CNH: Exploring social, ecological, and hydrological regime shifts in the Logone Floodplain, Cameroon

Summary. The devastating impact of large-scale dams on coupled social, ecological, and hydrological systems in African watersheds has been well documented, but what is less clear is how smaller, slower changes endogenous to these coupled systems may result in regime shifts that have equally disastrous consequences. In the Logone Floodplain in Cameroon, fishermen have been modifying the floodplain's hydrology by constructing thousands of individually owned fish canals. If the floodplain is characterized by critical transitions, the gradual increase in fish canals may result in a sudden and catastrophic transition that equals the impact of large-scale dams. The goal of this project is to build an integrated model that simulates the dynamic couplings between the social, ecological and hydrological systems of the Logone Floodplain in Cameroon. The model will allow us to simulate the impact of different human activities and climate change scenarios, in particular whether the impact of smaller but numerous fish canals resembles that of large-scale dams, and assess what the impacts are for its social, ecological, and hydrological systems. The project brings together a team of researchers from a broad range of disciplines and will use a transdisciplinary approach to investigate coupled human and natural systems using a combination of field research, remote sensing analysis, and modeling.

Intellectual Merit. African floodplains are an excellent example of coupled human-natural systems (CHANS) because there are strong couplings between the social, ecological, and hydrological systems. The intra- and inter-annual variations in the area, depth, and duration of seasonal flooding have direct and indirect impacts on ecosystems and human lives and livelihoods. However, African floodplains have not been modeled as coupled systems. Instead studies have focused either on the hydrological, ecological, or social system and have taken the couplings as a constant rather than as a dynamic system. This project will examine the dynamic couplings that are endogenous to social, ecological and hydrological systems in the Logone Floodplain in an integrated model. In particular, it will focus on the impact of human activities and climate change on the hydrology of the floodplain and transform our understandings of the nature of regime shifts in African floodplains.

Broader Impact. The goal of the project is to contribute to the sustainable management of African floodplains, which are of enormous ecological and economic importance. We will use our integrated model to assist stakeholders, in particular fishermen, in sustainable management of the Logone Floodplain by evaluating the impact of different human activities and climate change scenarios. The goal of the education program is to train graduate and undergraduate students at the Ohio State University and Maroua University, Cameroon in quantitative and qualitative, transdisciplinary approaches to the study and management of coupled human and natural systems.

RESEARCH PROBLEM

The devastating impact of large-scale dams on coupled social, ecological, and hydrological systems in African floodplains has been well documented (Denny 1993; Drijver and Marchand 1986; Hollis et al. 1993), but what is less clear is how smaller, slower changes endogenous to these coupled systems may result in regime shifts that have equally disastrous consequences. Floodplains are extremely important for the lives and livelihoods of millions of Africans, who over centuries have created productive landscapes by modifying the hydrological system through the construction of canals, dams, fields, and mounds. However, there is evidence that these strategies of landscape modification are no longer adaptive because they are now slowly changing the hydrology of floodplains to the extent that it may result in regime shifts. In the Logone Floodplain in Cameroon, fishermen have been modifying the hydrology of the floodplain by constructing thousands of individually owned fish canals. If the floodplain is characterized by critical transitions, the steady increase in fish canals may result in a sudden and catastrophic transition that resembles the impact of large-scale dams. Populations in the floodplain have noted changes in the ecosystem and expressed concern about the role of fish canals. Climate change, which in Africa is associated with greater intra- and inter-annual variation in rainfall patterns, will likely only accelerate the move towards a regime shift to a system with lower productivity. **Because African floodplains are of enormous ecological and economic importance for fishermen and pastoralists it is critical that we understand the role of fish canals and the dynamic couplings between the social, ecological and hydrological systems and examine the impact of climate change scenarios.**

African floodplains are an excellent example of coupled human-natural systems (CHANS) because there are strong couplings between the social, ecological and hydrological systems. The intra- and inter-annual variations in the area, depth, and duration of seasonal flooding have direct and indirect impacts on ecosystems and human lives and livelihoods. However, African floodplains have not been systematically studied as coupled systems. Instead studies have focused either on the hydrological, ecological, or social system and have taken the couplings as a constant rather than as dynamic couplings.

This project will examine the dynamic couplings that are endogenous to social, ecological and hydrological systems in the Logone Floodplain. In particular, we will focus on the impact of fish canals on the hydrology of the floodplain and the consequences of regime shifts for fishery and pastoral production systems. There is growing concern among fishermen that fish stocks are decreasing (Delclaux et al. 2010; Molenaar and van Santen 2006; Ziebe et al. 2010) and pastoralists in our studies have observed a reduction in vegetation regrowth after bush fires. Despite the growing concern among resource users, stakeholders have not been able to halt the growing number of canals, including a 2006 gubernatorial decree that prohibited new canals and limited maintenance of existing ones. This raises questions about the nature of feedback in the coupled system and why it does not seem to work in the Logone Floodplain.

The overall goal of this project is to examine whether the impact of fish canals resembles that of large-scale dams and what the nature of the social, ecological, and hydrological regime shifts are. We will build an integrated model that simulates the dynamic couplings between the social, ecological and hydrological systems of the Logone Floodplain in Cameroon that will allow us to examine the role of fish canals on the dynamics of the coupled systems and compare the impacts of canals versus large-scale dams. The project brings together a team of researchers from a broad range of disciplines and will use a transdisciplinary approach to investigate coupled human and natural systems using a combination of field research, remote sensing analysis, and modeling.

OBJECTIVES

The overall goal of this project is to examine whether the impact of fish canals resembles that of large-scale dams and whether it results in shifts to different social, ecological, and hydrological regimes in the Logone Floodplain. We will use a combination of field research, remote sensing analysis, and modeling to answer these questions. To achieve this goal we have the following objectives:

1) Collect field data for the different systems that can serve as indicators of a regime shift, e.g., flooding area, depth and duration, changes in quality and quantity of the vegetation, density of pastoral populations, fish communities, livelihoods, and economic differentiation.
2) Build an integrated model that simulates the dynamic couplings between the social, ecological and hydrological systems in order to examine the impact of fish canals. We will parameterize the model using existing data sets, field data, and remote sensing data.
3) Compare data from the field with output from our model simulations as well as with data from the period after the Maga Dam (1979-1993) to determine whether the impact of fish canals resembles that of large dams or whether it results in shifts to different regimes.
4) Run what-if simulations to examine the impact of different human activities, climate change scenarios, and policy interventions on the coupled systems of the Logone Floodplain and discuss the outcomes of these simulations with the different stakeholders.

RESPONSE TO REVIEWERS

This is a resubmission that has received helpful, encouraging reviews in 2010. The main concern of the reviewers and the panel pertained to the integration of the different models. We have addressed this by making explicit what the dynamic linkages are between the different systems and have summarized these in Figure 4. We have rewritten the postdoctoral mentoring plan, emphasizing professional training in research and writing about CHANS. We have rewritten the data management plan, emphasizing sharing of data and findings through our project website. In addition, we have made a number of other changes that strengthened the proposal: 1) we have limited our proposal to one case study: the Logone Floodplain; 2) we have made clearer how we will compare the impacts of larger dams with those of fish canals; and 3) we have added two new collaborators, Roland Ziebe and Paul Scholte, who have extensive experience in research and development of the fishery and ecological systems in the Logone Floodplain.

RESULTS FROM PRIOR NSF SUPPORT

The project brings together a team of experienced researchers who use a transdisciplinary approach to investigating and modeling coupled human and natural systems using a combination of field research, remote sensing analysis, and modeling. The researchers are from departments across the Ohio State University (Anthropology, Earth Sciences, Evolution, Ecology and Organismal Biology, Geography, and Mathematics) and have demonstrated a strong commitment to transdisciplinary research and training of graduate and undergraduate students by collaborating in innovative projects, including ones that have received prior funding from the National Science Foundation.

CAREER Pastoral Management of Open Access: The Emergence of a Complex Adaptive System, (BCS-0748594, 2008-2013), **Mark Moritz** (PI). This project examines how mobile pastoralists in the Logone Floodplain coordinate their movements to avoid conflict and overgrazing in a land tenure system that is commonly described as open access, a situation generally regarded as leading to a tragedy of the commons. This interdisciplinary study integrates spatial and ethnographic analyses as well as multi-agent simulations and

analytical modeling and has resulted in a number of papers (Moritz et al. 2010, 2010b, 2011; Jung et al. 2010) and strong collaborations with the University of Maroua, Cameroon.

Livestock Movements and Disease Epidemiology in the Chad Basin: Modeling Risks for Animals and Humans, (DEB-1015908, 2010-2015), Rebecca Garabed (PI), Song Liang (co-PI), **Mark Moritz** (co-PI), and **Ningchuan Xiao** (co-PI). The goal of this project is to understand the epidemiology of infectious diseases in the ecological context of networks of host movements. Specifically, the goal is to understand transmission and maintenance of Foot and Mouth Disease Viruses (FMDV) in networks of livestock movements in the Far North Region of Cameroon. Graduate and undergraduate students from OSU and the Universities of Maroua and Ngaoundére in Cameroon are being trained in the interdisciplinary study and modeling of the ecology of infectious diseases.

Glacier Recession and Livelihood Vulnerability in the Peruvian Andes (BCS-0752175, 2008 – 2010). **Bryan Mark** (PI), Collaborative Proposal with Jeff Bury (UCSC). This transdisciplinary project examined the complex nature of environmental change taking place across the Cordillera Blanca, Peru, and evaluated how these changes are linked to human decision-making and behavior. The grant supported primary dissertation research for three Ph.D. students and one M.A. student. Nine undergraduate students have participated in research and outreach, including fieldwork on a REU supplement (2009). The project has produced multiple publications (e.g., Baraer et al. 2009; Bury et al. 2008; Bury et al. 2010; French et al. 2009; Mark et al. 2010; Orlove et al. 2009).

Collaborative Research: Hydrologic Transformation and Human Resilience to Climate Change in the Peruvian Andes (BCS-1010550, 2010-2013). Co-PIs **Bryan Mark**, Jeffrey Bury (UCSC), Kenneth Young (UT Austin) and Mark Carey (University of Oregon). This grant funds an innovative and multidisciplinary project to evaluate water use, human vulnerability, land use and land cover change, watershed dynamics, water quality, and water governance in the Santa River watershed of the Cordillera Blanca, Peru, in order to understand this new system of hydraulic governance that is emerging in the Andes and how glacial dynamics are transforming melt water rates as they rapidly recede.

UBM – Institutional - BioMathletic Training: Creating the Next Generation of BioMath Stars at Ohio State University. (DBI-0827256, 2008–2013). **Ian Hamilton** (PI), with CO-PIs Laura Kubatko, Yuan Lou, Elizabeth Marschall, Tony Nance, and David Terman. This grant funds an interdisciplinary undergraduate research program in mathematical and statistical biology at Ohio State University through a collaborative effort between the Departments of Mathematics, Statistics, and Evolution, Ecology and Organismal Biology. Three key components of the program include: (1) the exposure of a broad group of students to research problems in the mathematical biosciences; (2) curricular development to prepare students for advanced study in interdisciplinary fields; and (3) participation of undergraduates in an intensive and integrated research experience.

Collaborative Research: Reducing Uncertainty of Climatic Trends in the Sierra Nevada: An Ensemble-Based Reanalysis via the Merger of Disparate Measurements (EAR 0943551, 2010-2012). **M. Durand** (PI), S. Margulis (UCLA). The goal of this grant is to merge a variety of different kinds of observations into a unified hydrologic model of snow processes in southern Sierra Nevada watersheds. Observations include in situ measurements of streamflow, in situ measurements of snow water equivalent, large-scale meteorologic estimates obtained via reanalysis products, satellite measurements of snow-covered area, and satellite measurements of microwave brightness. The reanalysis will then be analyzed to determine spatially-continuous multi-decadal trends in snow properties, which will be used to better understand the sensitivity of snow properties to climatic change as a function of physiographic regime.

CONCEPTUAL FRAMEWORK

Coupled human and natural systems (CHANS) are systems in which human and natural components interact. "Although human-nature interactions have long been recognized, the complex patterns and processes involved in such interactions have not been well characterized, let alone fully understood" (Liu et al. 2007:639). There are several reasons why we have limited understanding of these human-nature interactions, e.g., direct and indirect feedbacks across multiple spatiotemporal scales and the complexity of social and ecological systems and their interactions, as well as the organization of scientific inquiry along disciplinary lines. The study of CHANS requires an integrative, transdisciplinary approach that examines the complexities of social and ecological systems and in particular their interactions. One of the greatest challenges in the science of CHANS is cross-scale interactions between human and natural components, for example, how large-scale natural phenomena emerge from local interactions among human agents, which in turn influence human systems (Liu et al. 2007:639). Understanding the dynamics of coupled systems is important because human-natural interactions are undergoing rapid and unprecedented change, which is resulting in the collapse of natural and human systems across the globe (Gunderson and Holling 2002).

One of the big questions is what the nature of regime shifts is in coupled human and natural systems (Scheffer et al. 2009), more specifically, whether the changes are linear and smooth or non-linear and catastrophic? If the changes are linear people may have more difficulty noting the changes, but when they become aware and take action, it is relatively easy to change the system back to its original state. However, if the transition is critical as in a fold catastrophe model then change will happen suddenly, without much warning, and it will be difficult to reverse the changes and return the system to its original state. There are a number of well-documented cases of regime shifts of corral reefs, turbid lakes, and rangelands in which systems move from one dynamic state to another (Coppock 1994: Scheffer 2009; Scheffer et al. 2001). Often feedback loops between systems lead to a runaway process to another state and once a threshold is past, it becomes difficult for a system to return to its previous state. Critical transitions have been described mathematically and used to describe and explain regime shifts in complex social-ecological systems (Scheffer 2009). However, because of the complexity it is often unclear what are the dynamics of the runaway process and what the thresholds are in complex social-ecological systems. Scheffer et al. (2009) have argued that when dynamic systems reach a critical point (or tipping point) there are generic signs that indicate that an impending catastrophe in the fold bifurcation model is imminent. However, although theoretical arguments intuitively make sense and the effects have been modeled, formally and in computer simulations, there have been few empirical studies of this phenomenon (Scheffer and Carpenter 2003). We know from natural experiments in the Logone Floodplain that the coupled system has at least two regimes (see below). However, these regime shifts were the result of major infrastructural interventions, i.e., dams, not changes that are endogenous to the dynamics of the coupled systems in the Logone Floodplain, so it remains unclear what its resilience is, i.e., the ability of a system to recover upon disturbance, what the thresholds are at which slower changes in different systems result in a regime shift, and what the nature of the transitions is (smooth or critical).

The study of complex and dynamic coupled human and natural systems like African watersheds requires not only a transdisciplinary approach but also a shared overarching conceptual framework. Ostrom's nested framework allows us to integrate the different disciplinary approaches and come to a better understanding of the dynamics of the coupled social, ecological, and hydrological systems of African watersheds. Ostrom (2007, 2009) has developed an analytical framework to study the management of natural resources in Social-Ecological Systems (SES). Ostrom provides a structure for analyzing the system and its

interactions by dividing SES in a nested framework of different classes and sub-classes of variables that can be studied both within classes and in interaction with other classes of variables. The core classes or core systems of the model are: 1) the resource system (RS) (e.g., fishery, lake, grazing area); 2) the resource units (RU) generated by that system (e.g., fish, water, fodder); 3) the users (U) of 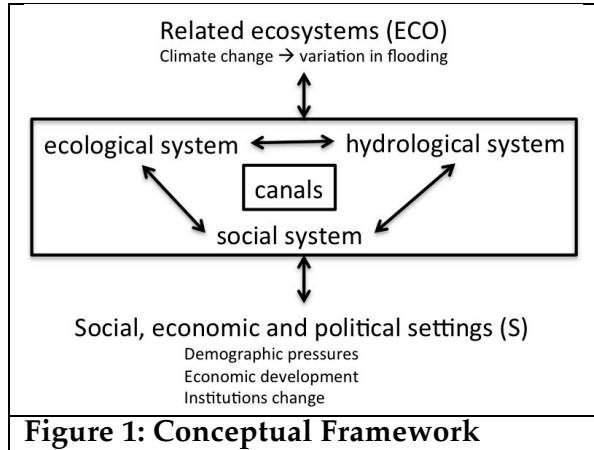that system; and 4) the governance system (GS) regulating use of the resource. The interactions (I) between these core systems lead to outcomes (O) that in turn affect the different core systems. Because the framework examines explicitly the linkages between social and ecological systems, it is well suited for the study of coupled systems. The SES framework allows researchers to examine three broad questions: 1) what patterns of interactions are associated with particular outcomes; 2) what are likely endogenous developments of social and ecological systems with and without outside intervention; and 3) what is the sustainability of certain configurations of resource systems, resource units, users, and governance to internal and external disturbances? Ostrom's SES framework allows researchers to compare cases of Resource Systems (RS), for example, Central African forests and lakes in northern Wisconsin. Ostrom's diagnostic framework will help us to understand the dynamic couplings endogenous to African floodplains and their role in regime shifts (see Figure 1).

Figure 1: Conceptual Framework

STUDY AREA: THE LOGONE FLOODPLAIN

There have been a number of natural experiments in the Logone Floodplain that make it the ideal site to examine the nature of regimes shifts in African floodplains. The Logone Floodplain is one of largest wetlands in West Africa (11,000 km^2) and of great importance for biodiversity. It contains Waza-Logone National Park, a Man and Biosphere Reserve, and is critical for the livelihoods of more than 100,000 farmers, herders, and fishermen (Delclaux et al. 2010; Haller 2010; Loth 2004; Scholte 2005).

The Logone Floodplain is flooded annually by water from the Logone River and its branches in September and October (Bénech et al. 1982; Jung et al. 2011; Mott MacDonald 1993, 1999). Because the area is relatively flat the flood spreads over a large area before it drains back to the Logone River and the El Beid River in the north. The extent of the flooding depends primarily on the magnitude of the peak flow and the duration of the floodwater exceeding the capacity of the Logone River (Delclaux et al. 2010; Westra and de Wulf 2007). Evaporative fluxes on the floodplain are remarkable. On the basis of pan and evaporimeter data, Delclaux et al. (2010) estimates an annual evaporation rate between 2,700 mm to 3,000 mm, while direct precipitation over the floodplain is less than 1,000 mm; this underscores the dependence of the floodplain on seasonal upstream forcing. After the Logone floods its banks in September and October, the southern shift of the Intertropical Convergence Zone (ITCZ) forces subjects the Logone Floodplain to hot, dry air. Strong evaporative potential coupled with the open water surface leads to the dramatic evaporation fluxes. The floodplain is an energy-limited evaporative regime; a future, warmer climate thus has important implications for the duration of inundation each year.

Natural Experiments. Two natural experiments have demonstrated that there are (at least) two regimes in the Logone Floodplain: one with high and one with low productivity. In 1979 the Cameroonian government constructed dams along the Logone River and

between Guirvidig and Pouss to create a 400-km^2 reservoir (Lake Maga) for the irrigated rice cultivation project SEMRY II (Loth 2004). The dams changed the hydrology of the floodplain and led to a significant reduction in flooding, which resulted in regime shifts with disastrous consequences for the ecological and social systems in the floodplain. Perennial grasses were replaced by annual grasses of lower pastoral quality, which led to a reduction of fodder for livestock and wildlife, and there was a significant reduction in fish populations (Loth 2004). In order to reverse the ecological degradation and promote sustainable socio-economic development of the floodplain, the Waza-Logone Project started a pilot reflooding effort in 1994 (Lienou et al. 2003; Sighomnou et al. 2002). The limited reflooding was an enormous success: the ecological system rebounded and the pastoral, agricultural, and fishery systems experienced strong economic development (Loth 2004).

A third natural experiment, the exponential growth in the number of fish canals in the floodplain (Figure 2)(Delclaux et al. 2010; Mahamat and Diaouré 2008), is currently underway and potentially undoing the reflooding efforts of the Waza-Logone Project. Fish canals connect depressions with the rivers that run through the plain. When the level of water decreases, it flows from the depressions to the river where fishermen catch the fish in nets (Figure 3). Digging fish canals is labor and capital intensive - many are longer than 1,000 meters. Because of the thousands of canals, the floodplain drains much earlier and dries much faster and this has considerable consequences for ecological and social systems. Fishery revenues are declining, while the pastures can support fewer pastoralists in the dry season because the soil moisture no longer sustains regrowth of pastures after fire.

Social processes. Three interrelated processes of social change are currently driving the increase in the number of fish canals: 1) demographic changes, 2) economic development, and 3) institutional changes. First,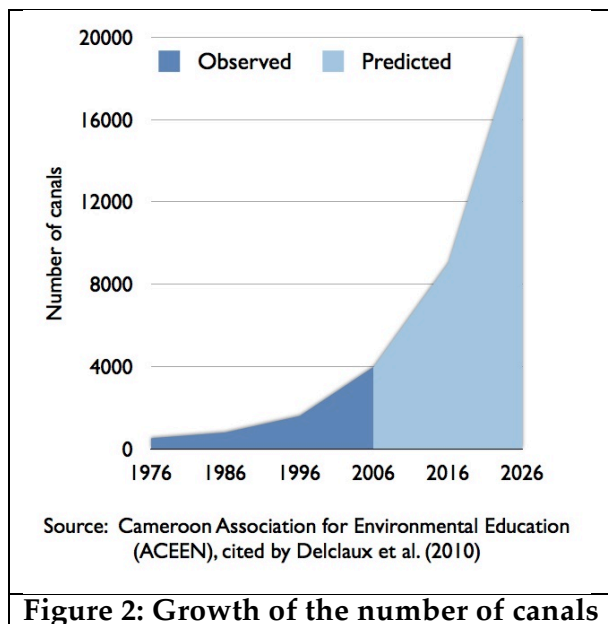 there has seen a steady and continuous influx of migrants in the last fifty years. This not only resulted in greater competition for resources but it also has resulted in political challenges to the traditional management systems. The Kotoko, original inhabitants of the floodplain, have traditionally regulated communal fishing in rivers and depressions as well as the number of fish canals (Delclaux 2010; van Est 1999). However, Musgum fishermen who have moved into the floodplain since the 1940s have challenged the Kotoko hegemony and this has resulted in the breakdown of fishery regulations (Delclaux et al. 2010; Haller 2010; Seignobos & Jamin 2003). While Kotoko authorities have maintained some control over communal fishing, they have been unsuccessful in regulating the private ownership of fish canals by wealthy Musgum and Kotoko fishermen. Second, fishermen have increasingly been incorporated in the larger market economy, which has resulted in a tighter integration of production and marketing systems linking fishermen in the floodplain to consumers throughout the Chad Basin. The result of this economic development has been an increase of capital investments in canals by wealthy individuals (Delclaux et al. 2010; Ziebe et al 2010). Third, the management of common-pool resources is best described as a situation of legal pluralism in with multiple institutions, including international treaties, national laws, municipal regulations, and traditional systems govern use of natural resources (Benda-

Source: Cameroon Association for Environmental Education (ACEEN), cited by Delclaux et al. (2010)

Figure 2: Growth of the number of canals

Beckman et al. 1999; Béné et al. 2003; Haller 2010). The current situation of legal pluralism is an outcome of long-term political processes of colonialization, decentralization, and democratization (Bayart 1993). In this situation of legal pluralism, parties with greater bargaining power are often successful in changing the institutions to their advantage (Ensminger 1992; Haller 2010; Knight 1992; Lesorogol 2008; North 1990; Peters 2004).

Feedback (or the lack thereof). In the last decade there has been a growing awareness among local populations and authorities that the growth in the number of canals has negative impacts on the fishery and pastoral systems in the floodplain. However, despite the increasing awareness, authorities have been unable to stop the growth. In 1995 governmental authorities have tried to impose a rule that would require fishermen to fill in canals that were less than 20 years old (Delclaux et al. 2010) and in 2006 the governor issued a decree that forbade the creation of new canals and the maintenance of older canals. Nevertheless we have observed that fishermen continue to create new canals.
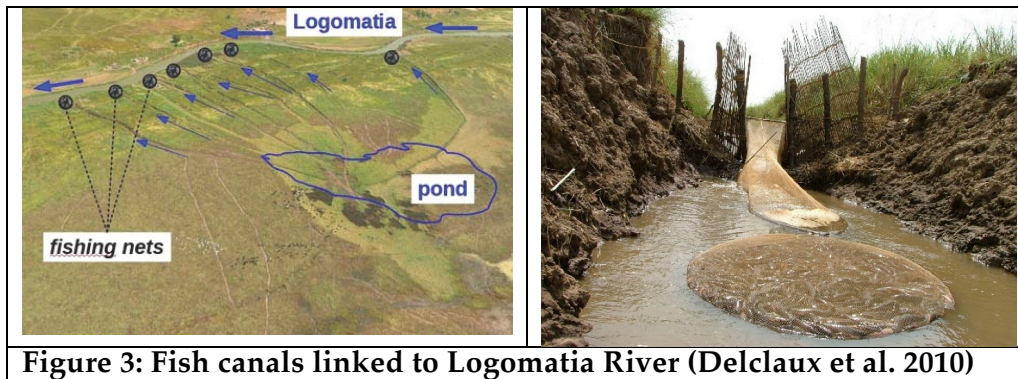

Figure 3: Fish canals linked to Logomatia River (Delclaux et al. 2010)

The question is why local populations and authorities have been unable to stop the growth of the number of fish canals? We hypothesize that there are two main reasons. First, the canals are owned by wealthy households and are still profitable for them, despite smaller catches. In the short term, there is no economic incentive for fishermen with canals (or the means to dig canals), to stop this profitable way of fishing, even though it may not be sustainable in the long-term. Second, there are thousands of canals throughout the floodplain and the authorities do not have the means to enforce the regulations. All this makes it difficult to reverse the changes in the coupled systems of the Logone Floodplain. Whereas in 1994 it was relatively easy for the Waza Logone Project (IUCN) to start the reflooding of the floodplain because they dealt primarily with a few government stakeholder and they only needed to make one opening in the dike along the Logone River (instead of filling thousands of canals distributed throughout the floodplain).

Kotoko and Musgum fishermen have not been able to avoid a tragedy of the commons. While fish canals bring economic benefit to individual owners, the exponential growth in canals has disastrous consequences for all production systems in the floodplain. The competition over diminishing fishery resources is one of the drivers behind wide-scale violent clashes between Kotoko and Musgum populations in 2007 resulting in multiple deaths that ended only after intervention of the Cameroonian security forces. However, it is possible that the increasing economic differentiation and growing resentment between those with and without canals, lower economic returns from fish canals, and community organizing by non-governmental organizations (NGO) may result in endogenous solutions that may be more effective than previous attempts from the region's central government.

REGIME SHIFT SCENARIOS

While the impact of the Maga dam on social, ecological, and hydrological systems has been clear and immediate, the gradual and cumulative impact of the fish canals has been less obvious. Although there is wide consensus among local populations that fish canals have

brought significant changes in the floodplain, we do not have a good understanding of the nature and magnitude of these changes, whether these changes may be indicative of a critical transition, and what the effects are for other couplings between the social, ecological, and hydrological systems. Here we outline two scenarios of regime shifts in the Logone Floodplain. The first scenario describes the changes that have been observed after the construction of the Maga Dam in 1979, while the second scenario describes the changes that we expect to result from the increase in the number of fish canals. The two scenarios result in qualitatively different regime shifts.

Scenario 1: Large-Scale Dams
- Large-scale dams result in an overall reduction of the area flooded and a reduction in the depth of the flooding.
- A reduction in the area flooded and the depth of the flooding results in a shift from palatable perennial grasses to unpalatable annual grasses in areas with less flooding and lower depth of flooding. A shift from perennial to annual grasses means that fewer mobile pastoralists will come to the floodplain in the cold and hot dry season because of the limited quality of the grazing resources.
- Reduced flooding results in changes in nutrient inputs, reduced area available for reproduction and reduced time for development, particularly of migratory species, and higher mortality resulting from high water temperatures. There is a decrease in fish populations, particularly for migratory species, and a shift in community composition from migratory species toward dominance by resident species.
- Changes to fish populations and fish communities result in lower catches and lower value of catches for fishers using canals as well as for communal fishers. We predict that catches from communal fisheries are more sensitive to fish population size because canals concentrate fish at a point where they can be easily captured. If so, we expect to see that canal construction increased when dams were present.

Scenario 2: Fish Canals
- An increase in the number of fish canals results in reduction of the duration of the flooding, in particular, in the depressions.
- A reduction in the duration of the flooding results in a quicker drying of the floodplain. This may not result in a shift from perennial to annual grasses, but it will diminish regrowth of grasses after bush fires. Limited regrowth of grasses (after bush fire) means that more mobile pastoralists leave the floodplain after the cold dry season because of the limited quantity of grazing resources to support them.
- Rapid drying through fish canals results in higher fish mortality, particularly of larger fish, because of direct fishing pressure, stranding of fish in rapidly-drying pools and higher energy demand. Removal of larger, older fish results in lower average fecundity. Consequently, fish populations are reduced and shifted in age and size distributions toward smaller and younger fish, and community composition is shifted away from taxa such migratory fish to a greater dominance of resident fish that can survive in pools.
- Changes to fish populations and fish communities result in lower catches and lower value of catches for fishers using canals as well as for communal fishers. We predict that catches from communal fisheries are more sensitive to fish population size because canals concentrate fish at a point where they can be easily captured.
- The smaller catches from communal fishing and the reduction in income will lead to greater differentiation between fishermen with and without fish canals.

- If catches from canals decline more slowly than do catches from communal fisheries and/or decline of income is less for fishers with canals, investment in canals may increase as fish populations decline.

RESEARCH PLAN

In order to examine whether the impact of fish canals resembles that of large-scale dams and whether it results in a shift to different social, ecological, and hydrological regimes in the Logone Floodplain, we will use a combination of field research, remote sensing analysis, and modeling. We will model past and present conditions, constraining the models with available satellite and in situ measurements of the hydrological, ecological, and sociological conditions. We will then extend the models into the future to characterize responses of the system to an increase in the number of canals, a changing climate, and policy interventions.

The study will focus on a 1,000-km^2 section of the Logone Floodplain with well-defined boundaries that overlaps with the pilot zone of the Waza Logone Project (1990-2003), which started reflooding of the pilot zone by opening an old waterway in the dike along the Logone River in 1994 (Scholte 2005). We will conduct field research in six different fishermen villages across the study area. In each of these locations we will collect detailed and in-depth data on the different systems (e.g., hydrological, fish populations, vegetation, fishermen, and pastoralists).

We will build social, ecological and hydrological models as well as an integrated CHANS model for the Logone Floodplain. We will use existing models where appropriate and use remote sensing, existing data sets, and field data to parameterize and calibrate our models. Although the Logone Floodplain has not been systematically examined as a dynamic coupled human and natural system, it has been studied extensively and there is a wealth of existing data available that will allow us to build an integrated model and examine long-term trends in the social, ecological, and hydrological systems.

HYDROLOGICAL MODELING

The hydrological models will be used to examine the effects of the fish canals and a future warmer climate on the floodplain hydrological processes. The hydrological models will be coupled with the ecological models to characterize the effects of the canals on fish populations and vegetation; the ecological models will in turn be linked to social models, as described in subsequent sections.

The specific hydrological modeling objectives are: (1) Model the effect of the canals and climate change on the duration of inundation on the floodplain. This will be accomplished by a **hydraulic model**. The hydraulic model will predict water depth and water temperature, which will be input to the fish population models. (2) Model the effect of the change in inundation duration and climate change on soil moisture and (thus) water availability for plants. This will be accomplished by a **surface hydrology model**; models are described below. The surface hydrology model will predict soil moisture across the floodplain, which will be input to the vegetation model. Both models will be run over the 1000-km^2 study area.

Canals by design divert water from the Logone onto the floodplain while the Logone is rising. Depressions are thus filled with water. When the Logone river level begins to fall, the canals allow the water in these depressions to drain back to the Logone. Thus, one effect of these canals is expected to be a decrease in the duration of flooding each year. The **hydraulic model** will explicitly calculate water flow from the canal to the depressions and back again by solving the so-called "shallow water equations". We will utilize the TELEMAC 2-D hydraulic model (www.opentelemac.org). The model requires inputs of the

floodplain elevation and input flows from the Logone, as well as local precipitation and evaporation. Floodplain elevations near fishing villages in our study area will be obtained by using differential GPS obtained in situ; away from the villages, we will use SRTM elevations initially, and calibrate these elevations using the observed remote sensing inundation maps using data assimilation methods (Durand et al. 2008). Logone flows will be obtained from the stream gage. The hydraulic model will be validated using water level measurements obtained in situ at six fishing villages. Precipitation will be estimated via local rain gages. Evaporation from the open water surface will be estimated via the Penman-Monteith equation, driven by local air temperature and radiation estimates, and constrained by local pan evaporation estimates. Water temperature will be modeled by assuming the surface temperature is equal to the air temperature. The hydraulic model will be run on a variable-sized 2-D mesh, allowing for small mesh elements near the canals, and larger mesh elements in the more homogenous depressions; model time step will be determined dynamically. Fractional inundation and average water depth at a uniform 1 km grid will be estimated from the hydraulic model for coupling with the fish population model.

Once the depression empties of water, we will utilize a **surface hydrology model** including only three processes: precipitation, evaporation, and infiltration. Evaporation from the soil to the atmosphere will be handled via the Penman-Monteith equation constrained by pan evaporation estimates. Precipitation will be estimated via gages. Richard's equation constrained by in situ measurements of hydraulic conductivity to model flow of water in the soil. Transpiration will be handled by parameterizing the Penman-Monteith equation for approximately ten vegetation types found in the Logone Floodplain according to FAO guidelines. The hydrologic model will be run on the same non-uniform mesh used by the hydraulic model, and at a daily timestep.

Our modeling exercises will include simulation of historical flooding, simulation of current canal operation, and simulation of future floodplain response to future canal building and future climate change. Simulation of *historical flooding* will be driven by in situ streamflow measurements, available for the last 100 years (height and discharge). The historical flooding simulations will be constrained by remote sensing measurements of floodplain inundation extent, available for the last for the last 35 years (Bénech et al. 1982; Delclaux et al. 2010; Jung et al. 2011; Mott MacDonald 1993, 1999; Naah 1990; Westra and de Wulf 2007). Simulation of *current canal operation* will be driven by in situ measurements of canal elevations obtained in situ via differential GPS at six fishing villages. We will constrain the model using measurements of water elevation obtained in situ at the same locations. We will model the filling and emptying of the depressions used for fishing, and generalize the hydraulic behavior of the canals via representative parameters, viz: characteristic canal Manning roughness coefficient, slope, etc. We will use the representative parameters to explicitly model existing canals in our study area for which we do not have in situ measurements. Simulation of *future* conditions will utilize the representative parameters to model the effect of what would happen if additional canals were built, as well as the effects of future climate change, discussed in the next section.

CLIMATE CHANGE SCENARIOS

For the analysis of climate change impacts on social-ecological systems, observational networks are often lacking or limited in spatial and/or temporal extent. In the last decade, though, gridded model climatologies from both reanalysis datasets and General Circulation Model (GCM) output have been extensively used to analyze and forecast climate change and its impact on social-ecological systems. Reanalysis and GCM fields have high vertical and temporal scales, which permit a better comprehension of the weather patterns.

Nevertheless, their low horizontal scales (from 125 to 400 km cell size) make it difficult to link predicted global atmospheric patterns to natural resources impact at smaller spatial scales.

In this project, near past, present and future (until 2030) natural and human interaction scenarios will be simulated by using climatic forcing such as precipitation and temperature. There are no weather stations in the study area itself, but there are at least 6 nearby, some of which have more than 25 years of data (Olivry & Naah 2000). The best available climatic data for the region are gridded reanalysis and GCM output, so the atmospheric boundary condition for the modeling will be given by merging available local weather station data and global gridded climatologies by means of statistical downscaling techniques. Downscaling techniques belong to roughly two categories: statistical and regional climate modeling (Chirstensen et al., 2007). For the proposed study we will employ the former, taking into account the relatively high density of stations in the vicinity of the study area and the relatively flat topography.

For the near past and present, the statistical downscaling of reanalysis data will set transfer functions to provide local climatic scenarios for the hydrological model. Here, the NCAR/NCEP (Kalnay et al 1996) and/or MERRA (Bosilovich, 2008) reanalysis will be downscaled to each station. In addition to transfer functions, this downscaling process will give the chance to fill gaps in the weather stations, as done by Hofer et al. (2010) to produce local records of temperature and specific humidity above a specific glacier in Peru.

Forcings for simulating future scenarios will be given by using the transfer functions developed in the previous step to downscale GCMs until the year 2030. We propose to use three global emission scenarios derived from the ECHAM4 GCM simulation, which has been used to predict precipitation changes in Cameroon (Penlap et al., 2004) and has been found accurate over Africa (Kamga, 2000). The scenarios will be obtained from the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (IPCC, 2007) and correspond to (1) "a future world of very rapid economic and low population growth" (SRES A1B), (2) "a very heterogeneous world with rapid economic growth" (SRES A2), and (3) "a convergent world with introduction of clean and efficient technologies" (SRES B1). If in the course of the project the IPCC releases new projections, we will include some of them.

FISH POPULATIONS

We will focus on the population dynamics of two functional groups: 1) small, migratory fishes such as Alestes baremoze (Alestiidae), 2) larger, resident omnivores such as Clarias and Oreochromis. Each of these will be further divided into size/age classes. The smaller functional group migrates into the flooded regions to spawn, and juvenile fish spend several months growing on the floodplain (Lemoalle 2005). These fish are of commercial importance, have historically supported fisheries in the Lake Chad basin, and are among the main catches of fish fences on the Logone floodplain. Alestes spp are also among the last fishes to enter the floodplain and among the first to leave as water levels drop (Lemoalle 2005); thus, they may be particularly sensitive to hydrological changes. Members of the larger functional group are resident on the floodplain and are tolerant of low oxygen and high temperatures associated with low water levels. Following drought in the 1970s, there was a shift in fisheries of the Lake Chad basin to high catches of resident omnivores (Bukar and Gubio 1985). The relative densities of the two functional groups may therefore be an indicator of regime shift in the aquatic ecosystem of the Logone Floodplain.

The dynamics of fish populations, particularly those of the migratory functional group, are influenced by factors at multiple scales, including those extrinsic to the Logone floodplain (such as fishing pressure and water levels in Lake Chad). To model the influence of floodplain-wide and extrinsic influences on fish populations at the scale of the floodplain,

we will fit autoregressive integrated moving-average (ARIMA) models for catch per unit effort of communal net fisheries over the flooding season for each functional group. Candidate models will include a priori combinations of: autoregressive terms, timing and extent of inundation in the current and previous seasons, canal density, communal fishing effort, and fishing catches and water levels in Lake Chad. Fit of candidate models will be assessed using Akaike's Information Criterion for finite sample sizes (AICc).

At the local level, we will model the dynamics of nutrients, detritus, macrophytes, phytoplankton and zooplankton, and the growth and movement of populations of the two fish functional groups in each of our focal village areas. These will be modeled as a set of difference equations, using a timestep of one day, over the entire season of inundation. Dynamics of size/age classes of the two fish functional groups will be modeled using a bioenergetic model, in which growth depends on food availability, water temperature and mass. Village fishing areas will be divided into a grid of cell size 500m x 500m. The population at time 0, and rates of migration into the focal area, will be functions of the population on the whole floodplain, obtained from the ARIMA model described earlier. We will examine the sensitivity of fish population sizes, catches from nets and canals, and the relative biomass of the two functional groups, to model parameters. In particular, we will investigate the effects of variation in variables at the local level (for example, the location and local density of canals or local fishing effort) and to those at the global level (for example, migration into the floodplain as a whole or extent of flooding over the entire floodplain).

To model the mortality resulting from declining water levels, we will use an approach based on Gaff et al. (2000). As water levels decline toward zero in any area, fish may move out of the area to adjacent flooded areas connected by natural waterways or canals, into pools connected to fish canals, to isolated pools that persist through the dry season, or they may be stranded and die. These proportions will depend on local topography and on how fish are assumed to move. Movement will be modeled using two candidate movement rules for each functional group: a reaction-diffusion process and a dynamic ideal-free process in which fish move up a resource gradient (DeAngelis et al. 2010; Sutherland and Anderson 1993).

We will model mortality from catches in pools as a function of the density and effort of communal fishermen in each village area. To model mortality from fish fences set across canals, which is of most importance to the small migratory functional group, we will assume that fish trapped in pools attempt to exit through canals or natural waterways as water levels approach 0 or at the onset of migration. The risk of mortality for each canal will be product of the mortality rate per fence over all fences encountered between the pool and permanent water. If there are multiple egresses from the pool, risk of mortality from all fences will then be the sum of mortality risks for each route weighted by the use of each route, which depends, in part, on flow through each escape route.

Parameters of bioenergetic growth models will be obtained from literature (e.g., de Merona et al. 1988). The dynamics of water levels in the focal areas, which influence water temperature and the risk of stranding, are obtained from the hydraulic model, and constrained by field observations. Inputs of detritus into the system at the time of flooding will be obtained from the vegetation model. Other model parameters will be obtained from historic time series data and field data collected for this project. We will measure the densities and size distribution of fish functional groups using a combination of catch per unit effort data from communal fisheries and existing fish fence data. We will set pairs of fyke net arrays at focal village sites. One array will be set in line with the direction of water flow and the other perpendicular to water flow. Because the arrays and fences act as sit and wait predators, passively capturing fish that move into the fence area, we can use standard foraging models to estimate encounter rates in canals and away from canals. Plankton

samples will be collected monthly using plankton nets with two mesh sizes (Rey et al. 1987) at the location of fyke nets and fishing sites. Seasonal water samples in the canals and floodplain will be taken in collaboration with local partners and analyzed annually at OSU for nutrient content and other physical chemistry

FISHERMEN DECISION-MAKING

Understanding the drivers behind the growth in the number of fish canals and their effects on the coupled systems in the Logone Floodplain is the central problem of this research project. But we also want to understand the failure of feedback mechanisms in the fishery system, i.e., why do fishermen continue to create new canals even though local populations observe negative changes in the floodplain? To examine these questions we will conduct an ethnographic study of six communities in the Logone Floodplain and study decision-making at the level of the household and the community. We will select communities that vary in the number of fish canals, importance of communal fishing, and history of conflict.

To understand decision-making at the household level we will conduct surveys with 20 households with canals and 20 households without canals in each of the six communities. The survey will document income of all household members from fishing and other livelihood activities. The survey will focus on the expenses for and revenues from communal fishing and fish canals, and use this to compare the economic returns of both fishing techniques. We will also use the survey to document changes in income and livelihoods and whether households are shifting from fishing to other economic activities, e.g., rice cultivation, which may indicate a regime shift. The data will be used to measure economic differentiation within communities, whether it correlates with canal ownership, and whether it is associated with greater conflict over resources in the communities.

In each of the six communities we will document the catches for the different fishing techniques, including the species, number of fish, and fish sizes. We will also document the monetary value of the different fish species and sizes as well as the costs of the fishing techniques. We will use this data to examine the economic returns communal fishing and fish canals and to estimate the break-even point at which investments in fish canals may no longer be profitable because of declining returns from catches. We will crosscheck this model with data collected in the household surveys and compare it with data from before and after the dam and reflooding (Bénech et al 1982; Bénech and Quensière 1983; Fritsch 1970; Quensière 1981).

To examine decision-making at the level of the community, i.e., the management of common-pool fishery resources and the regulation of fish canals, we will study cases of conflicts among fishermen within and between communities using an extended case method (Mitchell 1983; van Velsen 1979) focusing on the social and political processes and the role of the different agents, including traditional and governmental authorities and local NGOs (Moritz 2006, 2010). We will compare communities that may have been able to control the growth of fish canals and communities that have seen a rapid increase in the number of canals. The goal is to understand the conditions and processes that lead to different outcomes and whether this knowledge can be used to facilitate changes in the use of fish canals. One of the questions is whether and how ethnic tensions (Musgum versus Kotoko), economic differentiation (canal versus non-canal owners), NGO activities or any other factors can explain variation in the density of canals in the floodplain.

Finally, we also document changes in population densities in the communities, in particular whether fishermen have either temporarily or permanently migrated to other fishing areas in (or beyond) the Chad Basin (Delclaux et al. 2010). Shifts in population have been associated with the regime shifts in the Logone Floodplain: out-migration after the construction of the Maga Dam in 1979 and in-migration after the reflooding in 1994 (Scholte

2005) and are a good indicator of an impending regime shift. We will also compare these data with population densities before and after the dam (Elingui 1978; Podlewski 1966; Seignobos and Iyébi-Mandjek 2000).

VEGETATION DYNAMICS

In the Logone Floodplain changes in flooding have a direct impact on the vegetation dynamics and this has been documented after the construction of the Maga Dam in 1979 and the reflooding efforts in 1994 (Loth 2004; Scholte 2005). We expect that the growing number of fish canals will also have a direct impact on the vegetation dynamics. We expect no changes in flooding depth, but significant changes in the duration of the flooding. In studies conducted in 1994-96, Scholte (2007) examines changes in vegetation resulting from the dam and the reflooding efforts and found a strong correlation between maximum flooding depth and duration and vegetation productivity (biomass) and quality (% N). However, it is as yet unclear what the impacts are of the growth in the number of fish canals, for example, whether it will result in a shift from perennial to annual species. We expect that a shorter flooding duration results in a quicker drying of the floodplain, limiting the growing season, and subsequent maximum standing crop (biomass) and especially regrowth of grasses after fires.

Three states have been distinguished for the vegetation in the Logone Floodplain (Scholte 2005). State A, the pre-dam state, had diverse perennial grass vegetation, including rhizomatous grasses (*Echinochloa pyramidalis* and *Oryza longistaminata*) and tussock grasses (*Vetiveria nigritana*). This state can still be found in the area that has continued receiving floodwater after the Maga dam construction. The numbers and the condition of *Vetiveria nigritana* have remained remarkably constant throughout a period of relative drought (mid-1980) and more abundant rainfall in the 1990s, suggesting that during the pre-dam period it was a stable state. State B, the post-dam state, has different appearances due to the cyclic (Gleasonian) succession that takes place. Initially, the areas that received little or no flooding were invaded by *Sorghum arundinaceum* annual grasses. However, after the reflooding in 1994, the annual grasses were replaced by short living perennial grasses and subsequently by rhizomatous perennial grasses. It appears that the cyclical succession is directly affected by the flooding conditions. State C, on the edge of the floodplain, is dominated by annual herbs. It can be considered a further degeneration of State B, where even with limited floods no further changes in vegetation are observed.

The last time an ecological study of vegetation productivity in the Logone Floodplain was conducted was in 1996 (Scholte 2005) whereas vegetation composition has been followed until 1999 with a limited repetition in 2003. Since then the number of fish canals has grown significantly and there is some evidence that the reduction in flooding and greater inter-annual variation in flooding is due to the effects of climate change (Delclaux et al. 2010). It is unclear what the impacts are on the floodplain vegetation composition and productivity and whether there is a cyclical shift to a state with lower productivity, for example, *Sorghum arundinaceum* annual grasses are unpalatable for cattle.

In order to measure the impacts of the fish canals, we will measure changes in vegetation composition over the last 10-15 years (i.e., since the last studies in 1997-2002). We do this by studying the vegetation composition and maximum flooding depth and duration in 53 plots along an existing transect that has been used by ecologists since 1984 (Scholte 2005). This transect spans the main ecological zones in the floodplain: 1) no longer flooded, 2) reflooded since 1994, 3) always flooded, and 4) areas that have changed because of fish canals. We will also re-assess the relationships between maximum flooding depth and duration and vegetation production. Assessments of vegetation (above and underground)

biomass, as well as regrowth and soil moisture will be conducted in selected plots in the same transect, chosen in relation to their accessibility during the flooding season.

TRACKING PASTORALISTS' RESPONSES

The Logone Floodplain is not only of enormous ecological and economic importance for fishermen, but also for pastoralists in the Chad Basin. Thousands of pastoralists from Cameroon and neighboring Niger and Nigeria with more than 200,000 cattle trek each November to the Logone Floodplain when the water retreats to exploit the excellent quantity and quality of the grasslands (Moritz et al. nd; Scholte et al. 2006). One of the main reasons why we are tracking mobile pastoralists in the Logone Floodplain is because they respond in real-time to changes in the quality and quantity of the available forage. In our studies we have found that pastoralists are continuously monitoring the state of their herds and pastures and comparing those against other herds and pastures (Moritz et al. nd; Scholte et al. 2006). They will move whenever and wherever they are able to find better pastures for their animals. It is an open system and there are no natural or political boundaries that prevent pastoralists from moving to other pastures (Moritz et al. nd). In the case of the Logone Floodplain this means that pastoralists will either move to pastures around Lake Maga or to Chad. The timing of their movements (cold dry season or hot dry season) and spatiotemporal changes in the density of mobile pastoralists will be used as indicators of impending regime shifts and compare against post-dam data (1979-1993). We will also compare the mobility patterns with the predictions from the dam-scenario and canal-scenario to see which one fits better. We expect that in the dam-scenario there would be an overall reduction of the pastoral population in the cold and dry hot season (Moritz 1994; Schrader 1986), while the canal-scenario would lead to a reduction of the pastoral population in the hot dry season (February-May) because of the expected lack of regrowth (see above), but not in the cold dry season (November-January).

To understand how changes in the hydrology and vegetation of the floodplain affect mobile pastoralists we will document their mobility patterns using a combination of transhumance surveys and GPS mapping. The transhumance survey documents the whole population, i.e., all the groups of mobile pastoralists that use the study area at some point during the year, and the names and number of days of all the sites they have stayed in the previous year. We will also record the number of households and herds and estimate their size. In addition, we will use GPS technology to map the locations of mobile pastoralists in the floodplain three times a year in November, February, and May to validate the data collected in the transhumance surveys. We have successfully used these techniques in earlier studies (Moritz et al. 2010; Scholte et al. 2006) and have collected four years of mobility data for about 300 camps incorporating approximately 1,500 households and 150,000 animals (2007-2011). We will use GIS to examine correlations between intra- and inter-annual changes in vegetation and the spatiotemporal distribution of pastoralists.

In addition, we will conduct semi-structured interviews with mobile pastoralists who camp in the proximity of the six communities in our study, in order to understand how pastoralists perceive changes in their immediate environment and more broadly how they perceive the dynamic coupled systems of the floodplain and whether and how they perceive an impending catastrophic (or other) transition, and whether and how this shapes their decision-making. We will compare these data with the mobility patterns to examine whether they help to predict the adaptive responses of pastoralists.

INTEGRATED CHANS MODEL

The integrated CHANS model couples the models described above (fish population, vegetation, and hydrology) with two agent-based models (Gilbert and Terna 2000; Miller and Page 2007) for pastoralists and fishermen. In our project context, an agent is either a household of fishermen or pastoralists. At each time step (e.g., a season), a fisherman agent decides whether to continue investigating on canals given the fish production. A pastoralist agent decides whether to stay in the floodplain or to move out given the vegetation status.
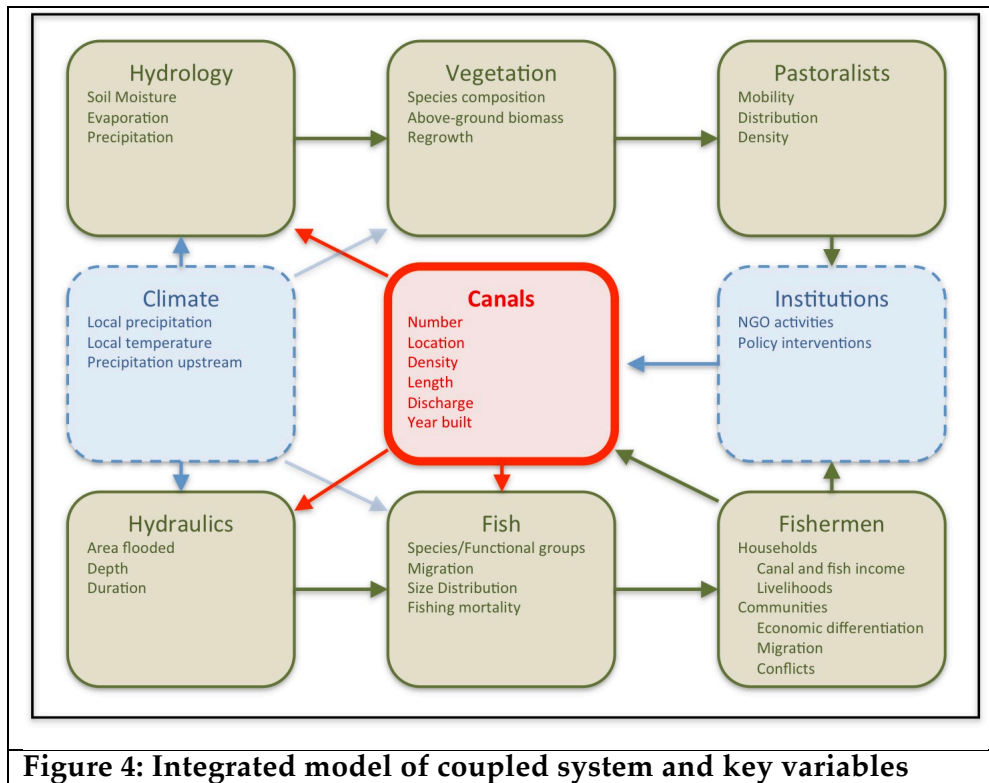
We will identify these decision rules from our household surveys as described above. Figure 7 outlines the structure of the integrated CHANS model. At each time step, the current status of canals, as well as the climate conditions, will be used to run the hydrological and hydraulic

Figure 4: Integrated model of coupled system and key variables

models. The output of these two models will be used to simulate the state of vegetation and fish, which in turn will be used as input for the fishermen and pastoralists agents to make their decisions to invest in canals or move respectively.

The integrated CHANS model can be used as a virtual laboratory to explore the coupled system. We will model past and present conditions, constraining the models with available satellite and in situ measurements of the hydrological, ecological, and sociological conditions. We will then extend the models into the future to characterize the response of the system to an increase in the number of canals and a warmer climate, and examine the effects of different policy interventions that would reduce the number of canals.

We will implement all our models using open source software packages. We plan to develop a web-based application to distribute the integrated model. The model will be available for download from our web site. More importantly, the web application will allow users to run the model to examine the effects of different scenarios.

DATA ANALYSIS AND MODEL INTERPRETATION

In order to examine whether the impact of fish canals resembles that of the Maga Dam and whether it results in shifts to different social, ecological, and hydrological regimes in the Logone Floodplain, we will use a two-prong approach. First, we will compare our field data

with existing data sets from the period after the construction of the Maga Dam (1979-1993) to examine whether and how the impact of canals is qualitatively and quantitatively different from the impact of the dam. For example, we will compare the current composition of fish populations, e.g., the ratio of resident and migratory species, with data from before the construction of the Maga Dam (Bénech et al 1982; Bénech and Quensière 1983), after the dam (Van Oijen & Haberland 1991), and reflooding (Bobo & Boukar 1997).

Second, we will compare the outputs from the model simulations with our field data to examine whether the current situation in the Logone Floodplain is more similar to that of the dam-scenario or the canal-scenario outlined above. For example, we will compare current size and ages of fish populations with the output from the simulations.

In order to validate the model we will also compare our simulations with existing data sets for three different time-series or time periods: 1) before the Maga Dam (1970-1979); 2) during the Maga Dam (1980-1993); 3) and after the dam (1994-present). These time-series are separated by two major exogenous interventions that resulted in regime shifts: the construction of the Maga Dam in 1979 and the reflooding in 1994. During all three periods the number of fish canals has steadily increased, even more so after the reflooding in 1994. In addition, there is some evidence that the effects of climate change have already affected flooding patterns in the Logone Floodplain.

We will use the model simulations to explore the nature of the regime shifts in the social, ecological and hydrological systems, for example, whether there are linear or non-linear couplings between flooding regimes and fish populations or between species composition of vegetation and population densities of mobile pastoralists. We will explore this by varying input variables such as: 1) the amount of water released by the Maga Dam (which will help us determine whether the historically recorded shift was linear or not), and 2) the number of canals at the start of the simulation and investigating the state of the systems (e.g., vegetation composition, populations of fish functional groups, distribution of pastoralists) at different years after the start of model runs.

We will also use the integrated model to run what-if simulations to examine the impact of different human activities, climate change scenarios, and policy interventions on the coupled systems of the Logone Floodplain. For example, what would have been the state of the Logone Floodplain if the governor in 1995 had succeeded in filling canals that were built after 1975? Or, what would be the impact of the IPCC's scenario of very rapid economic and low population growth (SRES A1B)(IPCC 2007) on flooding and the coupled systems in the next twenty years?

EDUCATION PLAN

The primary educational goal of this project is to train and educate undergraduate and graduate students at the Ohio State University and the University of Maroua to work innovatively, collaboratively, and productively in transdisciplinary research projects that examine complex social-ecological systems. The study of complex social-ecological systems is beyond the scope of any one discipline and requires a transdisciplinary approach (Lambin and Geist 2006; Little and Leslie 1999; Moran and Ostrom 2005; Poteete et al. 2010). In the future, these kinds of transdisciplinary studies will become ever more important as climate change has far-reaching effects on environments and the human populations that depend on them. It is critical that researchers, and in particular undergraduate and graduate students, are not only well-trained and educated in the theories and methods of their own discipline, but also that they acquire the skill set and perspectives of transdisciplinary research of complex social-ecological systems, and learn its potentials and challenges (e.g., Guyer and Lambin 1993; Taylor 2005; Turner 2002), for they are the future

scientists that will be studying these environmental problems and contribute to their solution (Borgerhoff Mulder and Coppolillo 2005).

At the Ohio State University we will organize a weekly lab for undergraduate and graduate students and faculty working on the research project. The goal of the lab is to create a community of practice in which students learn to think innovatively and rigorously as scientists. We will discuss epistemological, theoretical, methodological, ethical, and practical issues in transdisciplinary research. The lab will be a place where we discuss student work, e.g., grant proposals, research reports, posters, and where "expert" students learn to mentor "novice" students (Lave and Wenger 1991). The lab will prepare students for successful participation in the research project. Graduate students will design their own independent research within the larger study of coupled human and natural systems in African floodplains. All students will write research proposals, submit their research for IACUC and IRB review (if applicable), and write up the results in a report. In addition, we expect our graduate students to submit grant proposals to NSF, NASA, and other funding agencies, to submit their report for publication to a peer-reviewed journal, and to write a policy brief. We will work closely with all students at all stages of the research cycle, from design to writing.

Undergraduate research will be a central component of our proposed project. Undergraduate researchers will assist in data collection in Cameroon and in the parameterization and development of models. We will recruit highly qualified undergraduates in the social sciences, earth sciences, ecology and evolutionary biology and mathematics with the assistance of existing undergraduate research programs (see below). Undergraduate researchers will learn how to develop specific questions for empirical and modeling research, collect and analyze data, learn to address their questions using analytical and computational methods to solve models, interpret model results and communicate these results in oral and written form. We expect that undergraduate researchers involved in this project will present their research at local undergraduate research venues, such as the Denman Undergraduate Research Forum organized by the Undergraduate Research Office at OSU and at national meetings. We have included funding for students to present their research at national meetings.

We anticipate strong links with existing undergraduate research programs at OSU. We will advertise undergraduate research positions through the Undergraduate Research Office (URO) at the Ohio State University. Ian Hamilton is director of a NSF Undergraduate Research in Biology and Mathematics (UBM-Institutional) program at the Ohio State University: Research for Undergraduates: adventures in Mathematical Biology and its Applications (RUMBA). RUMBA provides funded research opportunities for team-based research experiences for undergraduate students in the mathematical and life sciences. We propose to involve at least two teams of RUMBA participants over the lifetime of this project. OSU also administers two programs that enable underrepresented minority students to participate in undergraduate research experiences: the Student Achievement in Research and Scholarship (STARS) program and the Summer Research Opportunities Program (SROP). We intend to work with these programs to identify underrepresented minority students who have a interest in research experiences in modeling CHANS.

An important goal of the education program is to provide training for graduate students and faculty at the University of Maroua in studying and modeling coupled human and natural systems of African watersheds. We will be working closely with an interdisciplinary team of researchers at the University of Maroua, which consists of **Kolyang Dina Taiwe**, computer scientists; **Mouhaman Arabi**, GIS and environmental science specialist; **August Ombolo**, hydrologist; and **Roland Ziebe**, veterinary doctor. We have developed four types of activities to achieve this goal. First, together with our Cameroonian collaborators we will develop a fellowship program in which graduate

students propose an independent research project within the larger study of coupled human and natural systems in African watersheds. We will mentor the fellows as they design their study, collect and analyze data, interpret and write up the results. Second, our Cameroonian collaborators will organize a laboratory dedicated to studying and modeling coupled systems in the Logone Floodplain with monthly presentations of research conducted by faculty and student fellows. Government officials, representatives of NGOs, and other stakeholders will be invited to these monthly meetings. Third, we will hold annual workshops with our Cameroonian collaborators and their students that coincide with our field visits in Cameroon in the first three years of the project. In these workshops we will discuss the ongoing project and CHANS-related research. Each of these three workshops will be devoted to training in different analytical and modeling techniques (e.g., Qualitative Data Analysis, Geographic Information Systems, Agent-Based Modeling, and different hydrological modeling techniques). Fourth, at the end of the project we will organize a conference at the University of Maroua in which we will present and discuss the findings and the integrated model of the Logone Floodplain. We will invite researchers from nearby universities and research institutes (e.g., PRASAC in Chad), and other stakeholders (e.g., representatives of the Lake Chad Basin Committee, representatives of local populations, non-governmental organizations). The research project will allow us to consolidate our collaborations with the University of Maroua by developing stronger and enduring research and teaching partnerships and enhance infrastructure for research.

MANAGEMENT PLAN

To achieve a productive interdisciplinary collaboration, we will have weekly lab meetings with the PIs, post-doc, graduate and undergraduate students. We also use a wiki for continuous sharing and discussing data, findings, and publications with OSU and Cameroonian researchers, and we will conduct fieldwork together in Cameroon. In the first three years of the project we will simultaneously develop the integrated model, using existing data sets and remote sensing data, as well as collect field data. Members of our research team have extensive experience in the Logone Floodplain and strong, long-term collaborations with researchers at the University of Maroua, the *Centre d'Appui a la Recherche et au Pastoralisme* (CARPA), a NGO that supports research and development of pastoral systems in Cameroon, and the *Association Camerounaise pour l'Education Environnementale* (ACEEN), an NGO that develops tools and strengthens stakeholders capacities in common-pool resources management and conflict resolution in the Logone Floodplain. Both NGOs have considerable experience in research and development of pastoral systems (CARPA) and fishery systems (ACEEN) in the Logone Floodplain. We collect field data together with our Cameroonian collaborators and our respective students and the NGOs will provide logistical support. We will combine the field visits of the OSU researchers with workshops at the University of Maroua. In the fourth year of the study we will finish our integrated model that will assist local populations, policy makers, and other stakeholders in sustainable management of the Logone Floodplain by evaluating the impact of different human intervention and climate change scenarios. We will discuss this model and the scenarios with all stakeholders in the final year of the project at the University of Maroua. The NGOs will assist with outreach activities aimed at engaging fishermen and pastoralists.

 Personnel. Below is a brief description of personnel expertise and their primary responsibilities. **Mark Moritz** is an ecological anthropologist with 17 years of experience working in the Logone Floodplain studying coupled systems, pastoral systems, and natural resource management using ethnographic methods. He will coordinate the ethnographic research and modeling of the fishermen and pastoral populations. **Bryan Mark** is a physical geographer with 15 years experience in Andean fieldwork, conducting glacier

environmental and hydrological research. He will coordinate the hydrologic and observational fieldwork, water and climate instrumentation and be responsible for the hydrologic modeling. Moreover, he will be responsible for developing the different climate change scenarios. **Ningchuan Xiao** is a geographical information scientist with expertise in software development, spatial database design, web-base applications using spatial data, spatial analysis and modeling, and remote sensing. He will coordinate the development of agent-based models and the integrated model. **Michael Durand** is a land surface hydrologist with experience in hydrology and hydraulic modeling and remote sensing. He will be responsible for the hydraulic modeling of the canals (implementation, calibration, validation). Moreover, he will be responsible for pulling together the remote sensing of floodplain inundation data for validating the hydraulic models. **Ian Hamilton** is an ecologist and evolutionary biologist with 17 years of experience using mathematical modeling and experimental work to study fish life histories, cooperation and social dilemmas, and modeling the spatial distribution of organisms. He will coordinate the research on fish population dynamics and life history change and contribute to the modeling of the social systems. **Roland Ziebe** is a Veterinary Doctor with experiences in strategy planning and development activities, strengthening capacity of development organizations, research action, monitoring and evaluation of development programs in Cameroon. He is currently completing a dissertation on fishery systems in the Logone Floodplain and will coordinate the research on fishery systems and fish populations. **Paul Scholte** is program director for the German development organization (GIZ) in Cameroon. He has more than 20 years of experience studying the ecology, wildlife, and pastoral use of the Logone Floodplain. He will coordinate the research on vegetation. Central to our project will be a **postdoctoral researcher (PD)**. This person will be hired as a full-time coordinator of the project, and will be responsible for assimilating all data from various modeling and measurement aspects. The PD will also participate in fieldwork in Cameroon. We will seek a candidate who has expertise in at least two components of the project.

EXPECTED PROJECT SIGNIFICANCE

Intellectual Merit. African floodplains are an excellent example of coupled human-natural systems (CHANS) because there are strong couplings between the social, ecological, and hydrological systems. The intra- and inter-annual variations in the area, depth, and duration of seasonal flooding have direct and indirect impacts on ecosystems and human lives and livelihoods. However, African floodplains have not been systematically studied as coupled systems. Instead studies have focused either on the hydrological, ecological, or social system and have taken the couplings as a constant rather than as a dynamic system. This project will examine the dynamic couplings that are endogenous to social, ecological and hydrological systems in the Logone Floodplain. Because African floodplains are of enormous ecological and economic importance it is critical that we understand these dynamic couplings between the social, ecological and hydrological systems and examine the impact of different human activities and climate change scenarios.

      Broader Impact. The goal of the project is to contribute to the sustainable management of African floodplains, which are of enormous ecological and economic importance. We will use our integrated model to develop an educational web-based model that will assist local populations, policy makers, and other stakeholders in sustainable management of the Logone Floodplain by evaluating the impact of different human interventions and climate change scenarios. The goal of the education program is to train graduate and undergraduate students at the Ohio State University and the University of Maroua in quantitative and qualitative, transdisciplinary approaches to the study and management of coupled human and natural systems.

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