. P., Skourtos, M. S., Kapsimalis, V., Kontogianni, A. D., Skoulikidis, N. T., Pagou, K., et al. (2005). An integrated approach to watershed management within the DPSIR framework: Axios River catchment and Thermaikos Gulf. *Regional Environmental Change, 5,* 138–160.

Kulawardhana, R. W., Thenkabail, P. S., Vithanage, J., Biradar, C., Islam, M. A., Gunasinghe, S., et al. (2007). Evaluation of the wetland mapping methods using Landsat ETM + and SRTM data. *Journal of Spatial Hydrology, 7*(2), 62–96.

Lambin, E. F., Rounsevell, M. D. A., & Geist, H. J. (2000). Are agricultural land-use models able to predict changes in land-use intensity? *Agriculture, Ecosystems & Environment, 82,* 321–331.
Lawal, A. F., Omotesho, O. A., & Adewumi, M. O. (2010). Land use pattern and sustainability of food crop production in the fadama of Southern Guinea Savanna of Nigeria. *African Journal of Agricultural Research, 5*(3), 178–187.
Lemke, R. L., VandenBygaart, A. J., Campbell, C. A., Lafond, G. P., & Grant, B. (2010). Crop residue removal and fertilizer N: Effects on soil organic carbon in a long-term crop rotation experiment on a Udic Boroll. *Agriculture, Ecosystems & Environment, 135,* 42–51.
Malézieux, É., & Moustier, P. (2005). La diversification dans les agricultures du Sud :À la croisée de logiques d'environnement et de marché: Un contexte nouveau. *Cahiers Agricultures, 14*(3), 277–281.
Malhi, S. S., & Lemke, R. (2007). Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emissions in a second 4-yr rotation cycle. *Soil and Tillage Research, 96,* 269–283.
Malley, Z. J. U., Taeb, M., & Matsumoto, T. (2009). Agricultural productivity and environmental insecurity in the Usangu plain, Tanzania: Policy implications for sustainability of agriculture. *Environment, Development and Sustainability, 11*(1), 175–195.
Maméri, C., Mohamed, K., & Miézan, M. K. (2008). Intensification de la riziculture de bas-fonds dans le Sine-Saloum (Sénégal). *Cahiers Agricultures, 17,* 451–455.
McCartney, M. P., & Houghton-Carr, H. A. (2009). Working wetland potential: An index to guide the sustainable development of African wetlands. *Natural Resources Forum, 33*(2), 99–110.
Mengistie, B. T., Mol, A. P. J., & Oosterveer, P. (2017). Pesticide use practices among smallholder vegetable farmers in Ethiopian Central Rift Valley. *Environment, Development and Sustainability, 19*(1), 301–324.
O'Dea, J. K., Jones, C. A., Zabinski, C. A., Miller, P. R., & Keren, I. N. (2015). Legume, cropping intensity, and N-fertilization effects on soil attributes and processes from an eight-year-old semiarid wheat system. *Nutrient Cycling in Agroecosystems, 102,* 179–194.
Ogban, P. I., & Babalola, O. (2003). Soil characteristics and constraints to crop production in inland valley bottoms in southwestern Nigeria. *Agricultural Water Management, 61*(1), 13–28.
Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., & Grace, P. (2014). Conservation agriculture and ecosystem services: An overview. *Agriculture, Ecosystems & Environment, 187,* 87–105.
Parris, K. (2011). Impact of agriculture on water pollution in OECD countries: Recent trends and future prospects. *Water Resources Development, 27*(1), 33–52.
Pascual, J. A., Ros, M., Hernandez, T., & Garcia, C. (2001). Effect of long-term monoculture on microbiological and biochemical properties in semiarid soils. *Communications in Soil Science and Plant Analysis, 32*(3–4), 537–552.
Pazou, E. Y. A., Lalèyè, P., Boko, M., van Gestel, C. A. M., Ahissou, H., Akpona, S., et al. (2006). Contamination of fish by organochlorine pesticide residues in the Ouémé River catchment in the Republic of Bénin. *Environment International, 32,* 594–599.
Pender, J., Nkonya, E., Jagger, P., Sserunkuuma, D., & Ssali, H. (2004). Strategies to increase agricultural productivity and reduce land degradation: Evidence from Uganda. *Agricultural Economics, 31,* 181–195.
Pirrone, N., Trombino, G., Cinnirella, S., Algieri, A., Bendoricchio, G., & Palmeri, L. (2005). The Driver-Pressure-State-Impact-Response (DPSIR) approach for integrated catchment-coastal zone management: Preliminary application to the Po catchment-Adriatic Sea coastal zone system. *Regional Environmental Change, 5,* 111–137.
Place, F., & Otsuka, K. (2000). Population pressure, land tenure, and tree resource management in Uganda. *Land Economics, 76*(2), 233–251.
Pretty, J. (1999). Can sustainable agriculture feed Africa? New evidence on progress, processes and impacts. *Environment, Development and Sustainability, 1*(3), 253–274.
Purushothaman, S., Patil, S., & Francis, I. (2013). Assessing the impact of policy-driven agricultural practices in Karnataka, India. *Sustainability Science, 8,* 173–185.
Qiao, J., Yang, L., Yan, T., Xue, F., & Zhao, D. (2012). Nitrogen fertilizer reduction in rice production for two consecutive years in the Taihu Lake area. *Agriculture, Ecosystems & Environment, 146,* 103–112.
Raiesi, F. (2006). Carbon and N mineralization as affected by soil cultivation and crop residue in a calcareous wetland ecosystem in Central Iran. *Agriculture, Ecosystems & Environment, 112,* 13–20.
Ranaivomanana, L. N. J. (2006). *Identification des conditions d'appropriation de la gestion durable des ressources naturelles et des écosystèmes*: « Cas du Grand Récif de Toliara » . Vol. Thèse de doctorat, 256 Ecole nationale Supérieure Agronomique de Rennes, France et de l'Université de Toliara, Madagascar.

Rasul, G., & Thapa, G. B. (2004). Sustainability of ecological and conventional agricultural systems in Bangladesh: An assessment based on environmental, economic and social perspectives. *Agricultural Systems, 79,* 327–351.

Reynolds, T. W., Waddington, S. R., Anderson, C. L., Chew, A., True, Z., & Cullen, A. (2015). Environmental impacts and constraints associated with the production of major food crops in Sub-Saharan Africa and South Asia. *Food Security, 7,* 795–822.

Rodenburg, J., Zwart, S. J., Kiepe, P., Narteh, L. T., Dogbe, W., & Wopereis, M. C. S. (2014). Sustainable rice production in African inland valleys: Seizing regional potentials through local approaches. *Agricultural Systems, 123,* 1–11.

Sakurai, T. (2006). Intensification of rainfed lowland rice production in West Africa: Present status and potential green revolution. *The Developing Economies, XLIV*(2), 232–251.

Sayer, J., & Cassman, K. G. (2013). Agricultural innovation to protect the environment. *Proceedings of the National Academy of Sciences of the United States of America, 110*(21), 8345–8348.

Schulze, R. E. (2004). River basin responses to global change and anthropogenic impacts. In P. Kabat et al. (Eds.), *Vegetation, water, humans and the climate* (pp. 339–374). Berlin: Springer.

Schuyt, K. D. (2005). Economic consequences of wetland degradation for local populations in Africa. *Ecological Economics, 53*, 177–190.

Sekovski, I., Newton, A., & Dennison, W. C. (2012). Megacities in the coastal zone: Using a driver-pressure-state-impact-response framework to address complex environmental problems. *Estuarine, Coastal and Shelf Science, 96,* 48–59.

Singbo, A. G., & Lansink, A. O. (2010). Lowland farming system inefficiency in Benin (West Africa): Directional distance function and truncated bootstrap approach. *Food Security, 2,* 367–382.

Smith, V. H., Tilman, G. D., & Nekola, J. C. (1999). Eutrophication: Impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution, 100,* 179–196.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature, 418,* 671–677.

Verburg, P. H., Veldkamp, T. A., & Bouma, J. (1999). Land use change under conditions of high population pressure: The case of Java. *Global Environmental Change, 9*(4), 303–312.

Vissoh, P. V., Gbèhounou, G., Ahanchédé, A., Kuyper, T. W., & Röling, N. G. (2004). Weeds as agricultural constraint to farmers in Bénin: Results of a diagnostic study. *NJAS-Wageningen Journal of Life Sciences, 52*(3–4), 305–329.

Wakatsuki, T., & Masunaga, T. (2005). Ecological engineering for sustainable food production and the restoration of degraded watersheds in tropics of low ph soils: Focus on West Africa. *Soil Science and Plant Nutrition, 51*(5), 629–636.

Wang, X., Hoogmoed, W. B., Cai, D., Perdok, U. D., & Oenema, O. (2007). Crop residue, manure and fertilizer in dryland maize under reduced tillage in northern China: II nutrient balances and soil fertility. *Nutrient Cycling in Agroecosystems, 79,* 17–34.

Windmeijer, P. N., & Andriesse, W. (Eds.). (1993). *Inland valleys in West Africa: An agroecological characterization of rice growing environments* (Vol. 52, p. 160). Wageningen: ILRI Publication.

Yabi, I., & Afouda, F. (2012). Extreme rainfall years in Benin (West Africa). *Quaternary International, 262*(7), 39–43.

Zedler, J. B. (2003). Wetlands at your service: Reducing impacts of agriculture at the watershed scale. *Frontiers in Ecology and the Environment, 1*(2), 65–72.

Zhu, Z. L., & Chen, D. L. (2002). Nitrogen fertilizer use in China: Contributions to food production, impacts on the environment and best management strategies. *Nutrient Cycling in Agroecosystems, 63*(2–3), 117–127.

Zorom, M., Barbier, B., Mertz, O., & Servat, E. (2013). Diversification and adaptation strategies to climate variability: A farm typology for the Sahel. *Agricultural Systems, 116,* 7–15.