Final report

Project ANR-13-AGRO-002

CERAO

Programme AGROBIOSPHERE 2013

A IDENTIFICATION

Project acronym	CERAO
Project title	Self-adaptation of tropical agro-socio-ecosystems to global changes? A long term study for ecological intensification of cereal production in West African savannas
Coordinator of the French part of the project (company/organization)	
Coordinator of the xxx part of the project (company/organization)	
Project coordinator (if applicable)	MASSE Dominique (IRD)
Project period (Start date – End date)	01/01/2014-31/12/2018
Project website, if applicable	

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B CONSOLIDATED PUBLIC SUMMARY

B.1 CONSOLIDATED PUBLIC SUMMARY IN FRENCH

Fondements sociaux et écologiques d'une intensification agricole durable in Senegal

Comprendre l'adaptation passée des systèmes agricoles pour faire face aux futurs changement sociaux et climatiques dans les régions semi-arides en Afrique Sub-Saharienne

Le projet CERAO a pour objectif de contribuer à l'émergence de nouveaux systèmes agricoles permettant d'atteindre la sécurité alimentaire, la préservation de l'environnement et l'adaptation aux changements climatiques dans les régions semi-arides en Afrique de l'Ouest. L'agroécologie et l'ingénierie écologique permettent aux agrosystèmes de conserver ou de retrouver des propriétés écologiques favorisant une capacité d'adaptation et de résilience dans un monde

changeant. Les systèmes agricoles « traditionnels » sont issues d'un long processus de sélection de pratiques agricoles adaptées à leur environnement spécifique. Il s'agit alors de comprendre les fondements écologiques et sociaux du fonctionnement d'un agrosystème qui lui confère cette capacité de résilience et d'adaptation. C'est à partir de cette lecture que pourront être définies les futures voies d'une intensification agricole durable. Les objectifs spécifiques du projet CERAO étaient d'analyser la dynamique au cours des 50 dernières années des trajectoires agricoles de 3 villages situées sur l'observatoire Population Santé Environnement de Niakhar (OPSEN) au Sénégal.

Dynamique spatiale et temporelle des structures sociales, des systèmes de culture, des cycles des nutriments, et de la diversité génétique du mil
Trois agrosystèmes ont été comparés : Barry Sine marqué par un fort développement de l'embouche bovine, tout comme à Sob mais où des agriculteurs ont récemment développé une production pluviale de pastèque. A Diohine-Sassem, la traditionnelle rotation triennale mil - arachide - jachère s'appuyant sur une gestion collective des espaces culturaux est toujours d'actualité. Les données climatiques, démographiques et d'occupation des terres ont été rassemblées. La dynamique socio-économique des ménages a été évaluée par enquêtes en ciblant les exploitations agricoles pratiquant de nouvelles productions. Par ailleurs, une large enquête a été initiée au cours du projet sur près de 600 ménages pour évaluer les capacités d'adaptation. Un diagnostic agronomique a été réalisé pour analyser les performances des systèmes de culture. Le bilan et l'efficience d'utilisation de l'azote ont été évalués par enquête à l'échelle du champ, du ménage et du village, et ont été simulées par des modèles mathématique et informatique (SMA). La diversité génétique des Mils et les processus d'échange des semences ont été caractérisés. Enfin, une approche participative a débuté en 2018 pour confronter les points de vue et valider les résultats avec l'ensemble des acteurs.

Les principaux résultats concernent (i) la variabilité des performances des systèmes de culture à base de mil (ii) la relative stabilité dans le temps de la diversité génétique des mils et l'importance des systèmes locaux de diffusion des semences, (iii) l'impact positif sur le recyclage des nutriments de ces systèmes agro-sylvo-pastoraux. Concernant les aspects sociaux, l'analyse de pratiques agricoles a révélé l'importance de règles foncières flexibles, des solidarités familiales ou celles issues de l'émergence de nouveaux réseaux de proximité pour une approche collective des risques, et enfin de la diversification des réseaux d'échange d'information.

Les résultats sont consignés dans des thèses de doctorat (deux ont été soutenues et quatre devraient l'être en 2019 ou 2020), dans une quinzaine de mémoire de master2 et 2 rapports techniques. Les publications scientifiques dans des revues à comité de lecture concernent l'analyse multi-échelle des cycles de nutriments dans les agrosystèmes par des approches de modélisation mathématique et informatique, ainsi que des modèles conceptuels définissant les processus de décision des agriculteurs quant à la gestion des biomasses et des nutriments. Une publication pose la question des relations entre migration, résilience et adaptation des populations de Niakhar. Ces documents seront déposés sur la plateforme internet réunissant l'ensemble des travaux réalisés sur l'OPSEN (https://lped.info/wikiObsSN/?HomePage).

Légende : Flux d'azote(kgN.kg^{-1}.an^{-1}) entre les différents compartiments d'un agrosystème de la région de Niakhar au Sénégal. D'après Grillot et al. Agr. Syst. 164(2018) 133-151. Crédits photo M Ba/D Masse

Le programme de recherches CERAO (2014-2018) a été coordonné par D Masse, chercheur à l'Institut de Recherche pour le Développement et dans l'unité mixte de recherche ECO&SOLS, et réalisés par un collectif de chercheurs appartenant aux unités et institutions suivantes : SELMET/CIRAD, ECO&SOLS/IRD, LPED/IRD, DIADE/IRD, LNRPV/ISRA et LPAOSF/UCAD au Sénégal. Le coût total du projet était de 3 414 752 € dont 628 930 € financé par l'ANR et 42 208 € par l'AIRD/IRD.

B.2 CONSOLIDATED PUBLIC SUMMARY IN ENGLISH

Social and ecological keystones for agricultural sustainable intensification in Senegal

Understanding past to present adaptation trajectories of farming systems to cope with future social and climatic changes in semi-arid Sub Saharan Africa

CERAO project aimed to contribute to the emergence of agricultural systems dealing with food security, environment preservation and climatic change adaptation in West African semi-arid region. Agro-ecology or ecological engineering allows agroecosystems to retrieve their ecological properties conferring adaptation and resilience capacity in a changing world. Traditional agricultural systems resulted from a long term selection of best adapted practices to the specific environmental context. Therefore, revisiting past to present agro-socio-ecosystems trajectories with the regard of their ecological and social keystones should allow to highlight principal keys for guidance in future agricultural intensification schemes. The specific objective of CERAO was to analyze contrasted agroecosystem and their dynamics along the past 50 years on the Health, Population and Environment Surveillance System of Niakhar (HPESS) in Senegal.

Assessing and modelling social changes, agronomic performances, nutrient cycling and cereal biodiversity management at temporal and spatial scales

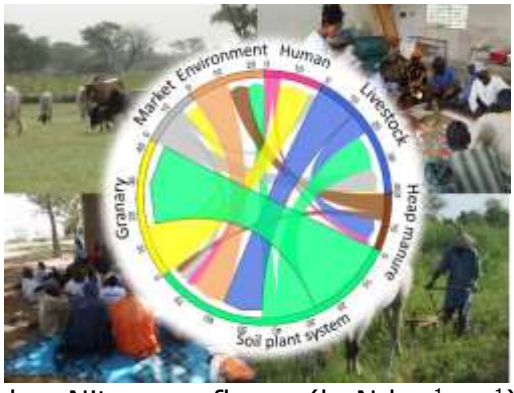
Three 10-km distant neighboring agroecosystems were chosen. Barry Sine farmers developed a market-oriented livestock system. In Sob, market-oriented livestock was also largely present, but innovate watermelon cropping system recently appeared. In Diohine-Sassem the traditional land use system marked by the collectively managed pearl millet-peanut-fallow triennial rotation still prevailed. Climate, demographic and land use changes during the last 50 years were updated with recent observations. Then, the dynamic of the social and economic status of households were assessed by surveys with a focus on new

practices. A large survey on 610 households was also initiated to assess the adaptation and resilience capacity of households. Agronomic diagnostic was used to understand the yield performance after long term contrasted soil fertility managements. Nitrogen balance and use efficiency were assessed at the scale of the field, the farm and the village. Mathematical and agent-based modellings were developed to estimate the nutrient cycling performance of the crop livestock systems over the time. Millet genetic diversity was characterized and seeds supply systems were assessed. Finally, multi actor workshops were carried out during the last year to share and validate the results with stakeholders.

Main results

Main results concerned (i) the Millet cropping systems performance variability, (ii) the temporal and spatial repartition of Millet genetic diversity and its adapted seed diffusion systems, and (iii) the positive impact of crop-livestock-tree systems on nutrient cycles. From a social point of view, the analysis of emergent practices highlighted the key role of (i) the land exchanges and its flexibility, (ii) the family solidarity an emerging brotherhood networks, and (iii) the diversification of information transmission channels to strengthen the collective management of the risks and the uncertainties (climate, market).

Results were reported in PhD theses (2 already defended and 4 to be achieved in late 2019 or early 2020), 15 Master theses and two technical reports. Five articles published in ISI indexed journals concerned the analysis of nutrient multi-scales fluxes based on mathematical and computer modelling, and on a conceptual model of farmers decision pathways on biomass management in the different integrated crop-livestock systems. One publication addressed the relation of migration, resilience and adaptation of people at Niakhar over time. These documents will be dropped on the web platform of the HPSSE of Niakhar (https://lped.info/wikiObsSN/?HomePage).



Legend : Nitrogen flows (kgN.ha^{-1}.yr^{-1}) between the main components of an agroecosystem in Niakhar, Senegal. D'après Grillot et al Agr.Syst. 164 (2018) 133-151. Credits Photo M Ba / D Masse

The CERAO research program (2014-2018) was coordinated by D Masse, a IRD scientist (French research institute for sustainable development), at ECO&SOLS unit and carried out by researchers the following research unit/institute SELMET /CIRAD, ECO&SOLS, LPED and DIADE /IRD, and LNRPV/ISRA and LPAOSF/UCAD for the Senegalese partners. The total cost of the project was 3 414 752 € including 628 930 € from ANR and 42 208 € from AIRD.

C SCIENTIFIC REPORT

Confidential scientific report: ~~yes~~ / no

C.1 REPORT SUMMARY

Increasing agricultural production based on sustainable intensification is a huge challenge of SSA countries. CERAO aimed to revisit past to present agro-socio-ecosystems trajectories with the regard of ecological and social properties. This will allow to highlight key principles for guidance in future agricultural intensification schemes. Three contrasted agro-socio-ecosystems and their dynamics along the last 50 years on the Health, Population and Environment Surveillance System of Niakhar (HPESS) in Senegal were compared: one having kept their traditional agro-sylvo-pastoral, and the others presenting agricultural intensification pathways. Household surveys, field experiments, climatic and demographic databases analysis, and modelling were carried out to identify some keystones of future farming systems.

Main results concerned (i) the past inherited variability of cropping systems performances which was also an adaptive response to erratic rainfalls and other risks as weed, (ii) the relative maintenance of local Millet diversity linked to an appropriate seed diffusion system, and (iii) the positive performance on productivity and nutrient cycling of the crop-livestock-tree integration system. In a social point of view, emergent practices analyse highlighted the key role of (i) the land exchanges flexibility, (ii) the family solidarity but also new emerging social groups brotherhood networks strengthening the collective management of the risk and the uncertainty (climate, market), and (iii) the diversification of information transmission channels. These social and ecological could be considered as the keystones of future sustainable farming systems in the context of the Groundnut Basin and other equivalent tropical semi-arid agrosystems.

C.2 CHALLENGES AND ISSUES, STATE OF THE ART

Increasing agricultural production is a huge challenge of Sub Saharan African (SSA) countries. However, it is necessary to propose a new paradigm of agricultural development that enhance agricultural production while preserving natural resources and being adapted to climate changes. Agro-ecology and more largely ecological engineering concepts were proposed to solve the equation of sustainable management for these complex issues[1,2]. In ecology science, some authors attributed a self-designing capacity of ecosystems that support the more efficient adaptation[3]. One challenge would be to help agro-systems to retrieve their ecological properties conferring resilient and self-designing capacity to adapt itself permanently. Traditional agricultural systems and farmers' practices resulted from a long term selection of best adapted practices in a specific environmental context. The hypothesis was that viable and sustainable agro-socio-ecosystem trajectories are guided by meta-rules referring to the social and environmental local context. Therefore, past to present agro-socio-ecosystems trajectories were revisiting with the regard of ecological and social scientific concepts such as biodiversity, nutrient cycling, socio-economy**.** This will allow to highlight key principles for guidance in future agricultural intensification schemes**.** The overall objectives of the CERAO project were to contribute to the emerging of future agricultural practices dealing with food security and environment preservation in a context of climatic and social changes in semi-arid sub-Saharan regions in West Africa. The specific objectives of CERAO were to analyze the social, ecological and agronomic dynamics along the last 50 years of contrasted agro-socio-ecosystem situated on the Health, Population and Environment Surveillance System of Niakhar (HPESS) in Senegal.

C.3 SCIENTIFIC AND TECHNICAL APPROACH

The HPESS was situated in the semi-arid zone of Senegal in the so called *the old Groundnut Basin*. Over the last decades, this region faced to significant climatic change, which started with severe droughts in the 70s, and experienced socio-economic disruption marked population growth, migratory movements and market deregulation. The climate was

typically representative of Sudan-Sahelian climate with a two contrasted periods: a short rainy season between July and September and a long dry season from October to June. Lixosols were the most dominant soils. The pearl millet cereal was the main staple crop. Peanuts, the main cash crop, and in a lesser extent black eye peas (*"niébé*") are the main cropped legumes. Livestock, bovid and sheep, was socially important for *Serer* people who was the dominant ethnic group. Trees were permanent in these ecosystems not only in non-cultivated area but also in fields with the parkland of *Acacia albida*. Other plant productions concerned the market gardening production during the dry season in lowlands, and watermelon which offered also incomes for farmers. Tillage practices combined manual and mechanized practices with horse traction.

Three neighboring agro-socio-ecosystems were chosen according to their contrasted characteristics highlighted in the ESCAPE project (ANR ANR-10-CEPL-0005). Barry Sine developed a market-oriented livestock system. In Sob, market-oriented livestock was also largely present, but innovate watermelon cropping system recently appeared. Diohine-Sassem represented the traditional land use system marked by the collectively managed pearl millet-peanut-fallow triennial rotation. The CERAO project will address related changes in biomass and nutrients cycles, in the cultivated plant biodiversity and the social and economic status dynamics of people. Before that, climate, demographic and land use changes during the last 50 years are clarified in accordance with recent observations.

C.4 ACHIEVED RESULTS

Analysing of 18 rain gauges between 1982 and 2015 situated in the HPESS of Niakhar indicated an average annual rainfall of 505 mm (CV 27%) with a trend of increase during the last decade to reach 600 mm of annual rainfalls in 2010s. The daily rainfall analyses highlighted the high inter- and intra-annual variability of dry and wet spells, but also the spatial variation between two points distant for less than 10 km (Fall CMN, ongoing PhD thesis). General overview of the demographic evolution of Diohine, Barry Sine and Sob showed similar structure by age and sex (Delaunay V monography). However, the population growth was sustained more particularly in Barry Sine (+3% per year between 1984 and 2013) led to high population density (530, 238 and 236 inhabitants per km^2 in Barry Sine, Sob and Diohine respectively in 2014). The population growth in Barry Sine and Sob was mostly related to natural growth, while that in Diohine it was more related to migration. Two *pleiade* remote sensing images analysis revealed past landscape structures always visible as corridor which facilitated livestock movement in the cultivated area and between village. Clearly visible circular shapes appeared also measuring between 10 and 20 m in diameter which were certainly evidence of old eroded termite mounds. Parkland trees distribution seemed to be linked to these circular shapes. Analysing satellite images of 1968 (Corona), an aerial photograph of 1989, and a satellite image of 2016 (Spot7) of the entire HPESS of Niakhar (447 km^2) revealed that the land occupation since 1960s did not radically change excepted some slight variations (Ndiaye ML et al. monography).

Households strategies of adaptation to deal with social and environmental changes were previously studied during the ESCAPE project (ANR). Based on the analysis of two new practices – watermelon production and the long cycle millet called "*matye*", it was shown that households concerned with these changes generally endowed the highest capital. But, key factors appeared also (i) the land tenure flexibility favouring land exchanges, (ii) the family solidarity or brotherhood networks in new emerging social groups that reinforced the collective management of the risk and the uncertainty (climate, market), and (iii) the diversification of information transmission channels (Mars C Master thesis). Traditionally, women had not access to land and capital and were implied in agriculture globally as workforce. They were more interested in off-farm activities to have incomes but they were limited by their capital endowment (Maffray H Master thesis). In 2014 and 2015 CERAO launched two rounds household survey. Among 600 households were randomly selected in the HPSSE databased. The three villages specifically studied in CERAO were concerned by the surveys. Qualitative and quantitative questions aimed to document the household's characteristic, the food system, the cropping system, the land resource, the natural

resources and climatic changes perception and adaptation, the livelihood and well beings of people (C Tine PhD thesis to be achieved, Fonton J Master thesis).
Yield performances of 23 farmers' fields in Diohine indicated the variable management of fields. Homefields, closed to the village, received preferentially organic inputs conferring highest plant growth and grain yields, reduced the soil acidity and increased the nutrients availability (Mbengue M Master thesis). Two fields experiments were launched in 2015 to evaluate (i) the cereals yields on the homefields and the outfields under a gradient of organic inputs addition crossed with a gradient of chemical fertilizers addition (ii) to assess the response of the millet production to chemical fertilizers in the context of 19 contrasted farmers' fields. These experiments showed that the performance of cropping systems was strongly influenced by contrasted long term soil fertility management i.e. homefield vs outfield. Supported by soil plant modelling, it was concluded that crop performance intensification needed to be adapted to this variability of past inherited soil fertility management practices, and that phosphorus availability was certainly a major constraint (PhD thesis Tounkara A to be achieved). Legumes, more particularly peanut crop and in a lesser extent black eye pea, were largely integrated in cropping systems and generally associated with other plant production (Oddos L Bachelor thesis). Experiments were launched in 2015 to test Cereal (pearl millet) – legume (black eye pea) intercropping to increase the contribution of legumes to increase primary production (Mbengue M PhD thesis, on-going).
Multi-scale nitrogen balances were assessed on the three studied villages: in Diohine-Sassem (Odru E master thesis) and in Barry Sine (Audoin E master thesis) with the collaboration of the EU project Animal Change in 2013, and Sob in 2015 (Saunier-Zoldobrota T and Dugy T master thesis). On each site, all farmers' fields and land use were mapping (ArcGis datafiles), and each field and farm were documented with regard to biomass and grain production and its fate, to the amount and origin of organic and mineral fertilizers, to the livestock systems, and to the use of parkland trees. Each farm was linked to the HPESS household database. Apparent average nitrogen balances were all negative at plot scale (respectively -9, -13 and -23kgN.ha^{-1}.y^{-1} for Sob, Sassem and Barry Sine) and positive at farm scale (respectively +12, +11 and +25kgN.ha^{-1}.y^{-1} for Sob, Sassem and Barry Sine), and village scale (respectively +4, +9 and +25kgN.ha^{-1}.y^{-1} for Sob, Sassem and Barry Sine. Despite apparent contrasts of agricultural practices between villages, livestock, and in a lesser extent the parkland of *Acacia albida*, remained essential as vector of nutrient and biomass to conserve positive nitrogen balances at the territory scale [4].
The ecological concept of meta-ecosystem was applied to understand how mechanisms interact between rangeland and cropland areas linked by livestock on nutrient cycles. Different modelling steps from a more complex to a more simply representation, highlighted the role of livestock as a "nutrient pump" from rangeland to cropland and the highest capacity of crop livestock integration system to produce biomass without any external inputs (Bisson A PhD thesis). Using the control theory, it was showed that the daily or weekly appropriate control of the herbivory pressure could produce additional total biomass including crop production for the same amount of nutrients transferred from rangelands to croplands [5]. Nitrogen cycle dynamics during the last century was assessed with a multi agent based modelling based on a conceptual model of adaptive management of biomass [6-8]. This new model called TERROIR [9] analysed nutrient cycles at three levels of organization: plot, household, and landscape. Simulating extensive livestock system based on free grazing and intensive livestock system based on stalled-fattening animals highlighted bottlenecks along the nitrogen (N) cycle like accumulation of N in manure heaps and housing areas. This reduced N recycling efficiency, especially in "intensive" systems. Analysing the N balance with TERROIR model on the agrarian transition along the last century highlighted the intensification of nitrogen flows, but also a reduction nitrogen use efficiency, due to incomplete return of nutrients to cultivated plots[10]. Some tested technologies to monitor N cycle as manure heap coverage could be used to control N losses (Grange G Master thesis).
The genetic resources of pearl millet and their wild relatives have been characterized combining population genomics and ethnobotany. All these results are based on extensive

data collection where more than 17,000 plants were phenotyped for 10 agronomic traits, 1500 plants were genotyped for more than 200,000 SNPs out of 16,000 genes and more than 200 farmer interviews were conducted. A temporal analysis of diversity comparing the diversity of local varieties over a 40-year period (1976-2016) showed a stable genetic diversity. Genomic scan and genotype-phenotype association approaches (GWAS) allowed us to identify genes linked to flowering, which is one of the first adaptive responses to climate change (Faye A Post-doctorate, Faye Al. Master thesis). A greater genetic similarity was noticed between today's early- and late-flowering landraces compared to 40 years ago (Olodo K PhD Thesis to be achieved, Cissé A Master thesis). Analysing the farmers' supply of millet seed over time showed that the local seed systems provide access to a diversity of varieties. This contributed to the capacity of adaptation of face to climate and plant pathogens risks. The introduction of improved varieties tends to modify the modalities of access to seeds, from "free" to monetary both for local or improved varieties (Suzanne G, Ledoussal S, Master thesis).
In 2018, an iterative and multi-stakeholder participatory approach were launched to confront the point of view of scientists and the vision of local actors (technicians, farmers and other social groups) on over time agricultural systems trajectories (Ba M, PhD Thesis, to be achieved). A series of workshops in Dakar and in the 3 studied villages were carried out in 2018. A participatory mapping and simulation offered a structured and efficient framework of reflexion and dialogue between actors. This allowed participants to re-build trajectories of the 3 studied villages according to social, cultural, economic, politic, and environmental drivers. The first conclusions were that viewpoints could be different between scientists and farmers. For instance, the former divided the 1960-2016 period by 3 climatic periods while farmers distinguished in detail five periods. Also, it was confirmed that history of settlement and initial relationship of dependence between groups of different statuses explained numerous decisions and comportments of people[11].

C.5 Discussion and conclusion

Spatial heterogeneity and variability for sustainable intensification,
The project aimed to review the history of 3 villages in the semi-arid region of Senegal according to different points of view. The high climate variability was noticeable and induced a great uncertainty and risks to which people and farmers were traditionally adapted more particularly concerning their agricultural practices[12,13]. The heterogeneity of soil fertility management according to the position of the fields in the agro-system was certainly a response to the environmental and social risk as it was also highlighted by other works[14,15]. Pearl millet phenotype supported by a high genetic variability seemed to be preserved and have to conserve for future adaptation. Co-existence of local and conventional principles of seeds diffusion could favour the genetic resources preservation. Two major properties appeared to be outlasting the transition in term of soil fertility management: (i) independence towards external inputs, based on crop-livestock integration, i.e. high biomass and nutrient recycling within the system; (ii) spatial heterogeneity linked to biomass and nutrient transfers from not cultivated lands to cropped lands with livestock as vector. We argue that the persistence of these two emerging properties is a key pattern of these agrosystems conferring a capacity of resilience. Consequently, one of the main hypothesis to be questioned is that for the necessary soil nutrients replenishment for agricultural production intensification, it would be better to introduce nutrients by animal feeds than directly by chemical fertilizers with the condition of an appropriate management of nutrients fluxes.
Social flexibility and networking for adaptation and resilience
It was already shown that migration played a role in the adaptation of households face to the climatic risk, but also to the economic context variation, e.g. peanut value chain deregulation[16]. High demographic rate was also a driver of change and multiple activities including temporary migration allowed the relative viability of high density population[17]. But migration was not an inevitable process[18]. For instance, it seemed that the village of Sob was less concerned by long migrations (to Dakar and other main Senegalese towns) than the other 2 villages. This could be related to more innovate agricultural practices observed in

Sob as the rainy season watermelon production. Off farms activities needs to be encouraged. This will benefit firstly to women who have not access to the land resource capital. Other main principle allowing the relative maintenance of agro-ecosystems in Groundnut basin were social flexibility and networking to allow information and knowledge flows. Flexibility was particular marked in the traditional land tenure model[19]. Future land tenure policy have to take into account the possibility of land exchanges as adaptation principle. In the same way, traditional society was marked by complex family network in which solidarity played majors roles more particular facing to global change[20]. Even if this family networking change mainly driven by migration, new brotherhood networks could appear and should be encouraged. Economic issue was not really considered in this program. The impact of agronomic and social factors on households' incomes were assessed in the two rounds surveys. Analyses of the results have to be performed. However, the capacity of investments appeared to be crucial as it was shown for instance in the transport facility issue e.g. for organic residues being distributed in the fields, or water supply and irrigation issue e.g. for watermelon production. Strong transformation could occur in the next decades given that more than half of households did not live actually from agriculture. The issue of deep changes on rural households have to be addressed. The workforce availability due to the temporary migration and off farm activities seemed to be already a serious constraint in farming systems.

C.6 REFERENCES

1 Mitsch, W. J. & Jørgensen, S. E. Ecological Engineering 20, 363-377 (2003).
2 Altieri, M. A. Agroecology: the science of sustainable agriculture. (Westview press, 1995).
3 Odum, E. P. Science 164, 262-270 (1969).
4 Audouin, E. et al. In Les sociétés rurales face aux changements environnementaux en Afrique de l'Ouest (eds B. Sultan et al.) (Editions de l'IRD, 2015).
5 Bisson, A. et al. Journal of Theoretical Biology In press (2019).
6 Grillot, M. et al. Cah. Agric. 27 (2018).
7 Bénagabou, O. I. et al. Revue Élev. Méd. Vét. pays Trop. 70, 31-41 (2017).
8 Audouin, E. et al. In 50 ans de l'Observatoire Population et Santé de Niakhar (eds V. Delaunay et al.) Ch. 17, 337-372 (IRD Editions - L'Harmattan Sénégal, 2018).
9 Grillot, M. et al. Environmental Modelling & Software 107, 267-280 2018).
10 Grillot, M. et al. Agricultural Systems 164, 133--151 (2018).
11 Masse, D. et al. In Niakhar, mémoires et perspectives. Recherches pluridisciplinaires sur le changement en Afrique (eds Delaunay V. et al.) Ch. 16, 311-332 (Éditions de l'IRD et L'Harmattan Sénégal, 2018).
12 Serpantié, G. & Milleville, M. in Le mil en Afrique (ed S Hamon) 255-266 (Editions ORSTOM, 1993).
13 Eldin, M. & Milleville, P. Le risque en agriculture. (ORSTOM, 1989).
14 Manlay, R. et al. Agricultural Systems 79, 83-107 (2004).
15 Tittonell, P. et al. Soil Science Society of America Journal 77, 525-538, (2013)
16 Lericollais, A. Paysans sereer: Dynamiques agraires et mobilités au Sénégal. 668 (Editions de l'IRD, 1999).
17 Delaunay, V. La Situation Démographique dans l'Observatoire de Niakhar 1963-2014. (IRD, 2017).
18 Delaunay, V. et al. Afrique Contemporaine, 75–94 (2016).
19 Pélissier, P. Les paysans du Sénégal. (Ministère de l'Education Nationale-CNRS Editions, 1966).
20 Mazzucato, V. et al. Social networks and the dynamics of soil and water conservation in the Sahel. Vol. 101 (IIED, 2001).

Final report

D LIST OF DELIVERABLES

Date livrai-son	N°	Intitulé	Nature*	Livrée	Partenaires (responsable)
	Task 1				
	Task 1 1				
2014	D1.1.1	Report of a survey	Report	- Fall CMN. 2014. Caractéristiques Climatiques De L'Observatoire Population Santé De Niakhar. Master UCAD. Dakar	LPAOSF
2014	D1.1.2	Databases of rainfalls and air temperature	Data-bases		LPAOSF
2014	D1.1.3	Report on agro-climatic indices	Report		LPAOSF
2020	D1.1.4	PhD defended	PhD	- Fall CMN Caractérisation et prédictibilité des événements extrêmes en Afrique de l'Ouest à travers des processus dynamiques et microphysiques associes à l'initiation des systèmes convectifs. Thèse de doctorat. UCAD. PhD in Progress to be defended 2020	LPAOSF
	Task 1 2				
2018	D1.2.1	Analysis report on the 50 years trends of demographic changes	Report	- Delaunay V 2018 Monographie des terroirs d'enquêtes du projet CERAO. Rapport. LPED. Université Aix Marseille IRD. 21p + annexe - Delaunay, V. (Ed.), 2017. La Situation Démographique dans l'Observatoire de Niakhar 1963-2014. IRD, Dakar. http://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers18-04/010071521.pdf - Delaunay, V., Sauvain, C., Franzetti, R., Golay, G., Moulay, A., Engeli, E., 2016. La migration temporaire des jeunes au Sénégal. Un facteur de résilience des sociétés rurales sahéliennes ? Afrique Contemporaine 75–94. http://hal.ird.fr/ird-01726848/document	LPED
2016	D1.2.2	Analysis report on the farms typology regarding their demographic and socioeconomic characteristics, their functional structure and strategies	Report	- Maffray E. 2014. Etude des relations de genre intégrée dans l'évaluation des performances des unités d'exploitation : cas de la société Sereer dans l'ancien bassin arachidier au Sénégal. Mémoire fin d'étude. ISTOM Cergy Pontoise France. 80p+annexes - Mars C. 2016. Appropriation technico-économique des innovations et analyse des	LPED

				facteurs sociaux et institutionnels pour leur adoption. Etude comparée de 3 terroirs villageois sereer dans la région de Fatick au Sénégal. Mémoire fin d'étude. ISTOM Cergy Pontoise France. 77p+annexe	
	Task 1.3				
2014	D1.3.1	Methodology description	Report	KickOff report	ECO&SOLS
	D1.3.2				
2015	D1.3.2.1	Land uses maps	Maps	Report in CERAO 2015 workshop report	ECO&SOLS
2016	D1.3.2.2 new	Long term dynamic of Land Use (new deliverable)	Report	- Ndiaye ML. 2016. Analyse par télédétection de la dynamique d'occupation du sol dans trois terroirs villageois du vieux bassin arachidier au Sénégal sur la période 1968-2016. Rapport. CIRAD-IRD-CSE. Dakar. 58p+annexe	SELMET
2019	D1.3.3	Soil carbon spatial distribution for the three villages	Report	Databases in Malou OP. Le carbone organique dans les sols du bassin arachidier du Sénégal : Variabilité spatiale et effets des pratiques culturales PhD Thesis. To be defended in 2019	ECO&SOLS
	D1.3.4	PhD Thesis defended	PhD	Abandonned	ECO&SOLS
	Task 2				
	Task 2.1				
2015	D2.1.1	a: Analysis Report on the modeling of rainfall-mobility relationship	Publica-tion, Report	- Lalou, R., Delaunay, V. 2015. Migrations saisonnières et changement climatique en milieu rural sénégalais : Forme ou échec de l'adaptation ? p57-83. Sultan B., Lalou R., Oumarou A., Sanni MA, Soumare A (Eds). Les sociétés rurales face aux changements environnementaux en Afrique de l'Ouest. IRD Éditions - Collection Synthèses. Marseille. - Delaunay V 2018 Monographie des terroirs d'enquêtes du projet CERAO. Rapport. LPED. Université Aix Marseille IRD. 21p + annexe - Delaunay V, Engeli E, Moullet A, Sauvain-Dugerdil C, 2018 Da la migration saisonnière à la migration temporaire. pp240-245 in Delaunay V, Desclaux A, Sokhna C. (eds) Niakhar, mémoires et perspectives. Recherches pluridisciplinaires sur le changement en Afrique. Marseille et Dakar. Editions de l'IRD et l'Hamatttan. 535p	LPED
2018	D2.1.1	b: Methodological and analysis report on migration motivations and decision-making migration from population-based survey			LPED
2015	D2.1.2	Methodological and analysis report on rural economic diversification	Report, Publica-tion	- Muller B., Lalou R., Kouakou P., Soumare M.A., Bourgoin J, Dorego S., Sine B. 2015. Le retour du mil sanio dans le Sine : une adaptation raisonnée à l'évolution climatique. 27 pp in Sultan B., Lalou R., Oumarou A., Sanni M A, Soumare A, (eds). Les sociétés rurales face aux changements environnementaux en Afrique de l'Ouest. IRD Éditions - Collection Synthèses. Marseille. - Mars C. 2016. Appropriation technico-économique des innovations et analyse des facteurs sociaux et institutionnels pour leur adoption. Etude comparée de 3 terroirs villageois sereer dans la région de Fatick au Sénégal. Mémoire fin d'étude. ISTOM Cergy Pontoise France. 77p+annex	LPED
2016	D2.1.3	Methodological and analysis report on a short-term adaptation: introduction of a new crop variety and rainfall variability			LPED

				- Yessoufou N.D., 2018. Enquête sur les stratégies et innovations des agriculteurs dans l'Observatoire de Niakhar, CERAO 2015, Rapport d'enquête. Dakar, 70p.+annexes	
2016	D2.1.4	Methodological and analysis report on integrated crop-bovine fattening farming system	Report	- Mars C. 2016. Appropriation technico-économique des innovations et analyse des facteurs sociaux et institutionnels pour leur adoption. Etude comparée de 3 terroirs villageois sereer dans la région de Fatick au Sénégal. Master Thesis. ISTOM Cergy Pontoise France. 77p+annexe	LPED
2016	D2.1.5 new	Comparative studies of village and farms strategies : agronomic performance and sustainability	Report Survey	- Survey research data on 610 households (two rounds 2015 & 2016) concerning the social, economic, agronomic, livestock issues. - Fonton SJ 2018 Etude sur la mesure et l'analyse multi-dimensionel de l'intensification agricole à Niakhar. Mémoire de Master ENSAE. Dakar. 64p+annexes. - Tine C Stratégies d'adaptation au changement global et transformations des sociétés rurales. Vers une durabilité des territoires agricoles du Sine. L'exemple de la zone d'observation de Niakhar. Mémoire de thèse de doctorat. UCAD. In progress. To be defended in 2019.	LPED
	Task 2.2				
2015	D2.2.1	Cropping systems typology	Reports	- Sabaly IK 2014. Impact de deux systèmes d'intégration agriculture-élevage sur la fertilité des sols des champs de case dans le bassin arachidier du Sénégal. Mémoire Mastère Gestion Durable des sols. Agrhymet. Niamey. Niger. 50p+annexes - Oddos L 2015. Modes de culture des légumineuses et impacts sur la gestion de la fertilité du sol en zone semi-aride. Mémoire Licence. ENSSA Bordeaux Aquitaine. 36p+annexes - Mbengue MM. 2015. Diversité de gestion et d'efficience des nutriments dans les systèmes de culture du mil (Pennisetum glaucum (L) R. Br.) pratiqués dans une petite région du bassin arachidier pendant la saison 2014. Mémoire fin d'étude ENSA Thiès. 64p+annexes	ECO&SOLS
2019	D2.2.2	Databases and a report on observed agronomic performances related to observed cropping systems	Data-bases	- Survey on 250 farms in Tounkara PhD Thesis - Simple Pairwise experiments in a network of 20 farmers' fields (2016- 2017) - Classical experiments in farmers homefields and outfields (2015- 2017)	ECO&SOLS
2019	D2.2.3	Peer-reviewed papers	Publica tion	- Thiam A. S. 2018. Méta-analyse de la production du mil en zones sèches d'Afrique de l'Ouest. Mémoire ingénieur ENSA, Thiès, 59 p.	ECO&SOLS
2019		PhD Thesis defended	PhD	- Tounkara A. Diagnostic agronomique et modélisation de l'efficience d'utilisation des nutriments dans les systèmes de culture Mil au Sénégal. PhD University of Thies, Senegal. To be defended in 2019.	
	Task 2.3				
2019	D.2.3.1	C, N and P contents in soil and biomass at plots and farms scales	Reports	Databases in Malou OP. Le carbone organique dans les sols du bassin arachidier du Sénégal : Variabilité spatiale et effets des pratiques culturales PhD Thesis. To be defended in 2019	ECO&SOLS , SELMET

2016	D.2.3.2	C, N, P flows at villages and territories scales	Report, publica-tions	- Audouin, E. 2014. Comparaison de deux terroirs en termes de flux de biomasse et de bilans azotés en vue de proposer des voies d'intensification écologique. Cas de Diohine et Bary Sine dans le Bassin arachidier du Sénégal. Institut nationale polytechnique de Toulouse, Toulouse. - Audouin, E. 2014. Terroirs comparison in terms of biomass flows and nitrogen balance. Study case of Diohine and Barry Sine in the former groundnut basin. ISARA- Ecole Ingénieur Purpan - Norwegian University of Life Sciences, Lyon - Toulouse - Aas. - Odru, M. 2013. Flux de biomasse et renouvellement de la fertilité des sols à l'échelle du terroir. Etude de cas d'un terroir villageois sereer au Sénégal. ISTOM-Ecole Supérieure d'Agro-Développement International, Cergy-Pontoise, France. - Saunier-Zoltobroda, T. 2015. Flux de biomasse à l'échelle du paysage et hétérogénité spatiale des bilans d'azote. Cas de trois terroirs du bassin Arachider au Sénégal. ISTOM - Ecole supérieure d'agro-développement international, Cergy Pontoise. - Dugy, T. 2016. Diagnostic des flux de biomasse à l'échelle de terroirs agro-sylvo-pastoraux. Etude comparative de trois terroirs, Sob, Sassem, et Barry Sine dans l'ancien bassin arachidier. ISTOM-Ecole supérieure d'agro-développement international, Cergy Pontoise. - Grange, G. 2015. Suivi du cycle de l'azote en fermes réelles : cas des systèmes agropastoraux du bassin arachidier du Sénégal. SupAgro Montpellier - VetAgro Sup, Montpellier. - Wade C. 2016. Suivi du cycle de l'azote (N) en milieux paysans : Cas des systèmes agropastoraux du bassin arachidier du Sénégal. Mémoire ingénieur ENSA, Thiès, 68 p. - Audouin, E., J. Vayssières, M. Odru, D. Masse, G. S. Dorégo, and P. Lecomte. 2015. Réintroduire l'élevage dans les terroirs villageois d'Afrique de l'Ouest pour accroître leur productivité et la fertilité de leurs sols – Le cas du vieux bassin arachidier au Sénégal.in B. Sultan, R. Lalou, A. Oumarou, M. A. Sanni, and A. Soumare, editors. Les sociétés rurales face aux changements environnementaux en Afrique de l'Ouest. Editions de l'IRD, Marseille.	SELMET ECO&SOLS ,
	Task 2.4				
2016 2019	D.2.4.1	Database collection including: passport of accession, GIS information, SNP data, and ethnobotanical surveys	Data-bases	- In Olodo K Dynamique temporelle et spatiale de la diversité génétique du mil cultivé et sauvage *Pennisetum glaucum*. Thèse de Doctorat UCAD, Dakar. To be defended in 2019 - Cisse A 2016. Caractérisation agromorphologique temporelle du mil. Master II MPTPA, UGB, Sénégal - Faye A 2016. Caractérisation agromorphologique du mil Sanio et du mil Souna Master II MPTPA, UGB, Sénégal	DIADE, LRNPV
2016	D.2.4.2	Identification of technologies (crop diversity, variety, farmer practices)	Reports	- Suzanne G, 2016. Réseaux d'échange de semences de mils améliorés et locales dans le bassin arachidier sénégalais. Master 2, Systèmes Agricoles et Agroalimentaires	DIADE, LRNPV

		in response to historical climatic and social changes		Durables au Sud, Montpellier SupAgro. 111 p. - Ledoussal S 2016. Étude des réseaux d'échange de semences de mil dans la région de Niakhar au Sénégal, Master 2, Génie de l'environnement, spécialisation Agriculture Durable et Développement des territoires, Rennes, Agrocampus Ouest, 60 p.	
2019	D.2.4.3	Spatial model of crop diversity	Model / Report	- Olodo K Dynamique temporelle et spatiale de la diversité génétique du mil cultivé et sauvage *Pennisetum glaucum*. Thèse de Doctorat UCAD, Dakar. To be defended in 2019	DIADE, LRNPV
2019	D.2.4.4	Scientific publications on : i) Pearl Millet genetic diversity , ii) Pearl Millet adaptation ; and iii) Seed system dynamics	Publica -tions	- In progress - Olodo et al. In prep for Genetic Resources and Crop Evolution How pearl millet landraces diversity evolves during the last 40 years? Microsatellites give an overview of subtils genetic changes - Faye et al. In prep Detecting signature of selection in early and late pearl millet landraces - Barnaud et al. In prep. The Dynamics of farmer pearl millet seed supply practices in Niakhar, Senegal	DIADE, LRNPV LPED CIRAD
	Task 3				
	Task 3.1				
2014	D.3.1.1	A conceptual model of the household functioning delivered at the kick-off meeting	Model / Report	Realised Kick off meeting report	SELMET, ECO&SOLS ,
2019	D.3.1.2	A soil-crop climatic-dependant model	Model / Experi m. Reports	- In Tounkara A. Diagnostic agronomique et modélisation de l'efficience d'utilisation des nutriments dans les systèmes de culture Mil au Sénégal. PhD University of Thies, Senegal. To be defended in 2019. - Grange, G. 2015. - Wade C. Master thesis - Sy Thiam A. Meta- analysis fertilizers impact on millet straw and grain yields in Sudano Sahelian region. Master thesis to be defended in 2019	SELMET, ECO&SOLS ,
2018	D.3.1.3	A household model	Model / Report	- Audouin, E. 2014. - Odru, M. 2013. - Saunier-Zoltobroda, T. 2015. - Dugy, T. 2016. - Frey H 2015. Analyse des déterminants de l'adoption des options de mitigation et d'adaptation à partir de l'implémentation d'un questionnaire générique sur des systèmes agricoles variés au Sénégal, au Burkina Faso et en France. Stage SupAgro Montpellier. - In Grillot M. 2018. Modélisation multi-agent et pluri-niveau pour simuler les conséquences d'une transition agraire sur la réorganisation du cycle de l'azote : le cas des systèmes agro-sylvo-pastoraux du bassin arachidier au Sénégal. Thèse de	SELMET, ECO&SOLS ,

				doctorat. ED GAIA. SupAgro Montpellier. 153p+annexe	
2018	D.3.1.4	Scientific publications on models description and application	Publications	- Grillot, M., J. Vayssières, and D. Masse. 2018. Agent-based modelling as a time machine to assess nutrient cycling reorganization during past agrarian transitions in West Africa. Agricultural Systems 164:133--151. - Grillot, M., F. Guerrin, B. Gaudou, D. Masse, and J. Vayssières. 2018. Multi-level analysis of nutrient cycling within agro-sylvo-pastoral landscapes in West Africa using an agent-based model. Environmental Modelling & Software 107:267-280. - Grillot M, Vayssieres J, Guerrin F, Lecomte P. 2018. Modélisation conceptuelle de la gestion adaptative de la biomasse face à l'aléa climatique en systèmes agro-sylvopastoraux. Cahiers Agriculture 27,55004.	SELMET, ECO&SOLS, DIADE
	Task 3.2				
2015	D.3.2.1	A first conceptual model of biomass flows between agents and spatial-units	Model Report	Realised, Kick off and 2015 meeting reports	SELMET, All partners
2018	D.3.2.2	A multi-agent system that simulates village functioning	Model Report	- In Grillot M. 2018. Modélisation multi-agent et pluri-niveau pour simuler les conséquences d'une transition agraire sur la réorganisation du cycle de l'azote : le cas des systèmes agro-sylvo-pastoraux du bassin arachidier au Sénégal. Thèse de doctorat. ED GAIA. SupAgro Montpellier. 153p+annexe	SELMET, ECO&SOLS
2018	D.3.2.3	Scientific publications on the village model description and companion modeling experiences	Publications	- Grillot, M., J. Vayssières, and D. Masse. 2018. Agent-based modelling as a time machine to assess nutrient cycling reorganization during past agrarian transitions in West Africa. Agricultural Systems 164:133--151. - Grillot, M., F. Guerrin, B. Gaudou, D. Masse, and J. Vayssières. 2018. Multi-level analysis of nutrient cycling within agro-sylvo-pastoral landscapes in West Africa using an agent-based model. Environmental Modelling & Software 107:267-280.	SELMET, ECO&SOLS
2018	D.3.2.4	PhD defended	PhD	- Grillot M. 2018. Modélisation multi-agent et pluri-niveau pour simuler les conséquences d'une transition agraire sur la réorganisation du cycle de l'azote : le cas des systèmes agro-sylvo-pastoraux du bassin arachidier au Sénégal. Thèse de doctorat. ED GAIA. SupAgro Montpellier. 153p+annexe	SELMET, ECO&SOLS
	Task 3.3				
2015	D.3.3.1	A conceptual model of nutrient transfers between agro-ecosystem components as available soon enough for the kick-off meeting	Report	Realised, Kick off and 2015 meeting reports	SELMET, ECO&SOLS
2018	D.3.3.2	A "simple" stock-flow model based on differential equations	Model Publica-tion	- Pichon Noémie (2015). Modélisation de la dynamique spatiale de l'azote dans un agroécosystème subsaharien. Master UM2 SupAgro. Montpellier. - Bisson A Influence de l'organisation spatiale et de la pression d'herbivorie sur les transferts de fertilité et la productivité des systèmes agro-sylvo-pastoraux. Approche écologique de questions agronomiques par l'utilisation de modèles mathématiques.	ECO&SOLS, SELMET,

				Thèse de doctorat. ED Gaia Montpellier SupAgro. Montpellier. 137p+annexes. - Bisson A, Casenave C, Boudsocq S, Daufresnes T. 2019. Maximization of fertility transfers from rangeland to cropland: the contribution of control theory. Journal of Theoretical Biology. Accepted. - Renaudier C. 2017. Viabilité des systèmes agro-pastoraux de savane d'Afrique de l'Ouest. Cas du bassin arachidier au Sénégal. Mémoire Master ENSTA Université Paris Saclay. 62p + annexes	
2018		PhD defended	PhD report	- Bisson A Influence de l'organisation spatiale et de la pression d'herbivorie sur les transferts de fertilité et la productivité des systèmes agro-sylvo-pastoraux. Approche écologique de questions agronomiques par l'utilisation de modèles mathématiques. Thèse de doctorat. ED Gaia Montpellier SupAgro. Montpellier. 137p+annexes	ECO&SOLS, SELMET,
2018	D.3.3.3	Nutrient flow databases and nutrient network analysis indicators at different scales	Model / Report	- In Saunier-Zoltobroda, T. 2015. - In Dugy, T. 2016. - In Grillot M. 2018. PhD thesis - Birnholz C 2015. Modèle recyclage biomasse (Animal, Fumier, Sol-Plante). Rapport de stage. Université Wagueningen - Sané M. 2015. Un système multi-agent pour simuler la distribution spatiale des apports de fumure organique par les troupeaux de bovins en terroir villageois agro-pastoral. Mémoire de Master II Recherche Systèmes Complexes (Syscom), UCAD, Dakar, 46 p. - Balandier M. 2017. Describing diversity and crop-livestock integration in smallholder mixed farming systems in Sub-Saharan Africa - An application of network analysis in the former Senegalese Groundnut Basin. Mémoire de Master II WUR, Wageningen, 38 p.	SELMET, ECO&SOLS, DIADE, LPED, LNRP
2018	D.3.3.4	Scientific publications on the link between integration, self-sufficiency and efficiency	Publications	- Grillot, M., J. Vayssières, and D. Masse. 2018. Agricultural Systems 164:133--151. - Grillot, M., F. Guerrin, B. Gaudou, D. Masse, and J. Vayssières. 2018. Environmental Modelling & Software 107:267-280. - Bisson A, Casenave C, Boudsocq S, Daufresnes T. 2019. Maximization of fertility transfers from rangeland to cropland: the contribution of control theory. Journal of Theoretical Biology. Accepted.	SELMET ECO&SOLS,
	Task 3.4				
2015	D.3.4.1	A list and glossary of key concepts - such as vulnerability, viability and sustainability- and ecosystem properties - such as diversity, heterogeneity, integration- delivered at the second year meeting;		Realized 2015 meeting report	ECO&SOLS, SELMET, DIADE, LPED, LNRP
2018	D.3.4.2	A report providing a list, the	Reports	- Reports of 4 multi-actor workshops in Dakar, Bary Sine, Diohine, Sob	ECO&SOLS, SELMET,

		definitions and ranking of meta-rules useful to design promising and sustainable ecosystems according to global changes		- Ba M. Analyse des déterminants des trajectoires de territoires par démarches participatives : cas du Bassin arachidier du Sénégal. Thèse de doctorat. Université Gaston Berger. In progress. To be defended in 2021	DIADE, LPED, LNRP
	Task 4				
2017	D.4.1	- A planning report after each meetings or workshops	Report	2014, 2015, 2016, 2017 meeting report	ECO&SOLS
2017	D.4.2	- One activity report per year	Report	2014, 2015, 2016, 2017 meeting report	ECO&SOLS
2015	D.4.3	- An up-to-date web site	Web site	http://www.umr-ecosols.fr/recherche/projets/44-cerao. Not updated	ECO&SOLS
2018	D.4.4	- At least one oral communication in an international conference to promote project results.	Com-munica-tion Film	- Masse, D. 2014. Analyse rétrospective des trajectoires à long terme : une perspective de recherche innovante ou revisitée. In Séminaire “Agricultures et écosystèmes : du développement durable aux changements globaux. Des programmes thématiques pour impulser des recherches nouvelles ?” Agence Nationale de la Recherche, Paris, 9 et 10 Décembre 2014. - Masse D. 2016.Le projet CERAO : des recherches pour une agriculture écologiquement intensive. Colloque IAVAO IESOL LAPSE « Biodiversité et processus écologiques au service d’une agriculture durable en Afrique de l’Ouest » 10-11 Mai 2016. Dakar. Sénégal. - Masse D. 2017 Approche systémique pour une intensification de la production agricole en Afrique de l’Ouest : cas des systèmes agro-sylvo-pastoraux. Communication orale. Conférence Intensification Durable 2017. Dakar, Sénégal, 24-26 Avril 2017. - Masse D. 2017 Gestion de la fertilité des sols, matières organiques et le cycle des nutriments, et dans les systèmes de culture des savanes ouest africaines, et dans les systèmes agricoles péri-urbains. Communication orale. Atelier Régional FAO sur la résilience climatique au Sahel et en Afrique de l’Ouest. Dakar, Sénégal du 25 au 26 Avril 2017. - Masse D., Lalou R., Tine C., Ba M., Vayssières J. 2018. Les trajectoires agricoles dans le Bassin Arachidier au Sénégal : éléments de réflexion à partir de l’observatoire de Niakhar. Chapitre 16. p311-332 Delaunay V., Desclaux A., Sokhna C. éd., 2018. Niakhar, mémoires et perspectives. Recherches pluridisciplinaires sur le changement en Afrique. Marseille et Dakar, Éditions de l’IRD et L’Harmattan Sénégal, 535 p. ISBN IRD : 978-2-7099-2669-0 - ISBN Harmattan : 978-2-343-15671-2 - Film « L’intégraton de l’agriculture et de l’élevage pour une diversification des cultures » IRD. https://youtu.be/urgNDsRQy7Y	ECO&SOLS

E PROJECT IMPACT

E.1 IMPACT ASSESSMENT INDICATORS

Number of publications and communications (to be detailed in E.2)

		Multi-partner publications	Single-partner publications
International	**Peer-reviewed journals**	6	
	Books or chapters in books	5	
	Communications (conferences)	26	6
France	**Peer-reviewed journals**		
	Books or chapters in books		
	Communications (conferences)		
Country xxx (foreign partner)	**Peer-reviewed journals**		
	Books or chapters in books	0	
	Communications (conferences)	8	
Outreach initiatives	**Popularization articles**	6	
	Popularization conferences	5	
	Others	26	6

Other scientific valorization factors (to be detailed in E.3)

	Number, years and comments (Actual or likely valorizations)
International patents obtained	
International patents pending	
National patents obtained	
National patents pending	
Operating licences (obtained / transferred)	
Company creations or spin-offs	
New collaborative projects	5
Scientific symposiums	
Others (specify)	

E.2 LIST OF PUBLICATIONS AND COMMUNICATIONS

International

Revues à comité de lecture

1. Bénagabou, O.I., Blanchard, M., Bougouma Yaméogo, V.M.C., Vayssières, J., Vigne, M., Vall, E., Lecomte, P., Nacro, H.B., 2017. L'intégration agriculture-élevage améliore-t-elle l'efficience, le recyclage et l'autonomie énergétique brute des exploitations familiales mixtes au Burkina Faso ? Revue Élev. Méd. Vét. pays Trop., 70 (2), 31-41.
2. Delaunay, V., Sauvain, C., Franzetti, R., Golay, G., Moulay, A., Engeli, E., 2016. La migration temporaire des jeunes au Sénégal. Un facteur de résilience des sociétés rurales sahéliennes ? Afrique Contemporaine 75–94. http://hal.ird.fr/ird-01726848/document
3. Grillot, M., F. Guerrin, B. Gaudou, D. Masse, and J. Vayssières. 2018. Multi-level analysis of nutrient cycling within agro-sylvo-pastoral landscapes in West Africa using an agent-based model. Environmental Modelling & Software 107:267-280.
4. Grillot M., Vayssières J., Guerrin F., Lecomte P., 2018. Modélisation conceptuelle de la gestion adaptative de la biomasse face à l'aléa climatique en système agro-sylvo-pastoral. Cahiers Agricultures 180048, 1-9.
5. Grillot, M., J. Vayssières, and D. Masse. 2018. Agent-based modelling as a time machine to assess nutrient cycling reorganization during past agrarian transitions in West Africa. Agricultural Systems 164:133--151.
6. Bisson A, Casenave C, Boudsocq S, Daufresnes T. 2019. Maximization of fertility transfers from rangeland to cropland: the contribution of control theory. Journal of Theoretical Biology. Accepted.

Ouvrages ou chapitres d'ouvrage

1. Audouin, E., J. Vayssières, M. Odru, D. Masse, G. S. Dorégo, and P. Lecomte. 2015. Réintroduire l'élevage dans les terroirs villageois d'Afrique de l'Ouest pour accroître leur productivité et la fertilité de leurs sols – Le cas du vieux bassin arachidier au Sénégal.in B. Sultan, R. Lalou, A. Oumarou, M. A. Sanni, and A. Soumare, editors. Les sociétés rurales face aux changements environnementaux en Afrique de l'Ouest. Editions de l'IRD, Marseille.
2. Sané M., Vayssières J., Grillot M., Bah A., Ickowicz A., 2016. Etat de l'art de l'approche multi-agents pour modéliser le comportement spatial des troupeaux en systèmes d'élevage extensifs. In: Gaye I.D. & Corniaux C. (Eds), La mobilité au cœur des sociétés et des systèmes pastoraux. PPZS, Dakar, Sénégal, 17 pp.
3. Delaunay, V. (Ed.), 2017. La Situation Démographique dans l'Observatoire de Niakhar 1963-2014. IRD, Dakar. http://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers18-04/010071521.pdf
4. Audouin E., Vayssières J., Bourgoin J., Delaunay V., Masse D., 2016. Identification de voies d'amélioration de la fertilité des sols par atelier participatif. Chapitre 17 pp337-372. Delaunay V., Desclaux A., Sokhna C. éd., 2018. Niakhar, mémoires et perspectives. Recherches pluridisciplinaires sur le changement en Afrique. Marseille et Dakar, Éditions de l'IRD et L'Harmattan Sénégal, 535 p. ISBN IRD : 978-2-7099-2669-0 - ISBN Harmattan : 978-2-343-15671-2
5. Masse D., Lalou R., Tine C., Ba M., Vayssières J. 2018. Les trajectoires agricoles dans le Bassin Arachidier au Sénégal : éléments de réflexion à partir de l'observatoire de Niakhar. Chapitre 16. p311-332 Delaunay V., Desclaux A., Sokhna C. éd., 2018. Niakhar, mémoires et perspectives. Recherches

pluridisciplinaires sur le changement en Afrique. Marseille et Dakar, Éditions de l'IRD et L'Harmattan Sénégal, 535 p. ISBN IRD : 978-2-7099-2669-0 - ISBN Harmattan : 978-2-343-15671-2

Communications (conférence)

1. Masse D 2014. Le projet CERAO pour une intensification écologique de la production agricole ou l'intérêt des observatoires pour les études sur les dynamiques des agro- socio-écosystèmes. Symposium scientifique « Niakhar : 50 années de recherche en population et santé ». Dakar 25-26 Février 2014.
2. Masse D. 2014. Analyse rétrospective des trajectoires à long terme : une perspective de recherche innovante ou revisitée. Colloque ANR Agricultures et écosystèmes - 9 et 10 décembre 2014, Paris.
3. Bénagabou O.I., Blanchard M., Vayssières J., Vigne M., Vall E., Lecomte P., Bougouma V., Nacro H. B., 2015. Crop-Livestock Integration improves the Energy Use Efficiency of smallholder mixed farming systems - the case of western Burkina Faso. In: 5th Farming System Design Conference, Montpellier, France, 7-10 September, 2 p.
4. Grillot M., Vayssières J., Bourgoin J., Bah A., Jankowski F., Lalou R., Masse D. 2015 Participatory modelling of the trajectories of agro-silvo-pastoral systems at landscape and community levels in West Africa. The case of the Senegalese groundnut basin. Poster communication in 5th International Symposium for Farming Systems Design 7-10 September 2015, Montpellier, France.
5. Tall-Diouf L., Mbengue M., Ndour Badiane N. Y., Masse D., Clermont-Dauphin C. 2015. Are cropping practices developed by SubSaharan farmers climate-smart? Case study of millet cropping system in Senegal. Poster. The 3rd Global Science Conference on Climate-Smart Agriculture CSA2015, 16-18 March 2015. Montpellier – France
6. Vayssières J, Blanchard M, Vigne M, Masse D, Albrecht A, Vall E, Poccard-Chapuis R, Corniaux C, Lecomte P. 2015. The risk of declines in soil fertility and crop productivity due to decreased livestock presence in agropastoral zones of West Africa. Oral communication in 5th International Symposium for Farming Systems Design 7-10 September 2015, Montpellier, France.
7. Baldé A.B., Tall L., Bakhoum N., Affholder F., Clermont Dauphin C, Corbeels M., Masse D, Scopel E. (2016). Modeling intercropping with cereals in smallholder agrosystems. From lessons learned in central Brazil to their application in the Peanut Basin in Senegal. The 6th Global Workshop of the Agricultural Model Intercomparison and Improvement Project (AgMIP). Le Corum, Montpellier, France, June 28-30, 2016.
8. Berthouly-Salazar C, Ousseini I S, Thuillet A-C, Rhoné B, Mariac C, Couderc M, Zekraoui L, Barnaud A, Bakasso Y, Assoumane A, Moussa D, Moussae T, Kane NA, Manicacci D, Tenaillon MI, Vigouroux Y 2016. Investigating genes linked to adaptations in wild pearl millet Plant Animal Genome, 14-18/01 2016, San Diego, USA. Communication
9. Bisson A., Pichon N., Boudsocq S., Daufresne T., Casenave C., Barot S., Masse D. (2016) Impact of land-use changes on biogeochemical cycles and fertility transfers in mixed-farming systems of West Africa: an ecological approach. Poster. 5th EcoSummit "Ecological Sustainability: Engineering Change", 29 August-01 September 2016 Montpellier, France,
10. Clermont-Dauphin C. 2016. Optimiser le compromis entre Productivité et Résilience des Systèmes de culture en Afrique de l'Ouest. Colloque IAVAO IESOL LAPSE « Biodiversité et processus écologiques au service d'une agriculture durable en Afrique de l'Ouest » 10-11 Mai 2016. Dakar. Sénégal.

11. Grillot M., Vayssières J., Gaudou B., Bah A., Masse D., 2016. An agent-based model to analyze the ecological functioning of agro-silvo-pastoral landscapes in West Africa. In: 8th International Congress on Environmental Modelling and Software, Toulouse, France, 10-14 July, 1 p.
12. Grillot M., Vayssières J., Lecomte P., Masse D., 2016. Ecological network analysis of nitrogen cycles at the landscape level: intensive versus extensive crop-livestock systems in the Senegalese groundnut basin. In: 5th EcoSummit "Ecological Sustainability: Engineering Change", Montpellier, France, 29 August-01 September, 1 p.
13. Masse D. 2016.Le projet CERAO : des recherches pour une agriculture écologiquement intensive. Colloque IAVAO IESOL LAPSE « Biodiversité et processus écologiques au service d'une agriculture durable en Afrique de l'Ouest » 10-11 Mai 2016. Dakar. Sénégal.
14. Ndao S., Bocquier F., Moulin C.H., Lecomte P., Manlay R.J., Traore E.H., Vayssières J., 2016. Facteur de variation du bilan gaz à effet de serre d'un terroir agrosylvopastoral de la zone subhumide du Sénégal. Proceedings of the French Symposium Rencontres Recherches Ruminants, Paris, France, 7-8 December, 1 p.
15. Sané M., Vayssières J., Grillot M., Bah A., Ickowicz A., 2016. Simulating spatial changes in vegetation-livestock interactions under different landscape structures: a multi-agent system applied to agro-pastoral territories. In: 8th International Congress on Environmental Modelling and Software, Toulouse, France, 10-14 July, 8 p.
16. Stark F., Vayssières J., Vigne M., Gonzalez-Garcia E., Moulin C.H., 2016. Ecological network analysis used to assess the agroecological properties of farming systems. In: 5th EcoSummit "Ecological Sustainability: Engineering Change", Montpellier, France, 29 August-01 September, 1 p.
17. Tounkara A et al . 2017. Diagnosing the causes of the variability of nutrient use efficiency for millet yield in a Sahelian village. Colloque IESOL LAPSE IAVAO "Conference Intensification Durable (CID)» 24 to 26 April 2017 Dakar. Sénégal.
18. Vayssières J., Birnholz C., Hutchings N. J., Lecomte P., 2016. Ex-ante farm-scale analysis of the impacts of livestock intensification on greenhouse gas emissions of mixed crop-livestock systems in western Africa. In: 6th Greenhouse Gas and Animal Agriculture International Conference (GGAA2016), Melbourne, Australia, 14-18 February, 1 p.
19. Ba M, Bourgoin J, Vayssières J, Seck M., Masse D., 2017 Une démarche participative pour analyser les déterminants des trajectoires de territoires agro-pastoraux : cas du bassin arachidier du Sénégal. In 'le Pastoralisme dans le courant des changements globaux : défis, enjeux, perspectives. Dakar 20-24 novembre 2017 Dakar Sénégal.
20. Bisson A. Boudsocq S., Daufresne T., Casenave C., Manlay R., Barot S., Masse D. 2017 Impact of land-use changes on productivity of agro-ecosystems of West-Africa: an ecological approach. Communication orale. JEF 2017 - Journées d'écologie fonctionnelle. 28-30 Mars 2017. La Grande Motte. France.
21. Fall CMN., Lavaysse C., Dione C., Gaye AT., 2017. Characterization of Dry Spell (DS) in Senegal; AfricaGis Meeting, Addis Abeba, Ethiopia.
22. Fall CMN., Lavaysse C., Dione C., Gaye AT., 2017. Impact of extrems wet and Dry spell on the crops yields in Senegal; COPERNICUS, Joint Research Center, ISPRA, Italy.

23. Grillot M., Vayssières J., Masse D., 2017. Persistent properties of agro-silvo-pastoral systems in West Africa. In: P2CG: Pastoralism in the curent of Global Changes, Dakar, Senegal, 20-24 November, 2 p.
24. Masse D. 2017 Approche systémique pour une intensification de la production agricole en Afrique de l'Ouest : cas des systèmes agro-sylvo-pastoraux. Communication orale. Conférence Intensification Durable 2017. Dakar, Sénégal, 24-26 Avril 2017.
25. Masse D. 2017 Gestion de la fertilité des sols, matières organiques et le cycle des nutriments, et dans les systèmes de culture des savanes ouest africaines, et dans les systèmes agricoles péri-urbains. Communication orale. Atelier Régional FAO sur la résilience climatique au Sahel et en Afrique de l'Ouest. Dakar, Sénégal du 25 au 26 Avril 2017.
26. Olodo K, Cissé A, Barnaud A, Kane N, Sekloka E, Diouf D, Vigouroux Y, Berthouly-Salazar C 2017. Climate change and adapative potential of pearl millet in Senegal: Preliminary results Conférence d'intensification durable 2017: Biodiversité et ingénierie écologique pour une agriculture durable, Dakar, Sénégal, 24-26 avril 2017 Organisation: IRD/CIRAD/LAPSE Communication orale.
27. Wade C., Vayssières J., Thiam M.B., Faye A., Diaw M.T., Dieng A., Lecomte P., 2017. Impact of livestock intensification and improved manure management on nitrogen use efficiency in mixed crop-livestock systems in central Senegal. In: P2CG: Pastoralism in the current of Global Changes, Dakar, Senegal, 20-24 November, 2 p.
28. Cisse A, Olodo K, Sall S N, Barnaud A, Kane NA, Berthouly-Salazar C 2018 Quelles évolutions agromorphologiques des variétés traditionnelles de mil au Sénégal ? Journées scientifiques ISRA, 05-09 Février 2018, Pole de Recherches de Hann, Dakar, Sénégal Communication orale
29. Fall CMN 2018. An increase of extreme events is one of the main phenomena accompanying the rainfall recovery GEWEX Convection-Permitting Climate Modeling II. Sept. 4–6, 2018, Boulder, CO, USA
30. Olodo K 2018 Changement climatique et potentiel adaptatif du mil au Sénégal : Le rôle du mil sauvage Conference : Promotion de systèmes de production performants, résilients, compétitifs et durables, Dakar, Sénégal, 5-9 Février 2018, Organisation : ISRA/UCAD/LAPSE Communication orale
31. Olodo K, Barnaud A, Kane NA, Faye A, Mariac C, Zekraoui L, Dequincet A, Vigouroux Y, Diouf D, Berthouly-Salazar C. 2018. Temporal and spatial dynamics of pearl millet diversity, ESEB Second Joint Congress on Evolutionary Biology, Montpellier 22-28 aout 2018 Poster
32. Wade C., Vayssières J., Thiam M.B., Diaw M.T., Faye A., Dieng A., Lecomte P., 2018. Impact de l'intensification de l'élevage et de techniques améliorées de gestion de la fumure animale sur l'efficience d'utilisation de l'azote en systèmes mixtes agriculture-élevage au centre du Sénégal. In: 24th French symposium Rencontres Recherches Ruminants, Paris, France, 5-6 December, 3 p.

Autres

Film

1. L'intégration de l'agriculture et de l'élevage pour une diversification des cultures (www.umr-ecosols.fr/recherche/animation-scientifique/111-video) Un film de 9 minutes 22 secondes de l'Institut de Recherche pour le Développement (IRD) en collaboration avec l'Institut Sénégalais de la Recherche Agronomique ISRA, le laboratoire mixte international IESOL, Intensification écologique des sols cultivés en Afrique de l'Ouest et le CIRAD. Réalisation L. Croes,

Conseillers Scientifiques D. Masse, C. Clermont-Dauphin, L. Cournac, T. Chevallier
2. Appui logistique et scientifique pour un documentaire conçu et écrit par Robert Ali Brac de la Perrière et réalisé par Idriss Diabaté « Éloge des mils : l'héritage africain » dans le cadre du projet CERAO en 2015. https://www.bede-asso.org/eloge-des-mils-lheritage-africain/

Rapports techniques

1. Ndiaye M.L., Soti V., Vayssières J., Masse D., 2016. Analyse par télédétection de la dynamique d'occupation du sol dans trois terroirs villageois du vieux bassin arachidier au Sénégal sur la période 1968-2016. Rapport CIRAD, IRD, CSE, Dakar, Sénégal, 59 p.
2. Delaunay V 2018 Monographie des terroirs d'enquêtes du projet CERAO. Rapport. LPED. Université Aix Marseille IRD. 21p + annexe

Autres action de vulgarisation

1. Masse D, Chotte J-L, Scopel E (Coord.) 2015. « L'ingénierie écologique pour une agriculture durable dans les zones arides et semi-arides d'Afrique de l'Ouest » Dossier thématique n°11. Comité Scientifique Français de la Désertification. Agropolis. Montpellier.
2. Appui scientifique pour un documentaire pour la promotion de l'Agroécologie au Sénégal réalisée par la Task Force multi-acteurs en 2016.
3. Conférence grand public à l'institut Français de Dakar « Les plantes face au changement climatique » Septembre 2015
4. Participation à l'atelier « Démarches multi-acteurs pour le développement de l'agroécologie en Afrique de l'Ouest » à Dakar en 2016 et animation d'un débat « Biodiversité et protection/valorisation des savoirs paysans ».

E.3 LIST OF VALORIZATION FACTORS

Nouveaux projets

- WAAP EFFAECES (ISRA, SELMET, ECO&SOLS) « « Elevage, Fertilité des sols et Economie des Fermes Agriculture-Elevage sous contraintes Climatiques et Environnementales au Sénégal » (financement WAAP-World Bank). Equipe SELMET, ECO&SOLS
- SIIL "Dual Purpose Millet" (ISRA, SELMET, ECO&SOLS) (financement USAID). Equipe SELMET, ECO&SOLS
- AMMA 2050 African Monsoon Multidisciplinary Analysis. Project funded by the program Future for the climate for Africa, DFID and NERC (Equipe DIADE et LNRPV ISRA leader WP5)
- ProIntensAfrica "Pathways to sustainable intensification of the agri-foof system in Africa. Coordination and Support Program (UE) - WP2 Etude de cas Bassin arachidier (co-financement IRD)". Equipe ECO&SOLS
- DSCATT. « Agricultural intensification and soil carbon sequestration in tropical and Temperate farming systems ». Projet étendard de la Fondation Agropolis et co-financement Fondation Total Budget 2 M €. 2019-2022. Equipe Eco&Sols, Selmet.

Création d'une plate-forme à la disposition d'une communauté

- Renforcement de l'observatoire Population Santé Environnement de Niakhar : https://lped.info/wikiObsSN/?HomePage
- Initiation de la plateforme Faidherbia Flux A new long term collaborative observatory on GHG fluxes and ecosystem services in a semi-arid agro-silvo-pastoral ecosystem – the groundnut basin in Niakhar/Sob, Senegal (www.agraf.msem.univ-montp2.fr/senegal.htm)

Modules d'enseignement

- Module d'enseignement sur le rôle de la biodiversité dans les principes de l'agroécologie. Modules dispensés aux étudiants en master de l'Université Gaston Berger et aux élèves ingénieur agronome de l'Université de Thiès

E.4 ASSESSMENT AND FOLLOW-UP OF PERSONNEL RECRUITED ON FIXED-TERM CONTRACTS (EXCLUDING INTERNS)

Identification				Avant le recrutement sur le projet			Recrutement sur le projet				Après le projet				
Nom et prénom	Sexe H/F	Adresse email (1)	Date des dernières nouvelles	Dernier diplôme obtenu au moment du recrutement	Lieu d'études (France, UE, hors UE)	Expérience prof. Antérieure, y compris post-docs (ans)	Partenaire ayant embauché la personne	Poste dans le projet (2)	Durée missions (mois) (3)	Date de fin de mission sur le projet	Devenir professionnel (4)	Type d'employeur (5)	Type d'emploi (6)	Lien au projet ANR (7)	Valorisation expérience (8)
OLODO Katina	F	Katina.olodo@ird.fr	Encore sur le projet	MASTER 2	Sénégal		IRD-DIADE	Doctorant	6	31/12/2015	Encore sur le projet	Recherche publique	Doctorant	Partenaire du projet	oui
FAYE Adama	M	adamafae@gmail.com	Récente	PhD	France	Doctorat avec l'IRD au Cameroun	IRD-DIADE	Post-doctorant	12	16/12/2017	Post-doctorant à l'ISRA	Recherche publique au Sénégal	Chercheur	Partenaire du projet	oui
GRILLOT Myriam	F	myriam.grillot@gamil.com	Récente	Master2	France		CIRAD Selmet	Doctorant	36	31/12/2017	Post doctorante	Université	Chercheur	Non	Oui
BISSON Anne	F	Anne.bisson@supagro.fr	Récente	Master2	France	1ere année doctorat INRA (abandion)	IRD ECO&SOLS	Doctorant	12	31/12/2018	Post doctorat	INRA	Chercheur	Oui	Oui
FALL CM Noreyni	M	Noreyni27@gmail.com	Récente	Master2	Sénégal		UCAD LPAOSF	Doctorant	24	31/12/2018	Finalisation de la thèse	Université	Doctorant	Oui	Oui
BA Marame	F	Marame.ugb@gmail.com	Récente	Master2	Sénégal	Ingénieur Recherche participative	IRD ECO&SOLS	Doctorante	24	31/12/2018	Finalisation de la thèse	Université	Doctorant	Oui	Oui
MALOU Pascal Oscar	M	opmalou@yahoo.fr	Récente	Master2	Sénégal	Assistant de recherche	IRD ECO&SOLS	Ingénieur de recherche	7	16/11/2016	Doctorant ARTS IRD	IRD – Campus France	Doctorant	Oui	Oui
TOUNKARA Adama	M	adotounkara@hotmail.fr	Récente	Master2	France		IRD ECO&SOLS	Ingénieur de Recherche	12	16/2/2016	Doctorant ARTS IRD	IRD – Campus France	Doctorant	Oui	Oui