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REVIEW ARTICLE
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Case study of innovations in commercial West African family fish farming that led to an ecological intensification

Delphine Lethimonnier[1,*], Barbara Bentz[1], Olivier Mikolasek[1,2] and Marc Oswald[1,3]

[1] APDRA Pisciculture paysanne, 9 avenue de France, 91300 Massy, France
[2] CIRAD, Avenue Agropolis, 34398 Montpellier Cedex 5, France
[3] ISTOM, ADI-Suds, 4 Rue Joseph Lakanal, 49000 Angers, France

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Abstract – Original fish-farming developments occur in west-central and south-western Côte d'Ivoire and in the forest area of the Republic of Guinea. *Oreochromis niloticus* and *Heterotis niloticus* are the main species produced in dam ponds with little or no feeding. Flooded rice is often grown here. The products supply local markets. In this article, we seek to understand the innovation trajectories that have led to three practices characteristic of these systems: 'large tilapia production with little feed in dam ponds', 'tilapia and *Heterotis* polyculture' and 'flooded rice cultivation in ponds'. We then assess the contribution of these innovations to ecological intensification. The practices that form the basis for current developments were developed in the 1990s on family farms. The suitability of technical choices at certain key moments depended entirely on the fish farmers who judged the tested techniques on their own terms. Our assessment shows that these farmers have contributed positively to ecological intensification. They suffer from recurrent cash flow problems and have thus natural resources and ecological functions in their fish farming system: stocking density to make the best use of the natural trophic resources, improved by polyculture and additional rice production that is more efficient than traditional lowland rice production. The promotion of reliance on existing know-how and anchoring in local culture strengthen the contribution to these systems' ecological intensification. The analysis shows that this development of integrated commercial fish farming in family farms questions ecological intensification and innovation in aquaculture.

Keywords: Ecological intensification / *Oreochromis niloticus* / *Heterotis niloticus* / flooded rice / innovation / small-scale fish farming / dam pond / Côte d'Ivoire / Guinea

1 Introduction

Thanks to aquaculture, the proportion of fish in the human diet has grown significantly over the last three decades (FAO, 2020) and its contribution to edible animal-source food is at similar levels to pigs and poultry, at slightly over 100 million tonnes (Edward et al., 2019). In Southeast Asia, aquaculture is the domain mainly of small enterprises, often farms, some of which specialize in aquaculture (HLPE, 2014). In contrast, in Africa, barring a few exceptions (Egypt, Nigeria), its development is at a standstill. However, some authors have pointed out that sub-Saharan West Africa has significant advantages that can help develop aquaculture (Chan et al., 2019; Aguilar-Manjarrez and Nath, 1998; Kapetsky, 1994). In the 1990s, even though a few small private farms were producing fish in peri-urban areas of Côte d'Ivoire and Ghana, there did not exist any aquaculture models adapted to rural areas (Prein et al., 1996; Koffi et al., 1993; Morissens et al., 1993). At that time, fish farming was struggling to develop in these countries and did not even exist in Guinea (FAO, 2020).

2 Material and methods

2.1 Context and survey

Today, fish farming is a socio-economic reality in these countries. Surveys show that the majority of aquaculture in Côte d'Ivoire is undertaken by small farms in rural areas (Amian et al., 2017; Yao et al., 2017; Kimou et al., 2016; Oswald et al., 2015), just as in Guinea (Keita, 2019). Given the lack of an exhaustive census, the 1500 fish farmers of the Rice-Fish Development Project in Guinée forestière (PDRPGF) project in Guinea (Keita, 2019) and the 664 fish

*Corresponding authors: d.lethimonnier@apdra.org

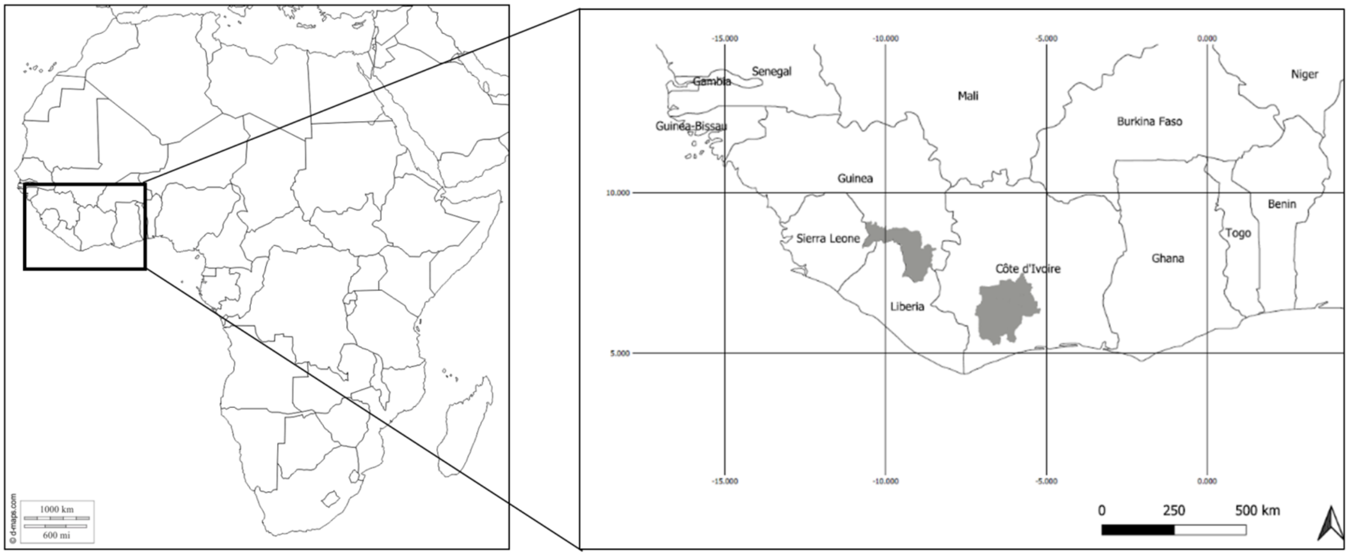

Fig. 1. In grey, the regions of Côte d'Ivoire and Guinea in which the surveyed family fish farms are located.

farms surveyed in Côte d'Ivoire (INS, 2014) reveal only part of the extent of this activity. For these authors, the farms mainly practice an extensive system of fish farming with little feed (with local by-products such as rice bran) or no feed at all. This fish farming has a commercial function; in Côte d'Ivoire it ranks in the five main cash crops of the farmers and for 23% of them it even is their first one (Oswald et al., 2015). Self-consumption or social functions concern less than one third of the fish production. These specificities were noted by (AFD et al., 2017) who propose to divide the category of small-scale aquaculture into commercial small-scale aquaculture and subsistence aquaculture.

Demographic growth is increasing the demand for food products and is pushing for further intensification of agricultural systems in order to feed the population, even though, at the same time, human activities continue to increasingly degrade the environment (Altieri, 1989). For aquaculture, Costa Pierce (2002) proposed an ecological vision that makes it possible to examine the evolution of systems and to assess the contribution to ecological intensification of innovations that are markers of the evolution of different fish farming models. More recently, Aubin et al. (2017) define ecological intensification in aquaculture as an increasing reliance on ecological processes and functionalities to improve its productivity, enhance the ecosystem services provided and limit disservices (negative services) and, more broadly, on biodiversity management and the leveraging of local and traditional knowledge.

(FAO, 2004) notes that the paths taken to make family fish farming in Africa a reality were very different from the strategies initially considered by development and research institutions in sub-Saharan Africa (such as credit, state-owned hatcheries, use of feed, local species, genetic improvement). Trying to find the reasons for this divergence leads to the examination of innovations that were not intentionally led or promoted by development institutions. The significance of innovation for development continues to be widely discussed and finds a prominent place in the literature (Faure et al., 2018; Hoffecker, 2018). Small-scale fish farming is not excluded from this debate (Blythe et al., 2017).

In this article, we analyse the trajectory of three innovations that underpin practices constitutive of current fish-farming systems in Côte d'Ivoire (Amian et al., 2017; Kimou et al., 2016; Oswald et al., 2015) and Guinea (Keita, 2019): the production of 'large' tilapia *Oreochromis niloticus* in ponds with little or no feed, polyculture of tilapia with the African bonytongue *Heterotis niloticus*, and tilapia-rice integrated culture with flooded rice cultivation using floating rice varieties. We then assess their contribution to the ecological intensification of the fish farming systems under consideration.

The case study focuses on the west-central and south-western regions of Côte d'Ivoire as well as in the southern forest area of the Republic of Guinea (see Fig. 1). These forest regions enjoy an equatorial climate with heavy rainy seasons.

The case study deals with family farms, mainly cultivating cocoa or coffee. The rapid and sustained development of these crops in the 1970s led to massive deforestation in Côte d'Ivoire as the agriculture frontier advanced deeper into forests. At the end of the 1980s, with increasingly limited possibility of this form of extension, producers were forced to seek to diversify their production. Today, the species most produced are tilapia (*Oreochromis niloticus*), followed by *Heterotis niloticus*. In Côte d'Ivoire, most fish farmers have dam ponds of around 0.3 ha (Oswald et al., 2015; Amian et al., 2017).

For this study, the material consists of interviews (85 fish farmers and 21 non-fish farmers, 23 interviews with development project managers or government officials in charge of fish farming) and grey literature from development projects, scientific publications and national statistics from sectoral services. The chronology of development actions and the emergence of the three studied innovations in this article is presented in Figure 2.

While Côte d'Ivoire has been benefitting continuously since the 1970s from successive development projects, with an interruption during the period of the Ivorian crisis, Guinea saw

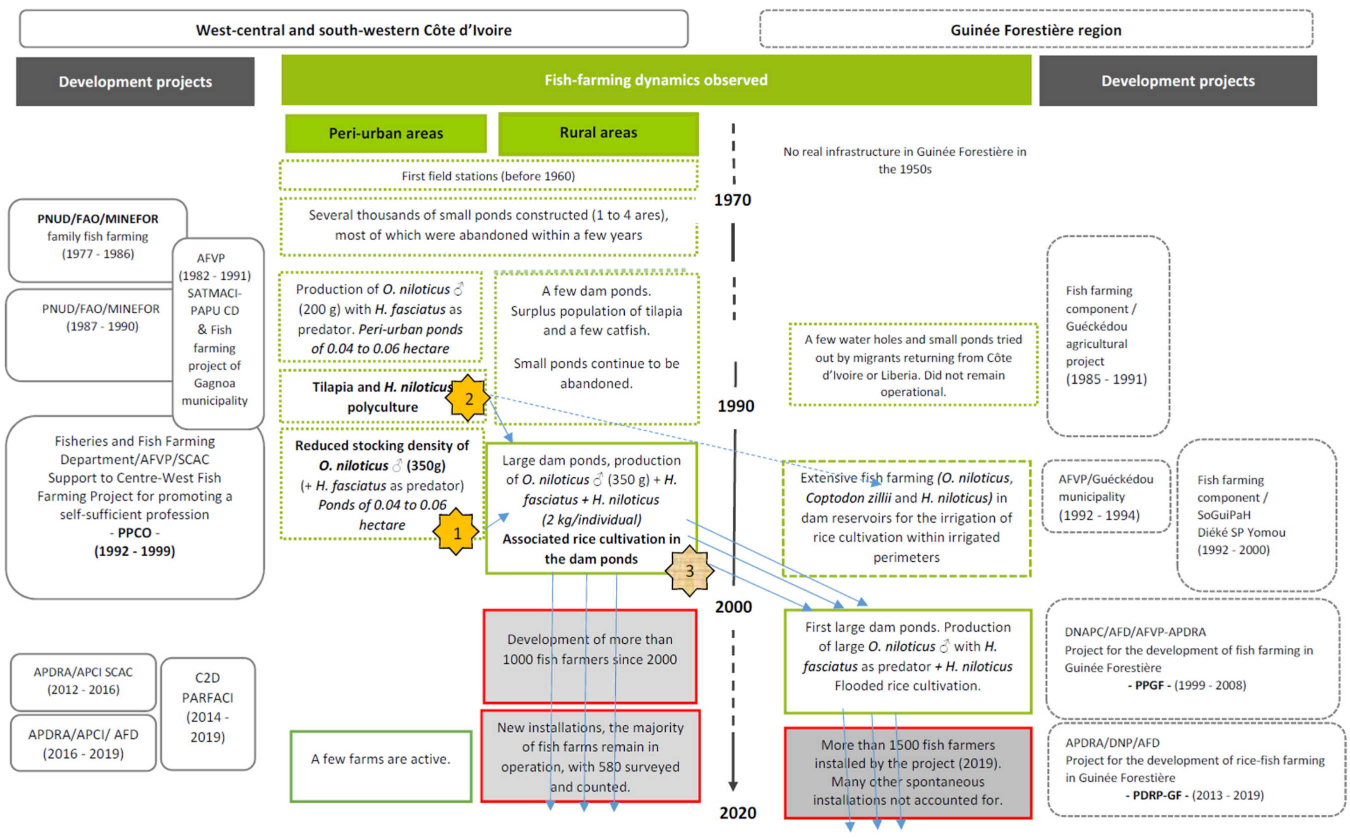

Fig. 2. Chronology of the implementation and dissemination of the three innovations in the regions studied (the stars represent their emergence: 1: production of large tilapia, 2: tilapia, Hemichromis fasciatus and Heterotis niloticus polyculture, and 3: flooded rice cultivation). The outer columns on the far left and far right show the main activities of fish-farming development in the regions studied in Côte d'Ivoire and Guinea. The main technical developments are described in the central columns. The arrows illustrate the path of their dissemination. The grey boxes present the current fish farmers.

the first efforts for developing fish farming only some 10 years later. The first and second innovations described – the production of large tilapia with little or no feed and tilapia and *H. niloticus* polyculture – were initiated in small ponds in peri-urban areas in Côte d'Ivoire (respectively 1 and 2 in fig. 2). These techniques were then replicated in fish-farming systems in large dam ponds in which long-stem rice was cultivated, described as a third innovation (3 in Fig. 2). These three innovations are also found in the current fish-farming systems described in the Guinea's forest area.

2.2 Analysis

For each of the three innovations, the analysis consists of two parts. First, by going back to their first descriptions, we report the story of the conditions under which each of these innovations emerged. To do so, we rely on the case study methodology applied to innovations as proposed by Douthwaite and Hoffecker (2017). It allows the authors to highlight the complexity of the innovation process through a description of the historical context during the innovation's emergence, its mechanism of development in response to constraints, and the role of the different people and institutions involved in the process, in particular producer organizations, management structures and research institutions.

The choice of the historical analysis makes it possible to situate past evolutions and to consider the hypothesis formulated by actors at a given time in a given context. The choices made by the producers are analysed with regard to current fish-farming systems.

Second, we analyse these innovations in terms of their contribution to the ecological intensification of the dam ponds, using the analytical framework proposed by Aubin et al (2017) to do so (see Fig. 3). Seven principles of ecological intensification must be taken into account when assessing the process of ecological intensification. Four are at the farm scale (Tab. 1) and three at the territorial scale (Tab. 2).

To fill in this analysis grid, we compare the additional contributions of the three innovations to the fish farming in dam pond. The considered initial situation is the one that pre-existed in rural areas: dam ponds with little or no feed with a surplus tilapia population and some catfish, mostly *Heterobranchus isopterus* (Lazard and Oswald, 1995; Oswald, 2015). The factual elements from all the collected information were used, with particular attention paid to the producers' perceptions, in order to understand what motivated their choice

Table 1. Characterization of the cumulative changes brought about by the three innovations described through the four principles of ecological intensification selected at the scale of the fish farming system by (Aubin et al., 2017).

	Innovation 1: The production of 'large' tilapia in ponds with little or no feed	Innovation 2: *Heterotis* and tilapia polyculture	Innovation 3: Flooded rice
1 - Minimizing dependence on external resources	Fish farmers produce tilapia weighing 250 to 400 g without the need for additional feed. Previously the tilapia produced did not exceed 50–100 g.	The farming of the new species (*Heterotis niloticus*) does not call for any additional inputs. It is trophically complementary. The natural reproduction of *Heterotis* in ponds produces a few hundred fry or juveniles which are exchanged within the fish farmers' networks. Its double breathing facilitates its transport.	Rice production (1.9 to 3.5 $t.ha^{-1}$) is higher than in the surrounding lowlands without specific inputs (0.8 to 1.2 $t.ha^{-1}$). The fertility of the uncultivated plot is 'saved'.
2 - Increasing the performance of aquaculture farming systems and product quality	Tilapia weighing more than 300 g is well appreciated by the consumer (more flesh/biomass) and preferred to imported fish. It is very much in demand.	The producer has 30% more fish to sell, with only a little additional labour. Sold at the same price as tilapia, *Heterotis* is considered a 'good fish' once its supra-gill organs are removed.	Rice cultivation does not reduce fish production. The water restrictions after transplanting and harvesting are compensated for by the better maintenance of the pond.
3 - Improving the robustness, flexibility and resilience of systems through the integration of functional complementarity	The risk of poor sales is low because it is a consumer product. Fish farming fits in well with other activities and requires only a little extra labour.The fish load is adapted to the gradient of productivity of little or no feed pond environments (from 0.2 to *1 Oreochromis niloticus*.m^2 with feed and from 0.015 to 0.04 *Oreochromis niloticus*.m^{-2} without feed).If because of drought the water-retention cycle is lengthened from 180 to 320 days, the yield does not reduce too much.	Two independent productions (*Heterotis* and tilapia) and different consumers for each of them make the system more robust. Moreover, *Heterotis* fry can be sold to generate additional income.*Heterotis* prevents the proliferation of molluscs, including the freshwater snails that are intermediate host of bilharzia (*Bulinus sp.*).	Less labour is required for the rice (no ploughing, little weeding). Water management in the dam pond ensures production (little risk of flooding or drought). The blocked water column eliminates weeds. Rice limits the development of invasive aquatic plants (nenuphars, *Pistias*).
4 - Diversifying the commercial ecosystem services provided by aquaculture systems	Because of the assurance of quality and freshness, local fish is prized by consumers and available all through the year.	This new product – a large fish (1 to 2 kg per individual) – is also suitable for other types of consumption in the village (festive dishes of large families). The different productions are combined on the same site with the additional possibility of sales of fry.	Rice is primarily produced for the family's own cocase stnsumption, fish is mainly sold after satisfying the family's basic needs. A 60% increase in the overall annual value produced.

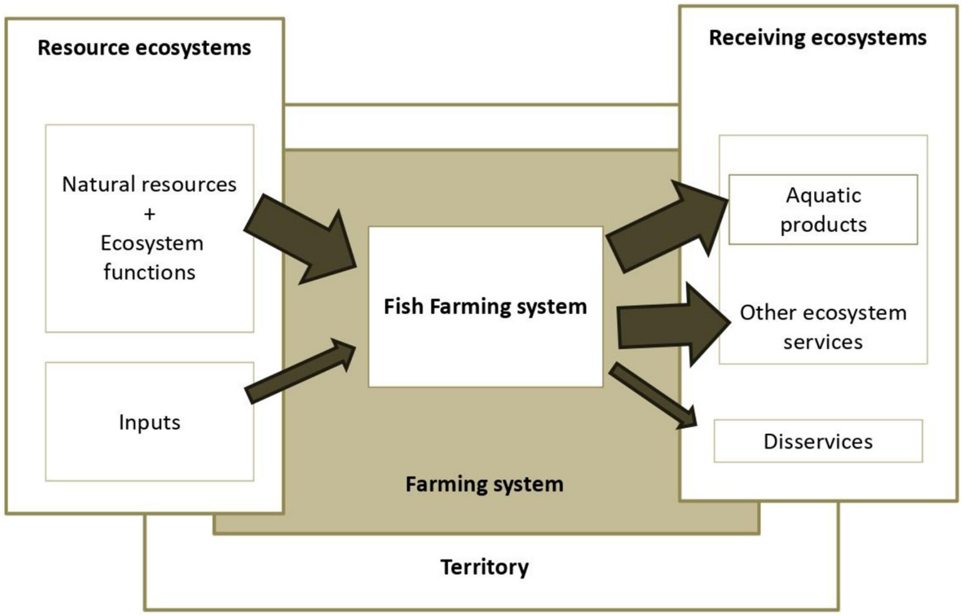

Fig. 3. Simplified diagram of the compartments involved in the ecological intensification of an aquaculture system (adapted from Aubin et al., 2017).

of these innovations. It should be remembered that since these processes took place on small farms and were adopted by small farmers, the data they used to make decisions are different from those that would be produced in the framework of experiments.

Tables 1 and 2 summarize this information in order to provide an overview of the contribution of each innovation to ecological intensification, mainly at the scale of the fish farming system and then at the scale of the farm and of the territory.

3 Results

3.1 The innovations story

3.1.1 The production of 'large' tilapia in ponds with little or no feed

The fish-farming model proposed in Côte d'Ivoire in the 1980s consisted of several diversion ponds (±200 m^2 to 400 m^2) stocked with *O. niloticus*, sometimes sexed manually, stocked at a density of 2 individuals m^{-2}, and using feed such as rice bran (Galbreath and Ziehi, 1988). Projects of the French Association of Volunteers for Progress (AFVP) adapted this model by systematizing the use of the banded jewelfish *Hemichromis fasciatus* as a predator to control unwanted reproduction resulting from sexing errors or the control of the proliferation of undesirable species. This system became established in peri-urban areas (Oswald and Copin, 1988). The initial hypotheses aimed at transferring the dominant technical models had to contend with the constraints of farmers in these regions, limited by their cash flow capacities and the local availability of fertilizer sources. The small size of the produced tilapia (around 50 g) did not meet the demand of the rural consumers, who could rely in the 1990s on an already well-established distribution network for frozen fish. However, marketing tests showed that at the market price of frozen fish (500 FCFA/kg), fresh tilapia weighing more than 330 g was preferred to all frozen fish.

Within the framework of the research and development component of the Centre-West Fish Farming Project (PPCO – years 1992 to 1994), tests carried out at field stations and with farmers had shown that in ponds with little or no feed, a reduction in density (to 0.1 to 0.2 individuals m^{-2}) made it possible to produce tilapia of more than 300 g (Glasser and Oswald (1997). However, these results were not applied in the field, and the project amended its discourse to curb the demands for installations from new applicants.

The situation changed when, in 1993, a group of cocoa farmers in Gnatroa village who wanted to start fish farming and who had started building small, non-drainable ponds, insisted that the project should provide support to them. As reported by Oswald (1997), '*A meeting was called to attempt to encourage people to stop these constructions from which they would not benefit. While many agreed to do so [...], some said [...] they [...] intended to continue [...]. It was therefore proposed to them to use this work to construct correct fish-farming facilities [good water and fish management, greater surface area of usable water] [...]. A training group was formed [...]. [Its members] appreciated the quality of the new facilities [the large drainable dam ponds]. Very low-density fish stocking was attempted in these large ponds, the growth was remarkable and the craze continued. In 1995, 21 dams were built within this group*'.

It is on the basis of this combination of innovative practices driven by the farmers that the extension service organized a first dissemination of fish farming up to 1999.

While retaining some of the techniques (male sexed tilapia and *Hemichromis* as a predator), this innovation (very low-density fish stocking and large drainable dam ponds) enabled their rural proponents to produce large fish in an attractive way,

Table 2. Characterization of the changes brought about by the three innovations through the three principles of ecological intensification selected at a territorial scale by (Aubin et al., 2017).

	Innovation 1: The production of 'large' tilapia in ponds with little or no feed	Innovation 2: tilapia and *Heterotis* polyculture	Innovation 3: Flooded rice
1 - Promoting the recognition of services and leveraging skills and know-how	This fish is appreciated in the villages. It moreover creates additional wealth in giving the opportunity to women processors to transform it into current dishes while other women specialize in its commercialization towards the peripheral cities. Those facts are a source of pride. As the density of producer hubs increases, the performance of services is improved: production of seines and fry, and the exchange of knowledge. Cooperation is encouraged by development structures based on information and the organization of services.	*Heterotis* is the show fish in the fish farming system due to its large size (up to 3.5 kg in ponds) and due to its jumps. This validates the know-how acquired by the farmers. The purchase and exchange of *Heterotis* fry imparts vitality into professional networks.New knowledge and insights are passed on, questions are shared such as 'the sex of *Heterotis*'. Knowledge generated by the research community is disseminated.	Local varieties of long-cycle flooded rice were shared spontaneously within networks in which knowledge and know-how about rice cultivation are valued. Within the local networks, know-how is fine-tuned: selection of varieties according to the water column or management of fish stocking depending on the filling level. The fish farmers use seasonality for rice cultivation in order to spread out the bird risk.
2 - Improving the territorial integration of aquaculture systems by promoting the production of non-commercial ecosystem services	This productive system is recognized as being part of territorial agricultural culture.Ponds are considered as water reserves and as an asset against bush fires. This system restores perennial wetlands.	*Heterotis* has become one of the symbols of this fish farming system at the local level. *Heterotis* has become an integral part of the agricultural and culinary culture of these territories.	Rice cultivation contributes to the pond's maintenance and of its services. The variety of rice to cultivate depending on the water column is being examined by the research community. Producer organizations in Guinea claim to be 'rice-fish farmers'. The authorities in Guinea showcase this production for food self-sufficiency.
3 - Adapting territorial governance mechanisms and instruments, and involving stakeholders	The recognition of this activity by local authorities facilitates land transactions peripheral to the development of the ponds and the recognition of the private ownership of the fish produced. Development organizations involve the research community (national agricultural research services and universities and international scientific institution).	*Heterotis* is easy to farm and contributes to fish farming's legitimacy and recognition.	Rice-fish farming is seen as a marker of development in the forest area of Guinea. Development agencies facilitate the participation of stakeholders, especially fish farmers, in the development and validation of the innovation.

for which there was a ready market since they were sold at the same price as frozen fish.

The mastery of the complete cycle of *O. niloticus* and *H. fasciatus*, with which *Heterotis niloticus* is combined and in association with rice cultivation (see below), requires genuine know-how. The same reference system was promoted in Guinea within the framework of the Fish-Farming Project in Guinea's forest area (1999–2008). For Simon and Benhamou (2009), this intervention is the basis of the most important development of fish farming in this country, with the number of producers increasing from 350 in 2007 to 1500 within the framework of the PDRPGF (Keita, 2019), figures which do not include spontaneous installations estimated by field sources to be as numerous.

3.1.2 Tilapia and *Heterotis* polyculture

Heterotis was identified as a species of interest early by colonial and post-independence research entities (Moreau, 1982). In Côte d'Ivoire, it was introduced from Cameroon at the end of the 1950s and the Water and Forestry Department maintained small numbers of it in their fish farms for stocking reservoirs. This fish suffered from a very poor culinary reputation and its selling price was the lowest on the markets of any fresh fish from inland fishing (Koffi, 1989).

In 1987, the Water and Forestry Department of Côte d'Ivoire offered a few young specimens to the head of the AFVP project in Daloa. During a discussion, an experienced fish farmer evinced interest in raising this fish species despite its poor reputation. He even stated that if he encounters difficulties to sell it, his family will consume it. When reared at very low densities (100–300 individuals ha^{-1}), *H.niloticus* did not compete with the existing polyculture system (*O. niloticus* sexed manually at a density of 2 individuals m^{-2} and *H. fasciatus* at a density of about 0.1 individuals m^{-2}). Less than a year later, the first in-pond breeding and fingerling harvests indicated the way to possible self-sufficiency in farming *Heterotis* (Oswald and Copin, 1988). The fish farmer expressed great satisfaction with this fish.

Around the 1990s, *Heterotis* was added to the polyculture system with tilapia in small fertilized peri-urban ponds in west-central Côte d'Ivoire (Copin and Oswald, 1993). Local know-how developed to help its sales: when sold alive, if its supra-gill organs are quickly removed, this fish's flesh does not retain its bad taste, in contrast to specimens caught in lakes. Sold on the local market at the same price as tilapia, sometimes even higher, it accounted for 10 to 20% of the pond's production. Farming this fish did not lead to an apparent drop in tilapia yield.

In the early 1990s in Côte d'Ivoire, following the first innovation described in this article, fish farming development projects in the country shifted to dam pond systems (Oswald et al., 1997) in which *Heterotis*'s contribution to the farm production was even higher, of the order of 30% and more.

In 1994, this fish was taken from Côte d'Ivoire to Guinea with the support of AFVP and the French National Research Institute for Sustainable Development (IRD, *Institut de Recherche pour le Développement*). The idea was to derive economic value from the hydro-agricultural reservoirs of the Guinea Oil Palm and Rubber Company (SOGUIPAH, *SOciété GUInéenne de PAlmier à huile et Hévéa*) by using them for fish farming (Hem et al., 2001). The Fish-Farming Project in Guinea's forest area obtained supplies of *Heterotis* from this company in order to build up its initial stock and popularize the farming of this species.

In 2014, a census of fish farms in Côte d'Ivoire showed that *H. niloticus* (57%) is second only to *Oreochromis niloticus* (97%) in terms of farmed fish species (Kimou et al., 2016). The practice of this polyculture of *O. niloticus* and *H. niloticus*, initially observed in Côte d'Ivoire's west-central regions, later expanded to certain western, eastern, southern and central regions of the country (Yao et al., 2017). In Guinea, *Heterotis* even enjoys a better position than in Côte d'Ivoire because it was associated with the early experiments and was included in the extension service's messages from the very beginning (Keita, 2019).

3.1.3 Flooded rice

The first descriptions of flooded rice cultivation in dam ponds date from the mid-1990s, most notably from the rural area of Gnatroa (see Innovation 1 above). A farmer of Malian origin associated rice with fish farming. According to his neighbours, he cultivated rice varieties that could thrive in deep water. The local name of the first variety which was the most cultivated was "Djou Keme", that means the grain that give a hundred (of grains), later the improved variety IR4 which could be cultivated as a floating rice was also used. This practice became more widespread locally and, at the end of the 1990s, led the PPCO to examine the interactions between rice and fish in dam ponds. The project's reports noted that 30% of fish ponds were being cultivated with rice. Niamien (2016) estimates that more than 70% of fish farmers practice rice-fish farming in at least one of their dam ponds.

In Guinea's forest zone, unlike in Côte d'Ivoire, the lowlands converted to fish ponds in the early 2000s were already being cultivated with rice. Rice cultivation in a dam pond was naturally associated with the first fish farming cycles, with new fish farmers benefitting from advice, as well as from exchanges and visits to Ivorian producers.

The entire water surface can be cultivated, with the exception of the area in front of the monk and the water channel bed. The use of floating rice varieties makes it possible to cultivate rice with water heights exceeding 1 metre, even up to 2 metres. The knowledge of rice cultivation by Guinean farmers and the very wide range of varieties used (Barry et al., 2008) means that in every installation certain local varieties are considered to be suitable: the choice of rice variety and its place in the pond becomes a subject of discussion. A crucial technical element is the control over the rise of water level as the rice stalk grows (too fast a rise causes the rice to be destroyed by the fish, too slow a rise in water level causes the rice to reach the heading stage when the pond is not yet filled, reducing fish production). The presence of monks in each pond facilitates this control. As soon as filling begins, the *Hemichromis* and tilapia fingerlings of about 30 g are stocked for growing. Rice can be harvested without interrupting the fish cycle (Simon and Benhamou, 2009).

In Guinea's forest area, flooded rice cultivation is almost systematically practiced in more than 90% of dam ponds. This is due to the fact that in the pond, ploughing is eliminated, the rice plants are directly transplanted into the mud when the pond is drained and weeding is limited to the pond's shallower periphery. The yield is twice as high as that of lowland rice before the pond was constructed. Estimates range from 1.9 to 3.5 t ha^{-1}, with most data indicating 2.5 and 2.7 t ha^{-1} compared to 0.8 to 1.2 t ha^{-1} for traditional lowland rice cultivation (Delarue and Naudet, 2007).

3.2 Analysis of the contribution to ecological intensification

As indicated in the methods section, the changes brought about by the three described innovations are grouped at the scale of the fish-farming system (Tab. 1) and of the territory (Tab. 2).

Tables 1 and 2 show the net contributions to ecological intensification of the three innovations analysed. In the context in which these innovations are implemented, they result in a transition towards an ecological intensification in the specific environment of the dam pond. The first innovation is based on a transformation of production value compared to the situation of a pond overpopulated with tilapia. This innovation has changed the perception of the profitability of fish farming for farmers in these areas; they now see it as a commercial activity rather than a subsistence one. The second innovation combines local understanding with scientific knowledge mobilized in response to farmers' demand and shows a net intensification in return (more fish produced for the same amount of input) for a little extra labour (Copin and Oswald, 1988). The third further transforms the system: two productions, a crop and fish farming, are combined in the same agroecosystem with their respective constraints. The value produced per unit area increases significantly.

Table 2 shows that the territorial dimension plays a major role in each innovation. The capacity of farmers to produce market-size fish, substituting imported fish, has led to the recognition that this fish farming model is an economic activity in its own right. Cooperation between producers has ensured the transmission of knowledge and constitutes an exchange framework for its dissemination. Recognition by local authorities and the government then became possible, followed by their promotion of this aquaculture. The legitimacy of the innovation was first always local, at the village level. Subsequently, however, this recognition varied depending on the country (the Guinean authorities give it more importance). Scientific studies have also contributed: Dabbadie (1996) studied the viability of rural fish farming with low inputs. For *Heterotis*, the few experiments carried out were conducted even though the technique was already widely in use. The same is the case for rice, which has prompted studies in both countries by scientific institutions not involved directly in development activities.

The separation between the three historical trajectories of these innovations gradually lost its significance as they came together in the same technical system. Indeed, in the 2000s, some Guinean rice-fish farmers embarked on fish farming because of the advantages that the dam pond offers for rice cultivation.

4 Discussion

4.1 Specificities of these innovations

These three dam pond innovations have trajectories based on several previous steps that are worth remembering (such as fish handling, water management, fish reproduction and supplies for stocking, sales management).

The lack of any substantial research studies shows that these innovations emerged only through the initiatives of farmers, who played the role of the main actors in this development. While they are often illiterate and face recurrent cash flow problems, they have a remarkable knowledge of their environment. These three initiatives also illustrate divergences and an attitude of questioning, with the model initially proposed being discarded. The suitability of the new technique depended at certain key moments entirely on the fish farmer(s). They judged the technique being tested on their own terms, terms that are not really understandable by support structures. These dynamics indirectly call into question action-research mechanisms in which the involvement of the researcher depends on his discipline being called upon to help resolve a problem (Fielke et al., 2018). Finally, they diverge from a certain vision of entrepreneurship that is supposed to be a vehicle for development (Bush and Marschke, 2014) and in which innovations are expected to reinforce specialization and entrepreneurship of the fish farmer, leading him to constantly and increasingly specialize (Belton et al., 2018).

Joffre et al. (2017) show that until the mid-2000s most research work on innovation in aquaculture was characterized by an approach focused on the removal of technical barriers, mainly in a linear logic of technology transfer, sometimes through approaches based on analyses of production systems. However, innovation's social dimension, which results from interactions and negotiations between actors with effects that are difficult to predict, was not sufficiently taken into account even though it is crucial (Long, 1989; Olivier de Sardan, 2005). In aquaculture, Douthwaite and Hoffecker (2017) use two significant case studies of the intervention of research institutions to note that the innovation process does not necessarily produce the expected results and that it mobilizes complex interactions such as the demands around a common question, appropriated first results, habits of experience sharing and discussion.

It is also interesting to examine the possible convergence of these innovations with other ongoing processes. For example, some similar practices, such as the rearing of large tilapia and *Heterotis* in dam ponds, are described in eastern Cameroon (Oswald et al., 2015), and probably constitute a response to farmer demands far beyond the contexts studied here.

These processes correspond to certain axes of the paradigm shift for ecological aquaculture defined by Costa Pierce (2002): the integration of ecology and social issues, an approach of sharing knowledge and promoting innovations, and the taking into account of concerns pertaining to social, economic and environmental contexts that are broader than those of aquaculture. However, the promotion of this path always involves the issue of how to provide farmers with more resources to innovate in this direction (Edwards, 1998).

4.2 Ecological bases of intensification processes

Fish in excess in a pond, in terms of numbers as well as biomass, have higher nutritional requirements than can be provided by the environment's biotic capacity (Hepher, 1989). Dwarfism in ponds overpopulated with tilapia is attributed to the impossibility of meeting food and reproduction needs in particular. For the first innovation, robust management of density by using a strict predator combined with quantified stocking of male tilapia fingerlings (which have the best growth capacities) can convert the environment's productivity into high quality production.

Heterotis and tilapia polyculture, even though common, has been little studied, and as far as we know, the complementarity of the niches for the two species in the pond has not been examined using a rigorous experimental protocol. However, the very numerous observations in the field and the interpretation shared by the concerned actors indicate that these two fish species are complementary in the pond. Several authors have confirmed this (Copin and Oswald, 1993; Oswald et al., 2002). *Heterotis*'s diet is variable, consisting of certain zooplankton, detritus, seeds, insects, small molluscs and various elements from the pond's bottom layers (Monentcham et al., 2009; Adite et al., 2013). It is nowhere mentioned that this diet is significantly different from that of tilapia, even though some elements of *Heterotis*'s diet (ostracods and molluscs) are not part of the latter's. At this stage, this complementarity can be said to be based on the probable combination of significantly different trophic niches and on positive synergies linked to the burrowing behaviour of *Heterotis*, which is able to put benthos and elements of the mud back into circulation. Moreover, Simon and Benhamou (2009) noted the absence schistosomiasis in the ponds where *Heterotis* is farmed.

The integration of floating rice changes the pond's functioning. It is surprising that, from the viewpoint of the producers, there is no significant decrease in fish production, even in the case of rice-fish farming in compartments (Halwart and Gupta, 2004). The diversion of part of light energy and the usage of mineral elements for rice growth are not detrimental to fish production, nor is the decrease in water level during transplanting and harvesting. These seemingly negative relationships are likely compensated for by other positive relationships (Wan et al., 2019): consumption of stem periphyton by tilapia, recycling of elements from the pond silt and its modification by the plant roots, and recycling of rice straw. Finally, the practice of flooded rice cultivation is a way of maintaining the dam pond and exerting pressure on floating plants (water lily and *Pistia*) which are a real nuisance. This agriculture-aquaculture integration allows fish production to be as effective as without rice, and rice production to be more efficient than traditional lowland rice farming.

Once these innovations become routine practices, the resulting increase in production does not depend on the mobilization of additional resources, apart from extra labour. The working capital needed for fish production is therefore better leveraged. As already noted by Koffi et al. (1993) in the context of this type of agriculture, producers remain constrained by their cash resources, leading in particular to limited access to inputs. These changes result in an improved efficiency of the system and of the self-sufficiency of farmers by favouring available natural resources and functions in a very original manner. As authors such as Altieri (2002) and Edwards (2015) have already noted, poor small-scale producers are the best practitioners of agroecology.

Two of the other principles that define ecological intensification – the promotion of local know-how and anchoring in a territory's agricultural culture – are added to the benefits provided by these innovations. It should be noted that the processes that led to the emergence of these innovations were not initially part of integrated territorial management; in hindsight, they seem to be well and truly part of it.

5 Conclusion

The processes that led to the emergence of these innovations were not foreseeable and did not follow any of the promoted trajectories. These three innovations have contributed to an increase in production in volume (complementary species in mixed fish farming – associated rice production) and/or in value (large fish fetching better prices on the market) by favouring available natural resources and functions in an original manner. These processes improve the territorial integration of aquaculture systems and their anchoring in agricultural culture, and enhance local skills and know-how. Investment constraints and limited cash flow have pushed farmers, although not systematically, to leverage ecological resources and services, and it is not altogether surprising that the results of innovations are contributing to ecological intensification. However, these innovation trajectories have also helped to remove obstacles to the development of peasant commercial fish farming, an example of local dynamism, and helped combat rural food insecurity. The use of specialized entrepreneurs is not at the root of these developments.

Giving a real place to small-scale producers in the process of developing new techniques is definitely a prerequisite for the ecological intensification of this type of aquaculture. In addition, these developments call for a reconsideration of the interest in promoting fish-farming models integrated into peasant farms by calling into question the modalities for achieving greater agroecological and economic efficiency.

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