Social-ecological feedbacks lead to unsustainable lock-in in an inland fishery

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Abstract:

This interdisciplinary paper presents an empirical analysis of techno-institutional lock-in in a regional fishery, in the Logone floodplain in the Far North Region of Cameroon. In the Logone floodplain, one fishing technique is spreading exponentially even though it is changing the social, hydrological and ecological dynamics of the system in ways that are largely considered problematic by local communities. We use a complex systems framework to analyze large hydrological and socio-economic datasets. Results show how social-ecological feedbacks foster the spread of the technique and contribute to the process of lock-in. The lock-in leads to a resistance to change despite awareness of the technique's impact, a situation that may also be described as a social-ecological trap. We identify and explain four kinds of positive feedback loops relating to socio-economic, behavioral, demographic and hydrological processes, respectively. We also identify possible solutions that consider the complexity of the feedback loops across multiple dimensions of the floodplain system.

Keywords:

social-ecological system, common-pool resources, lock-in, social-ecological trap, fishery, African floodplain

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Introduction

1.1. Theoretical framework

Governing common-pool natural resources requires understanding how social and natural processes interact. This research agenda has been pursued across various academic disciplines, and relatively recently in an integrated manner under the research umbrellas of social-ecological systems, and coupled human and natural systems. A community in its environment may be conceptualized as a social-ecological system because it is the interplay of social and ecological processes that drives system dynamics (e.g., Carpenter et al. 2009). A coupled system framework (e.g., Liu et al. 2007) emphasizes the bidirectional nature of these social-ecological interactions: for example, a community may use various practices and technologies to exploit natural resources, practices that can in turn change the natural processes that produce the resources they exploit.

Common-pool natural resource systems like fisheries, or global commons like the Earth's atmosphere, are complex social-ecological systems that can exhibit nonlinear transitions leading to abrupt or slow shifts between different regimes of system structure and function (Hughes et al. 2013). They may be studied using tools and concepts from the rapidly developing science of complexity (e.g. Moritz et al. 2013) to identify and analyze feedbacks between social and ecological processes (Liu et al. 2007, Carpenter et al. 2009). Unforeseen nonlinear transitions in social-ecological systems, such as collapse or saturation, and how to maintain or increase system resilience to avoid them, have also been foci of the common-pool resources literature (Ostrom 1990, Folke et al. 2004, Stern 2011). This paper draws on the intersection of these lines of research, with the premise that while scale and complexity are important factors when analyzing common-pool resource systems, some lessons can be drawn across them (Stern 2011).

We are especially concerned with social-ecological systems in which a changing environment is associated with inertia in the social system. By social inertia, we mean a situation where there is awareness in the community to be contributing to environmental change in ways that are damaging overall system resilience (the capacity of the system to maintain its functions in a changing environment), but where this acknowledgement does not lead to individual or collective action to change relevant practices. A mismatch between a fast-changing environment and a social system that is slow to respond characterizes many social-ecological systems, and has been described as the consequence of various feedbacks leading to a state of “lock” (Scheffer and Westley 2007). When these feedbacks push the social-ecological system towards an undesirable state, the situation has been called “social-ecological trap” (e.g. Cinner 2011). Social-ecological traps are path-dependent processes (Boonstra and de Boer 2014) that can lead to system overshoot (Scheffer et al. 2003) and the crossing of thresholds resulting in nonlinear transitions (Steneck et al. 2011, Rockstrom et al. 2009). A global and current example of such a trap is the apparent paradox of the continued increase of anthropogenic CO₂ in the Earth's atmosphere and the social, political and institutional inertia to shift away from fossil fuel energy production: feedbacks between social and ecological processes have led to a resilient yet undesirable state. The process leading to this trap has been called the

“carbon lock-in” in the ecological economics literature, as a case of techno-institutional lock-in (Unruh 2000).

Techno-institutional lock-in is a specific form of a collective action problem that characterizes the path-dependent co-evolution of social networks of users and institutions around a practice or technology, even as it is considered suboptimal (Arthur 1989). More specifically, it describes a situation in which a technology remains dominant because institutions have adjusted to it, and the benefits of switching are not perceived to outweigh the costs for individuals even though they would collectively benefit from a switch (Perkins 2003). In the example of the carbon lock-in, the combustion of fossil fuels has become the dominant form of energy production, while also shaping socio-economic life and habits since the industrial revolution. With time, this co-evolution has led to the dominance of a technology that is today known to be problematic in social-ecological terms, because of global warming. Another example is that of insecticide spraying to limit plant-hopper infestation in rice cultivation, a practice that has been shown to increase the rice crop’s vulnerability to pests, leading to more spraying in a feedback loop (Spangenberg et al. 2015). In other words, techno-institutional lock-in is a situation where the social system has become rooted in practices and institutions, in relation to a technology, which are making it slow to adapt to change in its environment – change to which the technology is contributing (Unruh 2000).

The concept of lock-in has roots in complexity economics. Positive socio-economic feedback loops have been associated with lock-in processes, in particular: social learning, adaptive expectations and network effects (Arthur 1994). First, the more a technology is ubiquitous, the easier it is to access the knowledge to operate it. This creates a positive learning feedback towards the adoption and use of that technology. Second, confidence in the technology increases with increased adoption, which also fosters early adoption and lock-in. Finally, lock-in has been associated with dynamic complementarities or network effects (Marechal 2007): interrelated activities and socio-economic fluxes that reinforce the institutionalization of the technology. In relation to the ‘carbon lock-in’, one may think for example of the co-development of the road network and the automobile industry (Unruh 2000).

In this paper, we use the concept of lock-in to analyze the mechanisms leading to a social-ecological trap as it unfolds in a regional social-ecological system: the Logone Floodplain fishery, in the Far North Region of Cameroon. We start by introducing the case study of the Logone Floodplain fishery. Second, we describe the methods used for the analysis underpinning this paper, including field surveys, satellite imagery, household surveys and ethnographic research. We then present an analysis of four feedbacks contributing to lock-in in the fishery: demographic, environmental, socio-economic and behavioral feedbacks, and their consequences. Finally, we discuss the theoretical and practical implications of our findings, for our case study and for social-ecological systems in general.

1.2. Research context

The Logone Floodplain is located in the Lake Chad basin where hydrology, ecology and human livelihoods are tightly interdependent (Bene et al 2003a; Scholte 2005). The floodplain on the Cameroonian side is populated by about 200,000 people, with large seasonal variations as some people follow fluctuations in resource availability, such as forage for pastoralists and migrating fish for some Musgum and Kotoko fishers (Delclaux et al. 2010). Every year the floodplain is inundated by water from the Logone River. This occurs at the end of the rainy season, with the peak flood in October. The floodwaters then recede between November and January (Fig. 1), leaving first a number of flooded depressions, and then a dry floodplain (Seignobos and Iyebi-Mandjek 2000). The area and timing of flooding and flood recession vary annually with climatic and river discharge conditions.

The seasonal patterns of flooding and flood recession drive the vegetation and fish productivity, on which mobile pastoralists, small-scale rice farmers and fishers directly depend. Two transitions in flooding regimes were documented in the recent past as combined effects of climatic trends and hydro-engineering interventions. First, a large dam (the Maga Dam, Fig. 1) was built in 1979 on the Logone River, limiting flooding and negatively impacting vegetation and fish biomass in the downstream floodplain (Scholte 2005). The dam construction coincided with a period of below-average rainfall in the 1970s and 1980s, a long drought that further reduced seasonal flooding of the plain and impacted the whole region (Hulme 2001). The second shift occurred in the mid-1990s, with the implementation of a re-flooding program via the engineered opening of two waterways into the floodplain to mitigate the effects of the dam (Loth and Acreman 2004). Around the same period, regional rainfall also recovered to average values (Delclaux et al. 2010). These past transitions in flooding regimes evidence that the system can shift from one dynamic state (large flooded plain) to another (reduced flooded plain and increased arid plain), and that the flooding regime is coupled with pasture quality (Scholte 2005), fish quantities (Benech and Quensiére 1982), and human migration patterns (Scholte 2005).

Fishing in the floodplain is an activity that has been carried out for centuries, historically by Kotoko households. Fishing techniques vary with the season and location. They include gillnets, cast nets, static hooks, various woven traps, grass fishing and fishing canals. The traditional rule of the Kotoko over the floodplain's fish resource waned in the 20th century, after a series of geopolitical transformations and an increased demographic pressure in part caused by the migration to the floodplain of other groups, such as Musgum people. In the last few decades, the tendency has been for increasingly open-access to the fish resource, as well as individual appropriation of small parts of fishing grounds, in contrast to the tight regulations that were once imposed by Kotoko chiefs over the fishery (Landolt 2010).

One consequence of this gradual change in fishery governance is that the digging and exploitation of individual fishing canals has become increasingly popular, leading to changes in the hydrology, ecology and social dynamics in the floodplain. A few natural channels had been deepened and exploited by Kotoko fishing communities in the floodplain for hundreds of years, to fish during the flood recession period (Vidy 1983). In

the last three to four decades however, there has been an unprecedented spread of individually owned fishing canals, man-made trenches that belong mostly to Kotoko and Musgum fishers and are now ubiquitous in the floodplain (Delclaux et al. 2010). The canals connect deeper points in the floodplain and a waterway in order to drain the floodwaters and fish during the flood recession (more detail in section 3.1.1). They require a large initial investment and some maintenance work, but constitute a very efficient fishing practice as fishermen use gravity and the natural flood recession dynamics to trap fish.

People in the floodplain argue that the spread of canals is not sustainable, because the resources they draw on - land, water and fish - are limited. If the spread of canals follows a simple technology diffusion model, the canals fishery system may stabilize along a S-curve (Geroski 2000) and reach a relatively stable state around a 'carrying capacity'. Note that here we are talking about a social-ecological carrying capacity, rather than a purely ecological carrying capacity that would only consider the fish stocks (for which there is no long-term data in the Logone Floodplain). Our use of the notion does not simply reflect the stability of the fish resource, but also the related stability of social and cultural institutions in the fishery (Seidl and Tisdell 1999), so the degree of social unrest and unresolved conflict related to canals is as relevant to the social-ecological stability of the fishery as the quantity of fish caught. Alternatively, the situation may be one of techno-institutional "canal lock-in", where the technique keeps spreading regardless of whether it is sustainable for the floodplain system. Because the Logone Floodplain fishery is a complex system that has been shown to exhibit alternative states, the system may overshoot as a result and the number of canals reach a threshold then fall with the resource, as canals that are not used for a few years fill-up with sediment and gradually 'disappear'. To quote a classic from the field of systems analysis (Meadows 1999: 9): "overlong delays in a system with a threshold, a danger point, a range past which irreversible damage can occur, causes overshoot and collapse" (see also Scheffer et al. 2003; Scheffer 2009). The question then is: how do we know if the canals fishery in the Logone Floodplain is in overshoot, or, as Hughes and colleagues put it (2013), "living on borrowed time"?

To address this question, we collected and jointly analyzed data on the natural system (hydrological data, climate data, vegetation and fish population data) and the social system (socio-economic and cultural data), starting with ethnographic fieldwork. The research methods are described below for the datasets used in this paper, which represent only part of the data collected in the overall project (Moritz et al. 2016).

1. Data and Methods

The data presented in this article was collected over a period of two years (2013-2015) in a study area extending in the south of the Cameroonian side of the floodplain, including three major waterways: the Logone River, the Lorome-Mazera and the Logomatya (Fig. 2A, black frame).

2.1. Geographical survey of canals

In February and March 2014, we conducted a census of all fishing canals (N = 1,172) along the three major waterways of the study zone (Fig. 2A). The field team was organized in groups of three: one local engineering masters student, one field and development specialist from our partner organization in the area, and one local guide and interpreter. The team identified each canal and its owner's contact details, and documented information on the canal location including GPS coordinates (with elevation) of start, end and intermediate points. They also recorded physical properties for each canal: total length (by following the canal from start to end on a motorbike with a tracing GPS); canal widths at the bottom and surface levels; and canal depths at the start and end. In March 2016, the team conducted a survey and identification of all new canals built since the 2014 survey.

2.2. Satellite imagery

To evaluate the impact of canals on floodplain flooding, in particular to examine whether the canals may be altering flooding rhythms, we combined canal survey data and Landsat satellite imagery from sensors ETM+ (Landsat 7) and OLI (Landsat 8), downloaded from the USGS Global visualization viewer. We selected the years with more than two available images for the flood recession period (September to December), thus acquiring at least one snapshot of flooding extent every 40 days or so. This resulted in 2009, 2011, 2013, and 2014 as suitable years for analysis.

The process to obtain flooding maps from Landsat scenes is based upon Jung et al. (2011). We first applied a linear least squares regression analysis to fill gaps in Landsat ETM+ images, in order to maximize the retrieval of flooded areas. Second, we determined permanent open water areas such as the Logone River and the Maga Reservoir using a clustering method on a Landsat image dated 21 October 2001. Third, we applied a cloud detection algorithm to mask these areas (Sakamoto et al., 2007), plus a buffer of 10 pixels to account for cloud shadows. Finally, the flooded areas were determined using a threshold of 0.08 in Top of Atmosphere (ToA) reflectance units (Westra and De Wulf 2009) applied to the band 7 of each sensor (2.09-2.25 μm for ETM+ and 2.11-2.29 μm for OLI).

In order to produce a standardized comparison between changes in flooding recession during the period of analysis, we focused on a specific sub region, *zone A* (Fig. 2) that contained greater canal density than the overall floodplain and featured a 23% increase in numbers of canals between 2009 and 2014. We calculated a ratio (R) between flooding extent within *zone A* at any given date and its corresponding total flooding extent (F):

$$R = \frac{A}{F} \times 100\% \quad (1)$$

Graphed in a scatterplot (R versus scene date), this ratio allows the comparison of the flooding recession rate between A and F across all analyzed years. In case of no change, we should expect A to be approximately the same proportion of F around the same date for each analyzed year. Accordingly, an increase (decrease) in the size of A with respect

to F would indicate that flooding in A recedes slower (faster) than F year to year around a given date.

2.3. Ethnographic fieldwork

Some of our understanding of social-ecological dynamics in the floodplain emerged from exchanges with local colleagues (e.g. authors A. Mahamat and S. Kari, and members of our field team who grew up in fishing household in the floodplain), and M. Moritz's decades of ethnographic fieldwork in the area. S. Laborde and M. Ahmadou also conducted ethnographic fieldwork (including visual ethnography) with floodplain fishers in February-March 2014 and in November-December 2014. The observations and interviews from these periods in the field informed the development of household surveys.

2.4. Household survey

We developed a survey including questions about demography, economic activities, fishing catches and techniques, and characteristics of the canals fishery (acquisition, maintenance, exploitation). The questionnaire also included questions about social cohesion, and conflict. In April and May 2014, our field team surveyed 416 households in our study zone (Fig. 2A, black frame). 208 canal-owning households were identified amongst all canal owners of the study zone, using a stratified random sampling technique in order to obtain a spatially coherent sample. We then interviewed 204 non-canal owning households, picking at random in each village the same number as canal-owning households surveyed in the village. The survey was administered by teams of two field assistants, including one with strong local networks and language skills (Musgum and/or Kotoko, Fulfulde, and French) to serve as a guide and interpreter. In 2015, another survey was conducted with a stratified sample of 222 respondents (113 canal owners and 119 non-canal owners). We use basic statistical techniques (% calculations) to present results from the questionnaire data.

3. Results

3.1. Fishing canals: characteristics and spread

The canals we surveyed in 2014 belong to Musgum and Kotoko fishers, in approximately equal proportion (51% and 49%, respectively). Fishing canals form hydraulic links between areas of lower elevation in the plain (depressions) and the rivers: they are designed to drain the receding floodwaters downstream (Fig 2A, B, C), allowing fishers to trap the fish they contain with fine-meshed stationary nets placed at the canal mouths (Fig 2D). The structures may be as deep as 3 m and as long as 10 km (respective averages are about 1.5 m depth and 1 km length). There are different ways to acquire a canal such as construction, inheritance, and purchase, and once built canals require annual maintenance to prevent sedimentation. Fishers dig and deepen them in the hardened clay of the floodplain during the dry season, or more commonly, they pay Chadian workers to do so (Fig. 2F). Reported investments and revenues vary widely across canals, along

long-tailed distributions, but as a reference for the 2013-2014 season, the median annual maintenance cost represented 30% of the median annual canal revenue. There are uncertainties in investments reports largely because not all fishermen hire workers, and personal and family members' time and work at digging and maintaining a canal was not quantified. For revenues, variability is related to parameters like age, volume and location of the canal, as well as the partly stochastic process of fish movement and capture. Despite this variability, the relatively large investment they represent and the fact that catches that are only concentrated during the two to three weeks of flood recession (November-December – Fig. 1), canals are widely regarded as one of the most profitable fishing techniques in the floodplain.

An analysis of the age for the 1172 canals surveyed in 2014 in the upstream area of the plain (Fig. 2A) showed that the number of canals has grown uninterrupted through the different flooding regimes of the plain (Fig 2E, see also Delclaux et al. 2010): first linearly until the 1970s ($R^2 = 0.974$ for a linear fit for the period 1915 to 1979), then exponentially ($R^2 = 0.993$ for an exponential fit for the period 1980 to 2014), which is a better model than an exponential fit to the whole period 1915-2014, with a $R^2 = 0.951$ in this latter case). The floodplain saw many hydro-ecological and geopolitical transformations during the 1960s and 70s. People interviewed often recalled that before then, the fish were more abundant (see also Landolt 2010) and, as a Kotoko informant explained, “there was no real need to dig the earth (to build canals) to catch fish – in fact it was rather considered a dishonoring practice for the Kotoko”. The popularity of the canals increased after the droughts of the mid-1970s combined with the effects of the Maga Dam built in 1979, which had reduced flooded area and impacted the fish population. The canals that were useable then (some went dry as the flooded area was reduced) were the most productive fishing technique during these times, as they allowed access and exploitation of the flooded depressions. The availability of inexpensive laborers fleeing the first Chadian civil war (1965-79) also facilitated the multiplication of canals; it is still the case today that many people working on canals construction and maintenance are paid Sara workers from Chad. Finally, the migration of Musgum people in the 1960s and 70s, along with the establishment of a state administration for natural resources, has also contributed to the gradual weakening of Kotoko institutions and deregulation of the fishery (Bene et al. 2003, Delclaux et al. 2010, Landolt 2010). The 1960s and 70s were therefore a pivotal time for the canals fishery, representing what Boonstra and de Boer 2014 call the “critical juncture” in the social-ecological trap process: the time when feedbacks kick-in.

While initial Kotoko canals were communally exploited, the canals are now mostly private property, with few restrictions on accessing land to dig them. There are no individual land or water property rights until a spatial area is exploited, and according to fishers interviewed, ‘anyone’ from the village can build a fishing canal if they can afford it and find a place to dig. Most villages, fields and canals are situated along the riverbanks, further limiting available space: in some places the canals are less than 10 meters apart from each other – all connecting to the same depression. As a result, fishers have recently reported buying land from a farmer to dig their canal. Once the canal is built it becomes property of the fisherman who built it. There are no established rules to

control the spread of canals beside a gubernatorial decree from 2006 altogether forbidding the digging of new canals and the maintenance of existing ones. The decree is not respected, and did not slow down the growth in the number of canals (Fig. 2E). Some of the other fishery systems in the floodplain are more communally governed: fishing in the depressions and some areas of the rivers, for example, is organized by the community and strictly regulated (Bene et al. 2003).

3.2. Lock-in

An analysis of socio-economic data shows that as they become more numerous, canals are less and less productive. A simple generalized model of the evolution of returns (benefits/costs) for a technology with increased scale of adoption is reproduced in Fig. 3A: early stages of adoption are characterized by increasing returns, then returns stabilize and decrease. In the Logone Floodplain, the dynamics is different: an analysis of 2014 benefits/costs for canals of various ages shows that the early phase of increasing returns is well over, while the exponential spread shows no sign of inflexion (Fig. 3B).

More recent canals are less profitable than older canals, especially so for canals built since the mid-2000s (Fig. 3B, black markers). Ethnographic data suggests that this is caused in part by the added value of annual canal maintenance and possibly lengthening and/or deepening, but also by greater competition: there is not much space left to build canals in the floodplain, as fishermen explained in ethnographic interviews, so newer canals are built in less desirable locations and require more maintenance work. Across the five fish groups mostly commonly caught in the floodplain, an average of 81% of fishermen interviewed in 2014 reported catching fewer fish than 10 years ago. Catches for the two main fish groups caught by the canals have decreased in size in the last 10 years, according to 62% of respondents (36% stated that the size had not changed, and 2% that it had increased). Some of the fishermen blame the growing number of canals for these changes in catches.

As a result of decreasing fish resources perceived by fishers and increasing density of fishing canals, conflicts around canals are frequent. Of the 212 canal-owning fishermen surveyed in 2014, 35 of them (17%) had been personally involved in conflict because of their canal (31% did not wish to answer the question). These conflicts may occur between fishers, herders and farmers because of the modifications to water flow paths caused by the canals. They also occur within families, for the heritage of canals. Finally, many canal-related conflicts are between neighboring canal owners, as they dig to drain as much water and fish into their own canal as possible, sometimes intersecting or sabotaging other canals in the process. Of the 219 fishermen (owning canals and not) who answered questions on such conflicts, 66% stated that conflicts had increased in the last few years. The conflicts take various forms, some more open than others. Black magic is sometimes used to sabotage another's canal, for example. Open conflicts are mostly resolved amicably, as a normal social process. However, some conflicts over canals have also lead to violent confrontation, including homicide (Boukar 2011).

While in the simple model of technology spread in Fig. 3A decreasing returns typically lead to a slowing down of the rate of adoption, in the Logone Floodplain the rate of canal construction shows no sign of inflexion; it is still increasing (Fig. 3B). There is a positive density-dependence in the rate of spread of canals in the floodplain, despite a negative density-dependence of new canals' profitability and an increase in conflict. In other words, canals are being built faster and faster even as their individual profitability is decreasing and their impact on the social-ecological floodplain system becoming more obvious. This indicates that the canals fishery is in a situation of techno-institutional lock-in in which the canals have become ubiquitous in the floodplain despite their impacts. We call this "canal lock-in", a situation expressed as follows by a fisherman interviewed in 2015: he said that he believes "many problems in the floodplain are linked to the canals" and that "every year he considers quitting, and would never encourage his children to build a canal." However he, like most others, keeps exploiting his canal. In the following section, we present the positive feedbacks that lead to canal lock-in in the Logone Floodplain.

3.3. Social-ecological feedbacks

Socio-economic feedbacks

Positive feedbacks drive the early phases of lock-in, some of which have been well documented in the economics literature as increasing returns to scale, in socio-economic terms, such as positive feedbacks related to learning, expectations and co-evolving activities (Arthur 1994). The case of the Logone floodplain canals fishery involves fewer ramifications than that of the fossil fuel industry as described by Unruh (2000), but similar processes, which we describe below, have been at play.

Existing literature and ethnographic interviews helped document how social learning fostered the canals fishery. In the early days of Musgum migration to the floodplain (first half of the 20th century), the Musgum lacked the technical knowledge to fish in the depressions and canals (Landolt 2010). However, in more recent generations, some Musgum fishers relocated for periods of time to go and work on Kotoko fishers' canals in order to learn the technique. Back in their communities, they then served as examples and spread the knowledge. Today, canal fishing is as widespread in Musgum communities as in Kotoko communities. The adoption of canals was also associated with the spreading of stories about the increased wealth and social status of early adopters of the technique: one of the villages in the floodplain where canals were constructed early on is still nicknamed "Dubai" by floodplain inhabitants, a reference to the sudden and localized increase in wealth due to early canals exploitation. Some early adopters of the technique became very wealthy in only a couple of fishing seasons, allowing some of them to afford marriages and/or, for example, a pilgrimage to Mecca. These stories and symbols of marked increases in material wealth and social status have not only contributed to the early spread of the canals, but they remain present in narratives about the technique, even as returns of individual canals are overall decreasing.

Other socio-economic feedbacks contributed to the institutionalization of the technique, as rhythms and institutions co-evolved with the canals. One of these processes has been

the relatively recent (last 10 to 20 years) establishment of a periodic migration of hundreds of Nigerian fish merchants during canal fishing season, connecting the high-demand for smoked catfish in Nigeria with the productive canals fishery of the floodplain. 48% of canal owners interviewed in 2014 stated that some of their production was destined to be consumed in Nigeria: the Nigerian merchants come every year to the floodplain to buy the bulk fish fresh from canal owners, smoke it and take it back to Nigeria, making the work easier for local fishers (who no longer have to dry and process the fish) and guaranteeing their income during the canal fishing season¹. Another feedback has been the development with the canals fishery of an informal taxing system by local authorities initially in charge of enforcing the 2006 “anti-canals” decree. They tax canals fishermen instead in order to benefit financially from the digging of new canals, thereby perpetuating and further institutionalizing the lock-in (Boukar 2011).

Behavioral feedbacks

A canal represents a significant investment, whether the owner has dug the canal himself, inherited it or paid for its construction or acquisition, either upfront or through a loan. Landolt (2010) evaluated that in the village of Lahai, south of the floodplain, 75% of fishermen have to take credits from fish traders to buy fishing gear – a situation that extends to the canals. Of the 113 canal owners interviewed in 2015, 52% had covered their initial investment in the canal (others had not paid for in initially, not yet covered their investment or declined to answer the question) – it took them an average of 4 years to cover the cost. This leads some canal owners to a sunk costs bias or escalation of commitment (Kelly and Milkman 2013), where they continue exploiting even those canals that are not profitable, some of them using funds from other economic activities such as their farming income to invest in canals maintenance.

The inter-annual variability in flooding and fish abundance, not captured in our data, also plays a role in the escalation of commitment by canal owners, expressed in some interviews by the term “tama” that translates as “greed” or “hope” (Badawi and Haleem 2008: 572). This is the case despite the perceived decreasing trend in fish abundance and size, because a handful of canals (not always the same ones) are still very productive every year (Fig. 4). The distribution of fishing income from 2014 data shows that canal owners earn more than fishermen who do not own canals, but even amongst them, the distribution is long-tailed with a deviation for large indices (small incomes): the majority of fishermen make relatively little money from fishing, while a few catch and sell a lot (Fig. 4 – which is a Log-Log plot). This type of distribution facilitates an escalation of commitment (Kelly and Milkman 2013): the hope is to leave the long-tail of the distribution and join the lucky few, object of *tama*. A local informant, non-canal owner, described it as “a kind of gamble”.

Not only have fishers invested wealth into their existing canals, they have spent time, developed skill and invested life in them, which make the canals an important part of their identity that transcends a rational benefits/costs decision-making process (Scheffer and Westley 2007). As an example, one of the older fisherman we interviewed has spent

¹ The Nigerian market for the floodplain’s fish has been impacted by the recent Boko Haram insurgency. See Henry (2016).

nearly every day of the last decade working at his canal that has become a central part of his life: financially, as it is his main source of income; socially, as it has defined his relationships with his neighbors and his life-narrative and reputation in the floodplain. Getting up before dawn to dig and work for several hours provides rhythm to his life and gives it a purpose. His canal is part of his habitus (Bourdieu 1972), an object of embodied commitment that strongly contributes to his resistance to change: he made it clear that he would do anything to preserve his canal and associated livelihood and identity.

Demographic feedbacks

Demographic data shows a feedback between the size of fishers' households and the ownership of canals. Census data from across 10 large villages in our study zone indicates that both the population and the number of canals more than doubled between 1977 and 2005 (Elingui and Tjeega 1978). Two processes are relevant to demographic growth in the floodplain: the growth of households via marriage and offspring (polygyny is practiced in the floodplain), and migration processes. Data from the 2014 and 2015 surveys and ethnographic data point to a positive feedback between canal ownership and household size: canal-owning households include more women (Fig. 5A) and are larger overall, even when correcting for the age of the household head.

Fishing canals lead to sharp periodic increases in wealth just after the short fishing season, which allows canal-owning fishers to afford marriages (Fig. 5B). 64% of the 113 canal owners interviewed in 2015 stated that their canal had allowed them to afford marriages. In turn, a larger family leads to the need for more income to sustain the household, thus intensifying the continued exploitation of the canal as well as other livelihood activities. Often, the family helps to operate the canal, which reduces costs. Fishers whose children help maintaining the canals have lower maintenance costs (by 37% on average). These data suggest that there is a positive feedback between the canals fishery and household size, the latter also being one of the marks of increased social status allowed by the canals.

Hydrological feedbacks

The last feedback we document here in relation to canal lock-in is hydrological. The canals fishery is highly seasonal: fish are caught in the canals only during the flood recession (November-December). During these few weeks, the canals drain large volumes of water from the floodplain and its depressions back towards the watercourses and downstream towards the North. People interviewed during ethnographic fieldwork worried that the increasing number of canals is affecting flooding regimes, and consequently forage quality and fish stocks. Many stated that because of the canals, some depressions were now dry in January, while when they were younger these depressions used to retain water throughout the dry season. Our analyses of satellite imagery show that the timing of flood recession seems indeed to be affected by fishing canals, even on a short timescale. We compared the speed of flood recession in a study zone (Fig. 6) with a large density of canals (connecting to the three waterways: Logone, Logomatya, Lorome-Mazera), to the speed of flood recession in the rest of the floodplain. For a period where mostly bi-weekly satellite imagery were available (2009 - 2014), flood recession was faster and faster in the study zone, where the density of canals grew by 23% in 5 years,

relative to the whole floodplain: it appeared dry almost one month earlier in 2014 compared to 2009 (Fig. 6).

The canals fishery is dependent on the volume of water and the quantity of fish going through the canals, but it is less dependent on the duration of flooding as other fishing techniques that catch fish in the floodplain during the flood, or the depressions. These other fishing techniques (such as traps in the floodplain when it is flooded) may be only viable when there is standing water in the floodplain, while canal fishing occurs only during the flood recession. The reduced flood duration caused by the draining action of canals therefore reduces the opportunity to use a range of other fishing techniques, but does not impact canals fishing as much (Delclaux et al. 2010). It also leads to a longer dry season, when the opportunity cost of digging canals is low, because few other activities are feasible in this season. This hydrodynamic feedback thus contributes to the spread of the canals by decreasing the opportunities to use other fishing techniques that have been traditionally used during the flooded season and, by the same token, making canals a more attractive option (see also Fokas 2007).

4. Discussion

Through an analysis of multiple datasets, we have shown how a series of social-ecological feedbacks have contributed to the process of canal lock-in in the Logone floodplain: an increasing rate of adoption for a fishing technique, despite indications that it is not a sustainable trajectory for the system. The analysis of interplaying feedback loops (Fig. 7) uncovered socio-economic, behavioral, demographic and hydrological interactions with the fishery, taking the analysis beyond classical economic explanations of techno-institutional lock-in. In such a context of mutually reinforcing social and ecological feedbacks, lock-in and social-ecological trap are comparable concepts (Cinner et al. 2011).

The ability of a system to reorganize itself in the face of change is key to social-ecological resilience (Dietz et al. 2003, Folke et al. 2005, Basurto and Ostrom 2007). Understanding ‘canal lock-in’ in systemic terms is therefore also key to finding leverages to maintain or increase the resilience of the Logone floodplain fishery (Meadows 1999, Scheffer et al. 2003). Our approach and conclusions are also relevant to the governance of common-pool resources and to the understanding of social-ecological systems, and may be helpful to understand social-ecological traps in other systems.

Our analysis makes three contributions. (1) We expand and connect the theory on social-ecological traps (Cinner 2011), lock-in (Unruh 2000) and social response lag (Scheffer et al. 2003) in social-ecological systems, through an empirical case study. (2) We discuss governance solutions to the problem of social-ecological lock-in. (3) We provide a methodological example of interdisciplinary study of social-ecological dynamics. This discussion will develop the theoretical and methodological implications of our findings, and evaluate the potential to leverage social-ecological feedbacks for system resilience in the Logone floodplain.

4.1. Theoretical and methodological implications

Lock-in is understood in economics terms as the spread of a technology because of increasing returns to scale (Arthur 1989 & 1994; Unruh 2000). In a social-ecological system such as the Logone Floodplain, we have shown that the process may continue despite a negative density dependence of returns because of coupled social, institutional, individual and ecological interactions with technology diffusion. Therefore in social-ecological systems, the interplay of social and ecological processes must be considered to understand techno-institutional lock-in. This has important methodological implications. It requires integrating insights from a variety of disciplines (Liu et al. 2007). We found that ethnography was particularly useful to identify key processes and to support communication across various disciplinary perspectives on the floodplain system dynamics, and the points of view of people who live in the floodplain. Ethnography itself is rarely named in social-ecological systems research (exceptions include Lansing 2012 and Moritz et al. 2013) even though methods associated with ethnography are often acknowledged as a key part of developing understanding of complex social-ecological systems (e.g. Liu et al. 2007).

A theoretical implication of our study is the connection of the economics literature on lock-in processes (e.g. Arthur 1989 & 1994; Perkins 2003; Unruh 2000) and that on social-ecological traps (e.g. Cinner 2011, Boonstra and de Boer 2014). Techno-institutional lock-in, when the technology has negative impacts on the resilience of a social-ecological system, is a situation of social-ecological trap. An important emphasis of lock-in as a theoretical concept is its path-dependency, which we have described in the Logone floodplain and recent conceptual research has also emphasized for social-ecological traps (Boonstra and de Boer 2014).

4.2. Governance implications

Our analysis has practical applications for the governance of the fishery in the Logone floodplain. The spread of new fishing technology and a delayed social response to environmental change has been shown elsewhere to lead to a regime shift and reduction in fishery productivity (Brown et al. 2012). Generally, positive feedbacks left unchecked (i.e. without the stabilizing force of a negative feedback loop) will run their nonlinear, self-multiplying course to result in a different and sometimes less desired system state (Meadows 1999, Scheffer 2009). The mutual reinforcement of social and ecological feedbacks, for example through sunk costs effects, which can push a social-ecological system towards an undesirable state or social-ecological trap (Cinner 2011), has been related to the collapse of ancient societies (Janssen and Scheffer 2004). In the floodplain, unchecked positive feedbacks could result in overfishing, and they could also result in widespread social conflict.

The question is, what governance strategy may be most effective in managing the common-pool resources in a social-ecological system such as the floodplain, which is experiencing lock-in? A characteristic of lock-in and social-ecological traps situations is

that they are often highly resilient to change (Maru et al. 2012). The top-down approach of the 2006 gubernatorial decree has proven unsuccessful in curbing the exponential spread of canals, as it did not account for the feedbacks fostering the spread. Another way may be to alter the feedback loops - a strategy that can be a powerful leverage to change a system's overall dynamics (Meadows 1999), such as a fishery (Cinner 2011).

Some of the feedbacks we described rest on deeply entrenched variables, and would be difficult to alter in the floodplain social-ecological system. The behavioral feedback rests largely on a sunk costs bias, which is difficult to overcome and some have argued has an evolutionary basis (Scheffer and Westley 2007). The demographic feedback depends on the availability of income peaks after the fishing season and on the long-standing cultural connection between household size and social status. The socio-economic feedbacks (social learning, adaptive expectations, network effects) are related to the nature of social networks in the floodplain, and would likely develop around another profitable technique regardless of impacts on the social-ecological system. In fact, ethnographic research suggests that this is occurring with what has been called 'grass fishing' in the floodplain rivers, featuring the creation of habitat and sheltering for fish by putting floating grasses in the water, then harvesting the fish with large nets around these shelters. This additional individual-based fishing technique appeared in 1993 and is spreading fast (Delclaux et al. 2010), although not at the expense of canals. It follows that, similar to the carbon-based industry, insuring the sustainability of the floodplain fishery is not simply a matter of 'escaping' canal lock-in, but requires renegotiating the bases on which natural resources are exploited (Unruh 2002). The literature on common-pool resources governance is helpful here. Case studies are very diverse (Agrawal 2002), but good communication and shared norms between users - whether formal or in the form of a tacit 'ethical know-how' (Varela 1999) - have been shown to be key contributors to resilience across case studies (Ostrom 2007, McCay et al. 2011, Levin 2014) and even for large scale, open-access systems (Moritz et al. 2013).

We argue that the hydrological feedback could be altered to foster such a shift by promoting a more communal governance of the canals fishery. This feedback lends itself to an intervention because it is directly dependent on attributes of the canals themselves (how much water they drain off the floodplain, and when). A modification of the canal hydraulics by postponing canal outflow, for example using the same kinds of small dams used by those fishers who block inflow into their canals at the beginning of the floods in order to limit canal sedimentation, could limit the accelerating flood recession (Fig. 7). This would increase the possible time of usage for other fishing techniques, thereby limiting the associated incentive to focus on canals. This approach would require fishers whose canals are connected to a common depression (typically a handful - e.g. Fig. 2C) to negotiate a common date to open the canals and start fishing. Decision on a common fishing date is not a new practice in the floodplain fishery - although it would be for the canals - as it is the way villages communally fish reserves in the river and seasonal rivers. Shifting to semi-managed canals would therefore require the development of shared rules, possibly fostering self-organization of canal fishers, depression after depression, similar to the "islands of orders" described in Bali's subak irrigation systems (Lansing 2012). Ostrom's notion of polycentric governance, which she proposes as an

effective approach to solve collective action problems, involves the nested operation of such self-organizing governance units within broader systems (2008).

Such modification could also lead to a diversification of livelihood strategies. A similar technique has been documented in Benin (Floquet et al. 2014): fishers use the retention of floodwaters in their canals to irrigate garden crops on the canal banks, and allow the fish to grow before harvesting them. A diversification of livelihood strategies (farming and fishing) has been shown to lead to more resilience in the floodplain (Bene 2003b) and fishers increasingly recognize income diversification as the solution towards food security - even Kotoko for whom farming is not a traditional livelihood activity: 71% of the 221 fishermen who responded to the question in 2015 stated that it is a better livelihood strategy to diversify activities in the floodplain, rather than to specialize.

5. Conclusion

The objective of this paper was to analyze an unfolding transition in a floodplain fishery, driven by the exponential spread of a resource-exploitation technique (fishing canals). An exponential increase is by definition unsustainable. Besides a fast rate of change, the canals fishery is also characterized by resource-related conflicts, difficult monitoring of resources dynamics, and a lack of coordination between fishers to establish harvesting and protection rules – signs of an unsustainable trajectory (Dietz et al. 2003, Anderies et al. 2004, Ostrom 1990).

The fishing community in the floodplain continues to invest in canals, despite an awareness of the damaging consequences of the technique's spread on the social-ecological system. We show that this social inertia is a consequence of canal lock-in, which is a case of a social-ecological trap (Cinner 2011) driven by a continued investment in the canals on an individual level associated with a series of positive feedback loops. Lock-in is typically described in economic terms as the path-dependent spread of a technology associated with increasing returns to scale (Arthur 1989). In the floodplain, we showed that canal lock-in has occurred through the co-evolution of a technological system (the canals) and its social, institutional and hydro-ecological context, and that it continues despite the initial phase of increasing returns being over.

Because social and ecological dynamics are tightly coupled within the floodplain, a social-ecological systems perspective proved helpful to take the analysis beyond a focus on socio-economical and institutional dynamics (Ostrom 2007, 2009). This perspective allowed us to identify indicators of the system's reduced resilience (Scheffer et al. 2012, Dakos et al. 2015, Meadows 1999, Liu et al. 2007): a trend towards homogenization of fishing techniques associated with the exponential spread of canals. We showed this exponential spread to be related to feedbacks between the fishery and individual behavior (e.g. sunk costs, but also *habitus*), socio-economic processes (e.g. network effects), demography, and hydro-ecology in the floodplain.

Top-down regulation of the fishery has recently failed to curb the spread of canals. We use a complex systems approach (Meadows 1999) to think about which feedbacks could

be altered towards a more sustainable canals fishery. We argue that one social-ecological feedback, between the canals fishery and hydrological processes, could be leveraged towards the establishment of shared norms and an incentive to self-organize across floodplain canal-owners at the scale of the depression. This alteration of the canals could help turn the system in a semi-managed fishery and irrigation system, similar to what has recently been documented in a river basin in Benin (Floquet et al. 2014). It has the potential to increase and diversify the output of canals (crops from canal banks and older, bigger fish), and would also require the establishment of common rules to coordinate the fishing, not as imposed by an institution but as developed by fishers whose canals are connected to a common depression (Ostrom 2008). This possibility requires a shift from thinking of the canals as a problem to be stopped, to thinking about them as an existing feature of the social-ecological landscape that can be modified to increase fishery productivity and resilience, through diversification of livelihood activities. As concluded by Meadows (1999): changing the way to look at a system is often an even more powerful leverage than altering feedback loops within it.

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Figures

Figure 1 (full width): A typical spatiotemporal pattern of flooding and flood recession in the Logone Floodplain. From processed Landsat satellite imagery captured between September 2014 to January 2015. South of the floodplain is the Maga Dam, built in 1979.

Figure 2 (full width): Fishing canals are changing the landscape of the Logone Floodplain. A: Flooded areas from three over-imposed Landsat images (from Fig. 1) and field-surveyed fishing canals (pink markers). B: Zoom of the black frame in A - pink lines are fishing canals. C: zoom of the black frame in B – black arrows represent flow paths of water during flood recession. D: Photograph of fishing trap located at the pin on frame C, at the end of a canal (photo: O. Atti). E: Growth of fishing canal numbers in the Logone Floodplain; linear fit until 1979 ($R^2 = 0.974$ for 1915-1979), then exponential fit ($R^2 = 0.993$ for 1980-2014). F: a Chadian worker deepening a canal in the dry season (Photo: S. Laborde).

Figure 3 (full width): A: Evolution of a performance/cost relation for a given technology with increasing scale of adoption (reproduced from Unruh 2000). B: By contrast, exponential increase in canals numbers and gradual decrease in profitability of new canals through time. Magenta markers are the cumulative number of canals in our study zone, for each year (1955-2014), based on canal-age data surveyed in 2014. Magenta circle is a data point based on a survey of 334 new canals in the study zone in 2016 (adding this data point to the prior series assume none of the canals surveyed in 2014 was abandoned in 2015 or 2016). Black markers are a 25-year moving average of the 2014 benefits/cost ratio of new canals until 1985 (few data), then 5-year moving-average from 1985 to 2014.

Figure 4 (single column): A: Log-Log rank size of total fishing income from 2014 survey (2013-2014 season), for canal owners (magenta) and non-canal owners (blue). Horizontal lines are respective total income medians, and black and grey lines are medians of initial canal investment and annual maintenance costs, for reference. Note the two following points: first, only financial investments were reported, while the canals also represent investments in time and work for many fishers and their families; second, 2014 was considered a relatively good year for canal fishing.

Figure 5 (full width): Positive feedback between canals fishery and demographic growth. A: demographic pyramid for canal-owning (lighter colors) and non-canal owning (darker colors) households (2014 survey, N=3596). B: Proportion of non-canal and canal fishermen who married a 1st, 2nd, 3rd, 4th wife, before or after canal construction (when relevant).

Figure 6 (full width): Influence of number of canals on speed of flood recession. Left: areas used to calculate the ratio of flooded areas (study zone with more canals density than the rest of the floodplain (=A)/whole floodplain (=F)) in figure on the right. Right: ratio (A/F in %) of inundated pixels through the flooded season, for the years 2009, 2011, 2013 and 2014 during which the number of canals in zone A increased by 23% (from 798 to 982 canals).

Figure 7 (1.5 column): Summary diagram of positive feedbacks leading to ‘canal-lock-in’ in the Logone floodplain fishery