ARTICLE

Linking Hydrology, Ecosystem Function, and Livelihood Outcomes in African Papyrus Wetlands Using a Bayesian Network Model

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Abstract Relationships between hydrology, ecosystem function and livelihood outcomes in Nyando papyrus wetland in western Kenya were integrated in a Bayesian Network model with 34 nodes which was populated with results of ecohydrological and socio-economic research and stakeholder consultations. Scenarios for dry and wet seasons were evaluated. For a current "average" year in Nyando wetland the probabilities of "Ecosystem function" and "Livelihoods outcomes" being "good" were 62 and 19 %, respectively. Under dry conditions, these values changed to 33 and 37 %; and under wet conditions to 85 and 6 %, respectively, indicating that wet conditions had a positive effect on the ecosystem but a negative effect on livelihoods. Ecosystem function and livelihood outcomes were most sensitive to flooding, conversion to agriculture, livestock grazing, and papyrus harvest. Flooded conditions limit cropping, livestock herding and vegetation harvesting but have a positive effect on ecosystem function. The advantage of this interdisciplinary and participatory modeling approach is that it allows incorporation of formal and informal knowledge, allows evaluation of policy scenarios and trade-offs between ecosystem services, and recognizes uncertainty in system outcomes. Further work will incorporate the impact of management policies and institutions on resource use. This approach will be useful in decision support for wise use of wetlands.

Introduction

African freshwater biodiversity in rivers, lakes and wetlands has been steadily decreasing as a result of anthropogenic activities (Darwall et al. 2011). Papyrus wetlands in the Lake Victoria basin in East Africa are no exception. They constitute 37 % of the total wetlands area of Kenya and compose a vital life support system for about 12 million people. About 75 % of the Lake Victoria wetland area has been significantly affected by human activities, and about 13 % of these wetlands is severely degraded (Kayombo and Jorgensen 2006). In the Kenyan part of Lake Victoria, these activities have increased at an alarming rate with up to 50 % area loss in some papyrus wetlands in the last 40 years (Owino and Ryan 2007).

Sustainable wetland management is important because wetlands perform ecosystem functions that are vital for the health and biodiversity of the terrestrial and aquatic systems that they connect. They also support the livelihoods of many people, both directly and indirectly, through their provisioning (water, food and other materials), regulating (flood control, climate regulation, water quality regulation, and others) and cultural ecosystem services (MEA 2005; TEEB 2010). Ecosystem services are based on the components, processes and functions of ecosystems (Maltby 2009; de Groot et al. 2010). The degradation of wetlands therefore threatens not only the ecology, but also the livelihoods of people both

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locally and on a larger scale. This linkage between ecosystem function and livelihoods is often not appreciated by policy makers due to a lack of knowledge about the importance and functioning of wetlands as social-ecological systems. To formulate effective, sustainable wetland policies and management strategies, it is essential to develop an integrated understanding of how wetland ecosystem functions are affected by natural and anthropogenic factors, and how wetland resources influence livelihoods. It is also important to understand how people make resource exploitation decisions and how socio-cultural and policy factors affect those decisions.

Wetland ecosystems are complex, variable, and uncertain and their management often involves a large number of stakeholders. Knowledge of their functioning spans scientific disciplines ranging from social sciences to natural science and engineering. A framework that supports policy making should incorporate both the eco-hydrological processes and the socio-political mechanisms controlling the exploitation for livelihoods. In addition, it should allow participation of local communities, scientists, policy makers and other stakeholders in formulating and operating the framework to increase its legitimacy and effectiveness in the policy process. Such an inter-disciplinary framework improves the accuracy and appropriateness of policies and management, as it provides a basis for discussion among stakeholders, common understanding of the environmental system, and shared conclusions and compromises on wetland management.

Bayesian Networks (BNs) are a tool for the structured analysis of complex systems. BNs can show relationships among variables graphically, allow the incorporation of uncertain and qualitative data and can be improved as more knowledge and data become available. BNs have been used routinely in medicine and artificial intelligence and more recently also in integrated natural resource management research (McCann et al. 2006). They allow ecosystem managers to investigate the impacts of management options through analysis of scenarios and provide an opportunity to share stakeholder perceptions on the potential impacts of management strategies (Uusitalo 2007). BN development often involves development of an alpha-level BN based on a causal diagram, and subsequent improvement of this first version into a beta-level model using data from case studies, secondary data, stakeholder opinion and expert judgement (Marcot et al. 2006; Chen and Pollino 2012). Validation with new data can lead to a gamma-level model that can be applied in prediction or management.

This article focuses on the first steps in the development of a trans-disciplinary framework that investigates the relationships between livelihoods outcomes and ecosystem functioning in papyrus wetlands. This is part of the project "The Ecology of Livelihoods in East African Papyrus Wetlands (ECOLIVE)", which aims at an understanding of papyrus wetland ecosystem functions and services in the context of

ecological, hydrological and socio-economic dynamics, using the Nyando wetland in Kenya as a case study (van Dam et al. 2011). The overall objective is to integrate the relationships between hydrology, ecosystem function, and livelihood outcomes in Nyando wetland into a beta-level BN model. Specific objectives are: (1) to construct a conceptual model of the Nyando wetland ecosystem based on an analysis of ecosystem functions and services; (2) to operationalize the network using a Bayesian Network model; (3) to involve stakeholders in model formulation and development.

Study Site and Ecosystem Functions and Services

Like other Lake Victoria wetlands, Nyando wetland at the mouth of the Nyando River on the north-eastern shores of the lake (Fig. 1) originates from extreme rainfall in the lake basin in the early 1960s (Thompson 1976). The Nyando basin receives annual rainfall of 1,000–1,600 mm during two rainy seasons (March-May and October-December) and mean annual temperature is 23 °C (Muthusi et al. 2005). Mean rainfall between 1950 and 2010 was 1,184 mm at the Ahero irrigation scheme near the Nyando wetland, wich currently measures 3,000 to 5,000 ha (P. Khisa, pers. comm.). The area is densely populated (Mungai and Nyakang'o 2004), with an average density of 214 persons km^{-2} for the Nyando river basin area ten years ago (Kenya 1999 census, Central Bureau of Statistics, Nairobi). The following review of ecosystem characteristics is based on a participatory state-of-the-system analysis at the beginning of the ECOLIVE project (Khisa, Nasongo and Rongoei, unpublished data), a small field survey (Table 1) and the literature. Then, ecosystem functions and services were analysed qualitatively (Table 2).

Nyando wetland, being located at the river mouth, does not have a strong floodwater detention function. Floods associated with rainfall, river discharge and overtopping at high river stage are persistent in the lower parts of the Nyando basin and damage to infrastructure, displacement of communities and loss of life due to floods occur every year (OCHA 2002). Bank overflow occurs twice per year when river discharge exceeds 40–50 $m^3 s^{-1}$ (Muthusi et al. 2005). Not much is known about groundwater recharge and discharge. Studies on erosion in the Nyando basin showed that deposition occurred in the wetland (Cohen et al. 2006). Sediment yields of less than 8 t ha^{-1} y^{-1} were estimated for the lower Nyando basin using a SWAT model (Swallow et al. 2009). Papyrus fringe vegetation is known to reduce the entry of fine silt and clay, sand and gravel particles into the adjoining lake (Boar and Harper 2002).

Nutrient retention withinin the wetland is determined primarily by storage in vegetation, burial in the sediment and gaseous losses. Papyrus generally exhibits high productivity with culm densities up to 20 shoots per m^2, culm lengths up to 5 m and
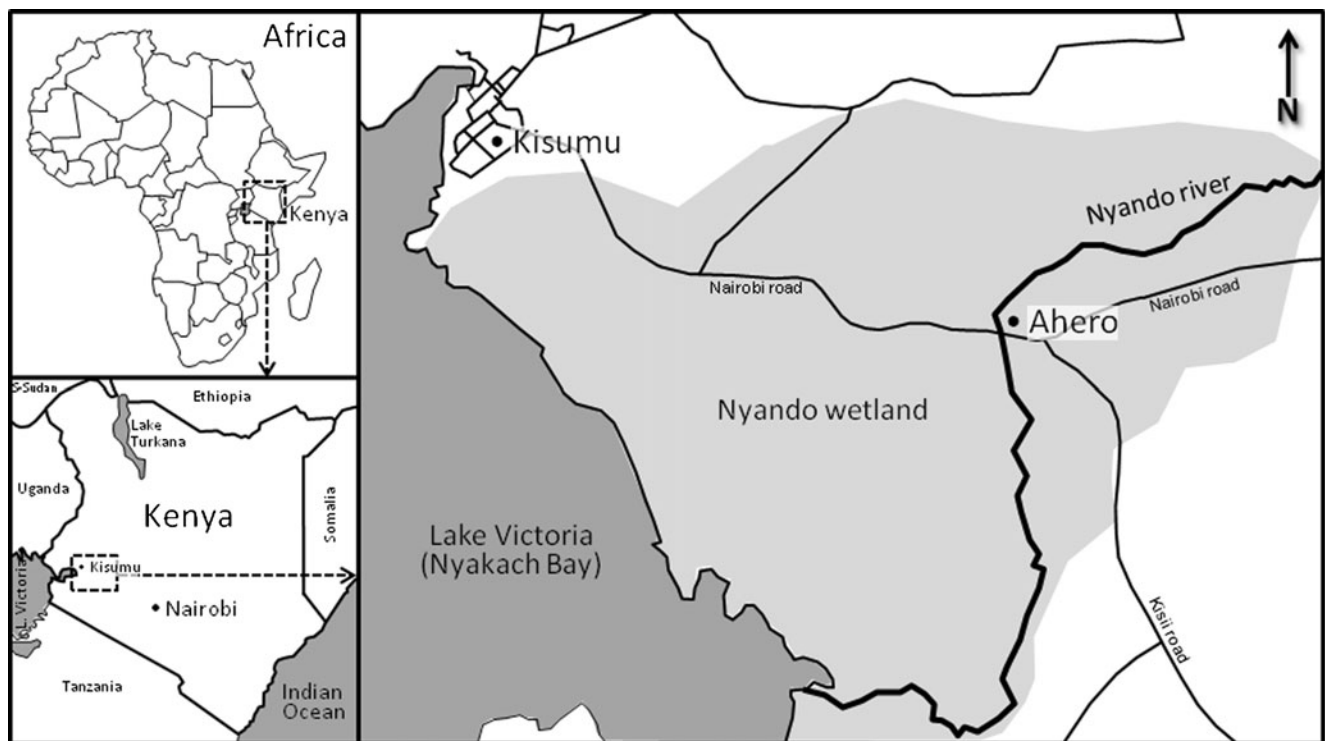
Fig. 1 Location and map of Nyando wetland, western Kenya. Coordinates: 0°11′ – 0°19′ S, 34°47′ – 34°57′ E

total biomass density of up to 10 kg dry matter per m^2 (Gaudet 1977; Thompson 1985; Muthuri et al. 1989; Kipkemboi et al. 2002). Storage is affected strongly by the age of the plants as the nutrient uptake rate of fast-growing young papyrus is much higher than of mature stands. Scenescing and dying plants will eventually return their nutrients to the wetland (Muthuri and Jones 1997). Vegetation harvesting contributes to nutrient retention at the wetland scale by removing nutrients, and by reducing the biomass of the remaining vegetation which leads to re-growth and higher nutrient uptake (van Dam et al. 2007). Burial is probably important as Nyando wetland accumulates thick layers of peat with high organic matter content (Jaetzold and Schmidt 1982; Henry and Omutange 2009). Little research has been done on gaseous nitrogen losses. Ammonia volatilization is probably insignificant because of the low pH (Gaudet 1979). Nitrogen fixation may be an important source of nitrogen

for papyrus. In Naivasha, it was estimated at a maximum of about 0.14 g Nm^{-2} day^{-1} (Gaudet 1979; Mwaura and Widdowson 1992). For phosphourous retention, binding to the sediment is important (Kelderman et al. 2007) but no data on Nyando wetland are available. Studies suggest that elevated concentrations of Pb, Cd, Cu, Zn and Mn exist in Nyando wetland (Nyangababo et al. 2005). There are no measurements of dissolved organic carbon (DOC), but papyrus wetlands are probably a source of DOC for Lake Victoria (Mwanuzi et al. 2003; Loiselle et al. 2008).

The ecological functions of Nyando wetland include habitats for a variety of wildlife. The vegetation is dominated by *Cyperus papyrus*, *Typha domingensis* and *Phragmites australis* interspersed with more than 35 other species (Gichuki et al. 2001; Kipkemboi et al. 2007b). At lake and river edges, a typical zonation of floating water hyacinth

Table 1 Community survey among 50 randomly selected households. Data presented as averages ± SE and sample size in parenthesis. The survey was conducted with the help of an experienced local school teacher. One senior person from each household was interviewed

Attribute	Singida	Ogenya	Sites combined
1. Household size	6±2 (25)	5±3 (25)	6±3 (50)
2. Distance of household from the wetland (km)	2.82±2.27 (25)	2.22±2.32 (25)	2.52±2.29 (50)
3. Maize yield (kg/ha)	742±407 (19)	765±246 (22)	754±331(41)
4. Papyrus harvest (kg DW/person/day)	4.2±4.3 (7)	4.1±2.7 (8)	4.2±3.4 (15)
5. Average no. of livestock units per household	6±8 (13)	6±5 (15)	6±7 (28)
6. Proportion of household income from wetland-related activities (%)	83±18 (25)	69±23 (25)	75±21 (50)
7. Frequency of sickness due to common diseases (times/person/year)	2±1 (25)	2±1 (25)	2±1 (50)

Table 2 Framework used for functional analysis of Nyando wetland. For wetland ecosystem functions, the categories defined by Maltby (2009) were used. For wetland ecosystem services, the categories defined in MEA (2005) were used. Because of the overlap between the regulating and supporting services in the MEA-framework with the ecosystem functions in Maltby's framework, regulating and supporting services were not assessed separately

Category	Function/service
Hydrological functions[a,c]	Floodwater detention
	Groundwater recharge and discharge
	Sediment retention
Biogeochemical functions[a,c]	Nutrient retention and export
	In-situ carbon retention
	Trace element storage and export
	Organic carbon concentration control
Ecological functions[a,c]	Structure/habitat for biodiversity
	Productivity, biomass and detritus for food web support
Provisioning services[b,d]	Food
	Fresh water
	Fibre, other construction materials and fuel
	Biochemical
	Genetic materials
Cultural services[b,d]	Spiritual and inspirational
	Recreational and aesthetic
	Educational

[a] Ecosystem functions are defined here as the result of interactions among characteristics, structure and processes of the ecosystem resulting in the capacity of natural processes and components to provide goods and services that satisfy human needs (de Groot et al. 2002)

[b] Ecosystem services are defined here as the benefits people obtain from an ecosystem (MEA 2005)

[c] Function categories based on Maltby (2009)

[d] Service categories based on MEA (2005)

(*Eichornia crassipes*), hippo grass (*Vossia cuspidata*) and papyrus can be observed (Denny 1984). From lake or river edges towards the upland, zonation is related to hydrology (water flow and depth) and livelihoods activities (conversion to agricultural crops and vegetation harvesting; see below). Wildlife includes mammals, such as hippopotamus (*Hippopotamus amphibius*) and sitatunga or marshbuck (*Tragelaphus spekei*), and amphibians and reptiles. Gichuki et al. (2001) identified 28 (predominantly river and lake) fish species in 12 families in the papyrus-dominated Sondu Miriu wetland. Typical fish species in Nyando wetland include lungfish (*Protopterus aethiopicus*); catfish (*Clarias spp.*); tilapia (*Oreochromis spp.*); and several haplochromine species. There is also a plethora of bird species, including species endemic to papyrus wetlands such as the papyrus gonolek (*Laniarius mufumbiri*); and the white-winged warbler (*Bradypterus carpalis*) (Maclean et al. 2006). Some papyrus wetlands are also important for migratory birds

(Ramsar 2011) although this is not an important function for Nyando wetland.

Provisioning services include food for humans (fish, crops, natural vegetation, other animals and plants, medicines) and animals (especially grass and wetland vegetation for livestock), fibre for production of handicrafts (e.g. water hyacinth, papyrus), fuel wood, building materials (such as papyrus fibre for walls and roof construction, clay and sand for construction as well as timber from wetland trees), and fresh water for irrigation and drinking (Kairu 2001; Kipkemboi et al. 2007a). There are numerous shallow wells that supply water to the communities living around the wetland.

With respect to cultural ecosystem services, Nyando wetland plays an important role in the tradition and culture of the Luo communities. The wetland is used to some extent for recreational fishing and swimming by the local community but there is little tourism. Traditionally, papyrus wetlands harboured sacred places but this practice is gradually disappearing (Kibwage et al. 2008). Nyando wetland has been studied by universities, government departments and NGOs; several MSc and some PhD studies were conducted there (e.g. Kipkemboi 2006; Rahman 2010).

Drivers of Change

The main direct drivers of change in the wetland are livelihoods activities and hydrology. Livelihoods activities include livestock herding, conversion to agriculture (including cutting or burning of vegetation, sometimes removal of vegetation rhizomes and roots, channelization for drainage and irrigation, and occasional application of pesticides and fertilizers), and harvesting of wetland products (see provisioning services above). During the dry season the wetland is visibly degraded when large areas of emergent macrophytes are converted to sugar cane, maize, rice and vegetable farms. Hydrological modification includes channelization to carry water from the river channel into the wetland for rice production, clearing of aboveground vegetation, and cultivation. Many farmers prefer burning the wetland vegetation as opposed to investing in labour intensive tilling. Vegetation harvesting targets mostly papyrus, but also *Phragmites*.

Livelihoods activities are strongly linked to flooding, which is controlled by seasonal bank overflow of Nyando river and daily inundation of the lakeward edges of the wetland due to lake seiches and wind action. The lake and river edges are permanently flooded and other parts of the wetland are periodically flooded (usually for a period of days) at least once or twice per year. Flooding has a strong impact on human activities. As soon as the flood has retreated, vegetation is (partially) removed and crops are planted. In dry years, the permanently flooded part of the

wetland is smaller and a larger area is cultivated. Papyrus harvesting, mainly for mat making, is also affected by flooding as flooding restricts access to harvestable stands. Sometimes, harvesting in flooded areas is done by boat. Papyrus rhizomes are generally not harvested and will develop a new stand when re-flooded. As long as wetland hydrology is not modified the papyrus vegetation will survive, thus contributing to the resilience of the wetland under cultivation pressure. Water depths of more than 20–30 cm also impede livestock herding. In contrast, fishing is enhanced during the rainy season.

Indirect drivers of change include population growth and unemployment, as well as formal and informal institutions and policy intervention. High population density and unemployment together lead to low incomes from non-wetland activities. More than 65 % of the Nyando basin residents live under absolute poverty (Swallow et al. 2009). Poverty and unemployment increase dependency on wetland goods and services and force the communities to exploit wetland resources. Commercialization of wetland products in local and nearby markets (Homa Bay, Kisii and Kisumu) acts as an important driving force for the harvesting of raw wetland materials (Ojoyi 2006). Innovation in the production of crafts from papyrus also determines the amount of papyrus that is harvested. Traditional papyrus goods (e.g. mats, baskets) fetch lower prices than improved products (e.g. furniture, bags, wall hangings, other decorations) that require less raw material and can produce 5–10 fold the current revenue (P. Raburu, pers. comm.). The level of awareness among the members of the local community of the importance of the wetland plays a role in people's resource use decisions. Nyando wetland is an open access resource and its exploitation, like in most of the Lake Victoria wetlands, is largely uncontrolled (Kibwage et al. 2008). Some activities, like livestock herding and fishing, are done by people from outside the Nyando wetland who have no concept of the history of the wetland or of preserving the resource for future use. There are also many informal institutions (traditions, customary land use arrangements) that affect wetland resource use (S. Nasongo, pers. comm.).

Methods

Conceptual Model

For BN model development we followed the guidelines provided by Cain (2001), Marcot et al. (2006), Henriksen et al. (2007a) and Chen and Pollino (2012). For the conceptual model we used DPSIR analysis as the basis (Smeets and Weterings 1999; Niemeyer and De Groot 2008). After group discussions with the community, individual interviews and field observations, DPSIR chains for the most important

ecosystem functions and services were constructed (functions: wetland habitat/biodiversity; groundwater recharge; nutrient and sediment retention; and services: wetland fish catch; livestock production; papyrus yield; crop yield; drinking water supply). The elements of the DPSIR chain were expressed in terms of ecosystem functions and services. Thus, "Drivers" were "Indirect drivers of change", "Pressures" were "Direct drivers of change", "States" were considered as "Ecosystem processes and components", while "Impacts" were taken to constitute "Ecosystem functions and services" (and indirectly human well-being). "Responses" were considered as policy or management decisions (either institutional or community based) that could influence drivers or pressures. The separate causal chains were then combined into one eDPSIR network (Niemeijer and de Groot 2008) which served as the conceptual model for an alpha-level Bayesian Network model (Marcot et al. 2006).

Bayesian Network Development

BNs are composed of three components: nodes, links and Conditional Probability Tables (CPTs). The nodes represent the variables of the environmental system, such as ecological, hydrological and socio-economic variables. The links represent the relationships between the nodes and are represented with arrows that originate from the cause (parent node) and end up with the effect (child node). The setting of parentless (or input) nodes can be changed to observe the effect on other nodes. In this way, different scenarios can be evaluated. The links are determined by conditional probability: the likelihood of an event given the occurrence of another event. Each link between two nodes in the BN is defined by a CPT containing the probabilities for the different combinations of node states.

The eDPSIR network of the Nyando wetland was converted into a BN by considering the variables of the network as the nodes of a BN. For the alpha-level version of the BN, nodes and CPTs were defined on the basis of the eDPSIR network, secondary information and consultation with ECOLIVE project researchers. For each node, a qualitative or quantitative indicator was defined (Table 3). Indicators were selected based on knowledge generated from the state-of-the-system analysis of Nyando wetland and the output of preliminary MSc research. When there were several potential indicators for one variable, indicators for which empirical information was easily available were selected. Initially, qualitative values were assigned to the different states of the variables (e.g., "poor", "moderate", "good"). Where empirical data was available from on-going research or the literature, states were defined quantitatively (e.g., for fish yield: "0–50", "50–100", "100–150" kg ha^{-1} y^{-1}). Three nodes were included to represent the trade-off between ecosystem integrity and human benefit: the "Ecosystem function" node with parent

Table 3 Indicators, units and states of the nodes in the BN model for Nyando wetland

Node	Indicator	Unit	States
Cachment_Rainfall	Annual rainfall over Nyando catchment	mm y^{-1}	1,900 to 2,200 1,600 to 1,900 1,300 to 1,600 900 to 1,300 500 to 900
Cash_based_Livelihoods:	Status of livelihoods based on cash income	(qualitative)	Good Moderate Poor
Drinking_Water_Supply:	Reliable water supply by boreholes	(qualitative)	High Low
Ecosystem_Function:	Status of ecosystem functions based on wetland biodiversity, nutrient and sediment retention, and groundwater recharge	(qualitative)	Good Moderate Poor
Fish_Yield:	Yield of fish from the wetland	kg ha^{-1} y^{-1}	100 to 150 50 to 100 0 to 50
Flood_Inundated_Area:	Maximum area flooded		4,000 to 5,000 3,000 to 4,000 0 to 3,000
Food_based_Livelihoods:	Status of livelihoods based on food provisioning	(qualitative)	Good Moderate Poor
Lake_Victoria_Rainfall:	Annual rainfall over Lake Victoria	mm y^{-1}	2,000 to 2,500 1,500 to 2,000 1,200 to 1,500
Lake_Victoria_WG_Water_Quality:	Chorophyll-*a* concentration in Nyakach Bat	µg L^{-1} of Chl-*a*	>=100 50 to 100 0 to 50
Livelihoods_outcomes:	Livelihoods outcomes in terms of cash and food	(qualitative)	Good Moderate Poor
Livestock_Herding:	Number of livestock grazing in the wetland per day	Number (no.) of individuals (ind.)	>=5,000 0 to 5,000
Livestock_Nos_per_ Household:	Number of livestock owned by an average household	no.	>=20 10 to 20 0 to 10
LV_Wat_Level	Water level in Lake Victoria	m above MSL	1,136 to 1137.5 1134.5 to 1,136 1,133 to 1134.5
Non_Wet_Income_Level:	Number of individuals in wetland community living under official poverty line	No. of ind. living under poverty line	>=10,000 5,000 to 10,000 0 to 5,000
Nutrient_Sediment_ Retention:	Degree of nutrient and sediment retention of wetland	(qualitative)	High Low
Pap_Crafts_Innovation:	Presence of absence of product innovation among papyrus craft industry	(Boolean)	True False
Papyrus_Market_Value:	Local market price of papyrus products (predominantly mats) in 2010	Kenya shillings per mat	>=50 30 to 50

Table 3 (continued)

Node	Indicator	Unit	States
Papyrus_Yield_Perm_Wetland	Total papyrus yield in perennial wetland assuming maximum of 20 tonnes per ha	Tonnes	15,000 to 25,000
			5,000 to 15,000
			0 to 5,000
Papyrus_Yield_Seasonal_wetland	Total papyrus yield in seasonal wetland assuming maximum of 20 tonnes per ha	Tonnes	60,000 to 90,000
			30,000 to 60,000
			0 to 30,000
Permanent_wetland_Area:	Area in which soil is permanently saturated with water	ha	750 to 1,250
			250 to 750
			0 to 250
Pop_Density	Population density in Nyando wetland	ind. km^{-2}	500 to 1,000
			250 to 500
			0 to 250
Pub_Awareness_Wet_Value:	Degree of awareness among wetland community of importance of wetland conservation	(qualitative)	High
			Low
River_Discharge	Discharge of Nyando river at Ahero	m^{3}s^{-1}	>=50
			0 to 50
Seasonal_Wet_Veg_Area_ha:	Area in seasonal wetland which is covered with wetland vegetation	ha	3,000 to 4,500
			1,500 to 3,000
			0 to 1,500
Seasonal_Wetland_Area:	Area in which soil is seasonally/temporally saturated with water	ha	3,750 to 4,250
			4,250 to 4,750
			4,750 to 5,000
Unemployment:	Number of persons unemployed	No. of ind.	500 to 1,000
			250 to 500
			0 to 250
Veg_Biomas_Harvest:	No. of persons harvesting papyrus at any given time	ind. ha^{-1}	>=15
			0 to 15
Wet_Biodiversity:	Diversity of wetland vegetation as measured by Shannon-index (H')	(dimension-less)	2.5 to 3.5
			1.5 to 2.5
			0 to 1.5
Wet_Conv_Agri_Percent:	Part of the seasonal wetland area that is converted to crops	%	40 to 60
			20 to 40
			0 to 20
Wet_GW_Recharge:	Groundwater recharge through infiltration in the wetland	(qualitative)	High
			Low
Wetland_Crop_Area_ha:	Area of the wetland converted to crops	ha	2,000 to 3,000
			1,000 to 2,000
			0 to 1,000
Wetland_Crop_Production	Total crop production assuming average of 900 kg/ha for dominant crop (maize)	Tonnes	2,500 to 4,500
			1,000 to 2,500
			0 to 1,000
Wetland_Fishing:	Number of people fishing	No. of ind.	200 to 400
			0 to 200
Wetland_Flood_Duration:	Duration of the flood	Days	>=3 days
			< 3 days

notes "Groundwater recharge", "Nutrient and sediment retention", and "Biodiversity"; the "Food-based Livelihoods" node with parent nodes "Drinking water supply", "Crop production" and "Fish yield"; and the "Cash-based Livelihoods"

node with parent nodes "Livestock production", "Papyrus yield perennial wetland" and "Papyrus yield in the seasonal wetland". "Food-based livelihoods" and "Cash-based livelihoods" nodes were joined in a node called "Livelihoods outcomes". The CPTs for these nodes were determined after discussion with stakeholders and experts (see Tables 4, 5, 6, and 7).

The BN was then compiled with values for the input nodes based on the current situation in an average whole year, according to data from research, expert opinion and stakeholders' views. Posterior probabilities of the nodes were recorded. The internal validity of the model was checked by compiling the network, changing the states of one node, noting the effect on its immediate child and verifying that the effect was logical and understandable (Cain 2001). In case of unrealistic results, the CPT was verified and re-adjusted on the basis of the best possible information until model behaviour was in accordance with available formal knowledge and stakeholder/expert views. Scenarios for dry and wet seasons were evaluated by setting

the nodes "Lake Victoria rainfall" and "Catchment rainfall" both to their lowest and highest values, respectively and looking at the effect on "Ecosystem function" and "Livelihoods outcomes" and their constituent nodes.

Sensitivity analysis was performed by applying the "Sensitivity to Findings" option of Netica to the output nodes "Ecosystem function", "Cash-based livelihoods" and "Food-based livelihoods". This procedure checks the degree to which variation in posterior probability distributions is explained by other variables given their prior probability distributions. For discrete variables, sensitivity is calculated as the mutual information (or entropy reduction) of the two variables (which tells us the reduction in uncertainty about a variable when the distribution of the other variable is known) and expressed in bits. Sensitivity of the three output nodes was calculated for each indirect driver, direct driver and state (see Fig. 3) and expressed as the percentage of the mutual information of each variable with itself (percentage entropy reduction).

Table 4 Conditional probability table (CPT) for the output node "Cash-based livelihoods" in relation to its parent nodes "Livestock number per household", "Papyrus yield in the seasonal wetland", and "Papyrus yield in the permanent wetland"

Livestock number per household	Papyrus yield seasonal wetland	Papyrus yield permanent wetland	Good	Moderate	Poor
>=20	60,000 to 90,000	15,000 to 25,000	100	0	0
>=20	60,000 to 90,000	5,000 to 15,000	95	5	0
>=20	60,000 to 90,000	0 to 5,000	90	10	0
>=20	30,000 to 90,000	15,000 to 25,000	50	50	0
>=20	30,000 to 90,000	5,000 to 15,000	30	70	0
>=20	30,000 to 90,000	0 to 5,000	20	80	0
>=20	0 to 30,000	15,000 to 25,000	15	85	0
>=20	0 to 30,000	5,000 to 15,000	10	90	0
>=20	0 to 30,000	0 to 5,000	5	95	0
10 to 20	60,000 to 90,000	15,000 to 25,000	95	5	0
10 to 20	60,000 to 90,000	5,000 to 15,000	90	10	0
10 to 20	60,000 to 90,000	0 to 5,000	80	20	0
10 to 20	30,000 to 90,000	15,000 to 25,000	50	30	20
10 to 20	30,000 to 90,000	5,000 to 15,000	20	60	20
10 to 20	30,000 to 90,000	0 to 5,000	5	70	25
10 to 20	0 to 30,000	15,000 to 25,000	0	75	25
10 to 20	0 to 30,000	5,000 to 15,000	0	60	40
10 to 20	0 to 30,000	0 to 5,000	0	55	45
0 to 10	60,000 to 90,000	15,000 to 25,000	0	70	30
0 to 10	60,000 to 90,000	5,000 to 15,000	0	60	40
0 to 10	60,000 to 90,000	0 to 5,000	0	55	45
0 to 10	30,000 to 90,000	15,000 to 25,000	0	50	50
0 to 10	30,000 to 90,000	5,000 to 15,000	0	40	60
0 to 10	30,000 to 90,000	0 to 5,000	0	30	70
0 to 10	0 to 30,000	15,000 to 25,000	0	20	80
0 to 10	0 to 30,000	5,000 to 15,000	0	10	90
0 to 10	0 to 30,000	0 to 5,000	0	0	100

Table 5 Conditional probability table (CPT) for the output node "Food-based livelihoods" in relation to its parent nodes "Drinking water supply", "Wetland crop production", and "Fish yield"

Drinking water supply	Wetland crop production	Fish yield	Good	Moderate	Poor
High	2,500 to 4,500	100 to 150	100	0	0
High	2,500 to 4,500	50 to 100	95	5	0
High	2,500 to 4,500	0 to 50	90	10	0
High	1,000 to 2,500	100 to 150	60	40	0
High	1,000 to 2,500	50 to 100	55	45	0
High	1,000 to 2,500	0 to 50	50	50	0
High	0 to 1,000	100 to 150	5	60	35
High	0 to 1,000	50 to 100	5	55	40
High	0 to 1,000	0 to 50	5	50	45
Low	2,500 to 4,500	100 to 150	80	20	0
Low	2,500 to 4,500	50 to 100	75	25	0
Low	2,500 to 4,500	0 to 50	70	30	0
Low	1,000 to 2,500	100 to 150	20	60	20
Low	1,000 to 2,500	50 to 100	10	65	25
Low	1,000 to 2,500	0 to 50	5	25	70
Low	0 to 1,000	100 to 150	5	10	85
Low	0 to 1,000	50 to 100	0	5	95
Low	0 to 1,000	0 to 50	0	0	100

Stakeholder Participation

A consultation meeting was organized on 8 December 2009 with experts and stakeholders. Participants were: community representatives, government and non-governmental organisation (NGO) officials and experts, and scientists in the on-going ECOLIVE project. At the beginning of the workshop, the purpose of the exercise was explained. The eDPSIR network as well as the alpha-level BN were presented to the stakeholders to obtain their feedback about the variables (sufficiency, definition and state) and the links. Stakeholders were asked to review the proposed variables and offer their opinion on the cause-effect relationships. Drafts of the network (consisting of variables and links) and of the alpha-level BN model were presented using Powerpoint and hard copies.

The experts and stakeholders then formed break-away groups of ecology, hydrology and socio-economics and governance/policy based on their interest and areas of expertise. The approach proposed by Cain (2001) was used to populate the CPT tables. Stakeholders were provided with questionnaires to guide them in providing information on conditional probabilities based on their professional beliefs. Since the tables were generally small, participants could fill them out directly as long as the logic was clear to them. Each group was asked to discuss and agree on compromise values where differences arose. In addition to expert/stakeholder opinion, actual data were used to improve parameter estimation when available. Where there were difficulties, assistance was provided through explanation and help with scoring and averaging among different stakeholder perceptions. The

averaged values for state were then reviewed with stakeholders to check for consistency. Based on the discussions, some additional nodes were included in the beta-level BN to represent cause-effect relationships more accurately (compare Figs. 2 and 3). All this input from stakeholders and experts led to the beta-level model which is reported here.

Additional feedback on the model was obtained from stakeholders, experts and wetland scientists at local and international scientific meetings, including the ECOLIVE Annual Project Meeting (Kisumu, Kenya, 23–25 May 2011), the Society of Wetland Scientistts Conference (Prague, Czech Republic, 3–8 July 2011) and the INTECOL Wetlands Conference (Orlando, Florida, 3–8 June 2012).

Table 6 Conditional probability table (CPT) for the output node "Livelihoods outcome" in relation to its parent nodes "Cash-based livelihoods" (see also Table 4) and "Food-based livelihoods" (see Table 5)

Cash-based LH	Food-based LH	Good	Moderate	Poor
Good	Good	100	0	0
Good	Moderate	50	50	0
Good	Poor	25	75	0
Moderate	Good	50	50	0
Moderate	Moderate	0	100	0
Moderate	Poor	0	75	25
Poor	Good	0	50	50
Poor	Moderate	0	25	75
Poor	Poor	0	0	100

Table 7 Conditional probability table (CPT) for the output node "Ecosystem function" in relation to its parent nodes "Wetland biodiversity", "Wetland ground-water recharge", and "Nutrient and sediment retention"

Wetland biodiversity	Wetland GW recharge	Nutrient and sediment retention	Good	Moderate	Poor
2.5 to 3.5	High	High	100	0	0
2.5 to 3.5	High	Low	90	10	0
2.5 to 3.5	Low	High	90	10	0
2.5 to 3.5	Low	Low	75	25	0
1.5 to 2.5	High	High	0	100	0
1.5 to 2.5	High	Low	10	80	10
1.5 to 2.5	Low	High	15	70	15
1.5 to 2.5	Low	Low	10	75	15
0 to 1.5	High	High	10	60	30
0 to 1.5	High	Low	10	50	40
0 to 1.5	Low	High	0	25	75
0 to 1.5	Low	Low	0	0	100

Results

Conceptual Model

Central in the network (Fig. 2) are the "State" variables describing the components of the wetland as determined by hydrology and exploitation. The inundated area (as determined by lake water level and river discharge) determines the relative size of the perennial wetland (dominated by papyrus) and seasonal wetland area (prone to conversion for agriculture). The size of the seasonal area and the degree of conversion to agriculture determine the relative size of the cropping area and seasonal wetland vegetation area. The three wetland functions and five services are strongly related to the perennial wetland area, the seasonal wetland vegetation area and the wetland crop area; and to the direct drivers of change. Fish catch depends on fishing effort and permanent wetland area; livestock production on herding and the size of the seasonal wetland vegetation area; papyrus yield on vegetation harvesting and both the permanent and seasonal wetland area; crop yield on the wetland crop area; wetland biodiversity on both the perennial and seasonal wetland area; groundwater recharge on the flood inundated area; nutrient and sediment retention on the different wetland zones and on wetland flooding; and drinking water supply on groundwater recharge.

Bayesian Network

The beta-level BN model consisted of 34 nodes and 55 links (Fig. 3). The CPTs for all nodes are presented in Supplement A. For a current "average" year in Nyando wetland (as defined by current knowledge about climate, hydrology and expert/stakeholder opinion; see input nodes in Fig. 3a), the probabilities of "Ecosystem function" and "Livelihoods outcomes" being "good" were 62 and 19 %, respectively.

Under dry conditions, these values changed to 33 and 37 %; and under wet conditions to 85 and 6 %, respectively, indicating that wet conditions had a positive effect on the ecosystem but a negative effect on livelihoods (Fig. 4). This can be understood from the effects on the parent nodes: wet conditions enhanced biodiversity, wetland fish yield, the size of the perennial wetland and the seasonally flooded vegetation area of the wetland, whereas dry conditions had a positive effect on livestock numbers, papyrus yield in the seasonal wetland and crop production (Fig. 5). The overall positive effect of wet conditions on the ecosystem (Fig. 4d) was more pronounced than the negative effect on livelihoods (Fig. 4c), because some livelihoods activities, such as fishing and papyrus harvesting are little affected or even enhanced under wet conditions. People can adapt to changing conditions fast by switching to other activities.

Of the indirect drivers, catchment rainfall had the strongest impact on livelihoods and ecosystem function with 9.2 % entropy reduction of ecosystem function and 3.7–4.9 % on the livelihoods indicators (Fig. 6a). Non-wetland income and public awareness had a small impact on food-based livelihoods (both 2.1 %). All the other indirect drivers had very small impacts on the output nodes (<1 %). The effects of direct drivers (Fig. 6b) were generally stronger. Conversion to agriculture had a strong effect on food-based livelihoods (25 %) and ecosystem function (17 %), but the impact on cash-based livelihoods was much less (1.6 %). River discharge and flood duration impacted most strongly on ecosystem function (both 15.2 %) but also affected food-based livelihoods and cash based livelihoods (6–8 %). The wetland states (Fig. 6c) had stronger effects on ecosystem function and on livelihoods characteristics with entropy reductions ranging from 10.7 to 18.2 %. Exception was the seasonal crop area, for which the effect on food-based livelihoods was stronger (25 %).
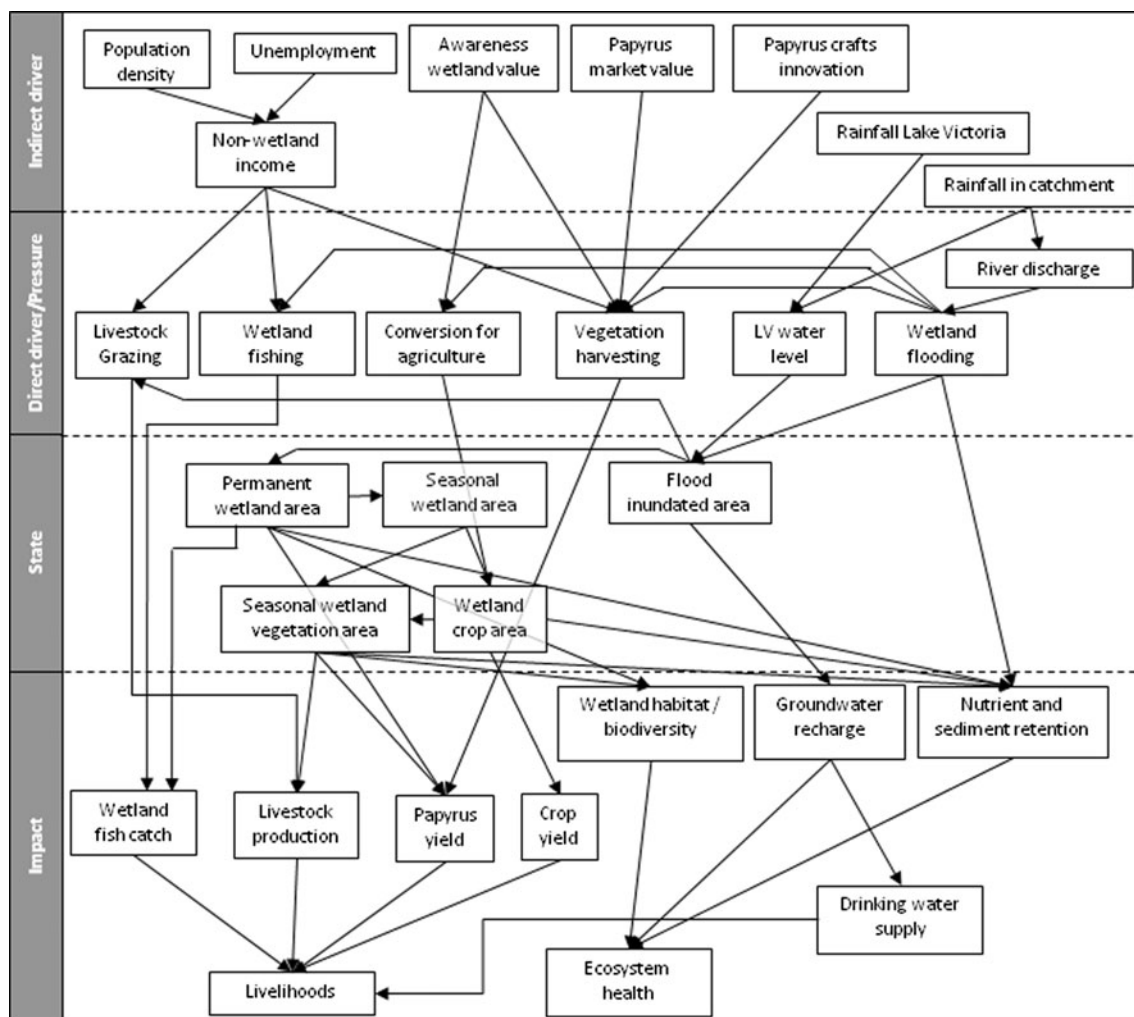
Fig. 2 Causal network of the Nyando wetland, Kenya, based on a combination of DPSIR analysis and the Ecosystem Services framework. For more explanation, see text

Discussion

Based on the model output for the present condition in an average year, the most probable state of livelihoods dependent on Nyando wetland is "moderate" (58 %) while ecosystem function has a high probability of being "good" (62 %; see Fig. 3). The settings of the input nodes for an average year result in high probabilities of the wetland being flooded and therefore high probability of the cropping area being small (Fig. 3). The effect of flooding on livelihoods and ecosystem is more clearly demonstrated in the scenarios for dry and wet conditions (Figs. 4 and 5). Wet conditions prevent the conversion of wetland vegetation into crops, and therefore have a positive effect on ecosystem function and a negative effect on livelihoods. The stronger effects of direct drivers and states on the output nodes (ecosystem function and livelihoods outcomes), as shown in the sensitivity analysis, can be partly attributed to their closer proximity to these nodes in comparison with the indirect drivers.

Comparisons of drivers should therefore be made only within groups of nodes with similar proximity to the output variables.

The model assumes that the intact wetland (natural vegetation) delivers more regulating services than the converted wetland (crops) and that the ability of the wetland to perform ecological, hydrological and biogeochemical functions is directly proportional to the area under natural soil and vegetation. This is a reasonable assumption, based on findings in mangroves, tropical forests and coral reefs (Balmford et al. 2002). In the model, this makes the size of the natural wetland area with natural vegetation, in combination with different pressures from livelihoods activities, important in determining the regulating services of the wetland. Natural vegetation occurs both in the permanently flooded and seasonally flooded parts of the wetland, but the pressures from livestock grazing, vegetation harvesting and conversion to agriculture are very different.
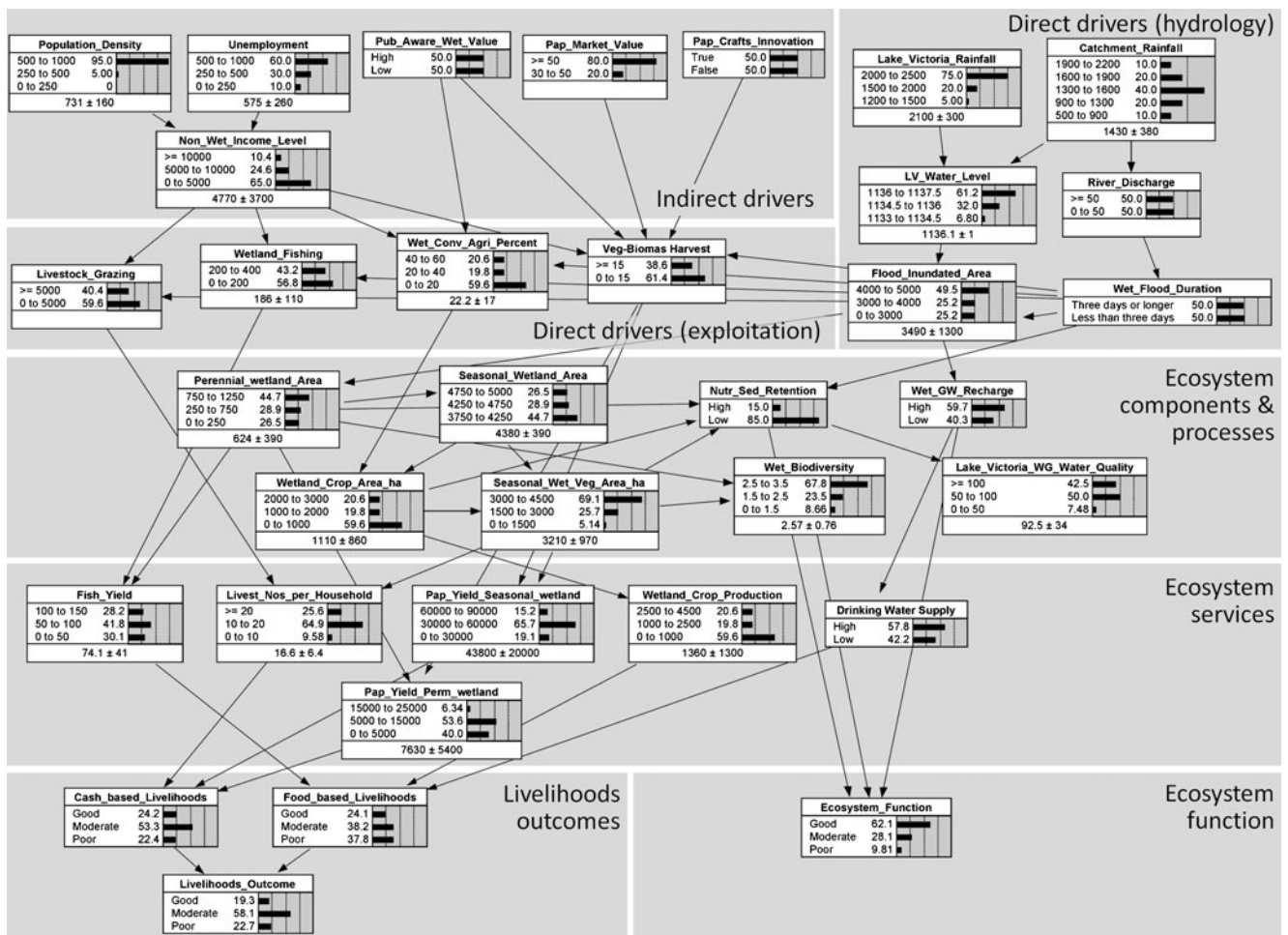
Fig. 3 Bayesian Network model of the Nyando wetland ecosystem with settings of input nodes for an average year according to stakeholder opinion. Grey boxes refer to the underlying structure of the causal network in Fig. 2

In the perennial wetland, agriculture is impossible and vegetation grazing and harvesting are limited to the outer fringes when water levels are low. The papyrus vegetation consists largely of mature stands in which growth rates are low, except for a limited number of sites where vegetation harvesting leads to temporary opportunities for other plant species but where *C. papyrus* eventually dominates. These perennial wetlands are important habitat for fish, birds and mammals. By contrast, the seasonal wetland during the dry season is vulnerable to livestock grazing, vegetation harvesting (including removal of rhizomes), burning and channelisation. Mineralisation of soil organic matter is enhanced by reduction of soil moisture and by tillage. This makes nutrients available for crop production. During the wet season, the stock of organic matter is replenished through partial re- growth of the natural vegetation in combination with reduced organic matter degradation under flooded, anaerobic condtions.

In terms of ecosystem functions and services, the perennial wetland zone is important for the hydrological, biogeochemical and ecological functions, whereas in the seasonal zone the provisioning services are more important, especially during the dry season. As long as pressures from livelihoods activities are limited to the dry season and the wetland is allowed to recover during the wet season, the provisioning services of the seasonal wetland are enhanced while maintaining a certain level of regulating services. Crops, like natural vegetation, offer habitat for macroinvertebrate, mammal and bird biodiversity. For example, some bird species are associated with pure stands of papyrus whereas others thrive more at the boundary between papyrus and crops (Maclean et al. 2006). Similarly, nutrient retention can still occur in cropland if no fertilizers are applied. Although nitrogen removal through denitrification is probably lower in crop fields than in the original wetland (Gettel et al., unpublished data), nutrient export may be enhanced through harvested crops. Intensification of agriculture (e.g. by permanent drainage of the wetland) can lead to the loss of soil productivity through oxidation of organic matter and soil erosion and compaction. Farming then maximizes the short-term food provisioning services of the wetland, but reduces
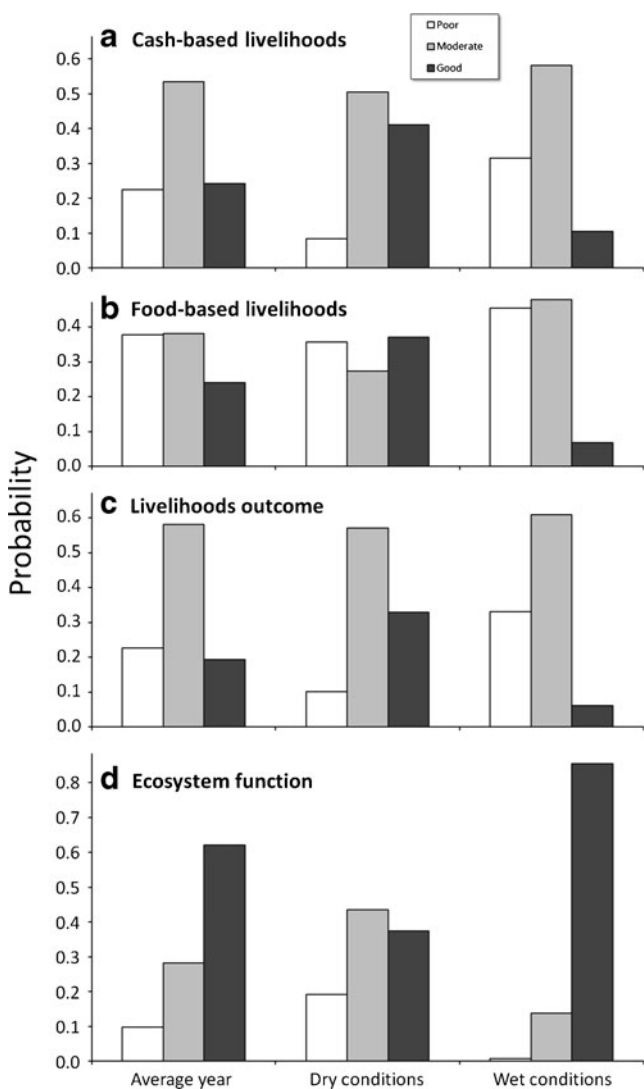
Fig. 4 Effect of dry and wet conditions on probability distributions of the objective nodes "ecosystem function" (a) and "livelihoods outcomes" (b) in the Bayesian Network model for Nyando wetland
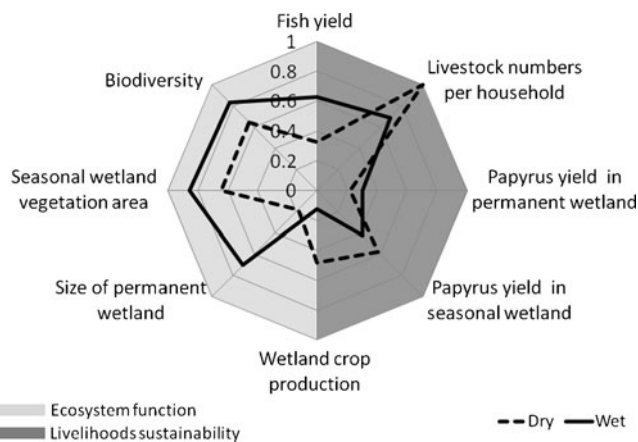

Fig. 5 Spider diagram of the effects of dry and wet conditions on Nyando wetland ecosystem functions (biodiversity, size of the permanent wetland, vegetated area in seasonal wetland) and services/livelihoods (fish yield, livestock numbers, papyrus yield in permanent and seasonal wetland, crop production). Scale expresses the value of the node according to the model as a proportion of the maximum possible value of that node

the wetland's ability to provide regulating ecosystem services in the long term.

Sustainable management would likely consist of a combination of protecting the perennial wetland zones, mainly by ensuring the water flows from river and lake needed to maintain the saturation of the wetland throughout the year; and regulating livelihoods activities in the seasonal wetland. Regulation can include e.g. limitations to the use of fertilizers and pesticides, limitations to livestock grazing and vegetation harvesting or burning, and rules with respect to tillage (e.g. removal of rhizomes) and channelization. This combination could ensure the continued delivery of ecosystem functions while allowing the production of food and materials (provisioning services). Another strategy is to intensify agricultural production from a limited area, but this may require land use methods (channelization, fertilizer and pesticide application)

that have a negative effect on ecosystem functions. Alternative strategies, such as other income generating activites (e.g. beekeeping, ecotourism), can also be considered. The remainder of this discussion focuses on the role of the Bayesian Network model in supporting the formulation and implementation of such a management strategy, and particularly on its validity, acceptance by stakeholders and potential for use in decision making.

With respect to the validity of the model, the overall objective of integrating the relationships between hydrology, ecosystem function and livelihoods was achieved by constructing a Bayesian Network model that was based on DPSIR analysis. This provided a systematic approach for understanding the complex relationships between drivers of change and ecosystem functions and services. The effects of dry and wet conditions on ecosystem functions and services seem to be predicted well by the model. However, the current beta-level model is not ready for use in planning and management. Research on the Nyando wetland is on-going (van Dam et al. 2011) and new data will be used to improve the CPTs. Currently, the CPTs linking the indirect and indirect drivers to the livelihoods activities (e.g., conversion to agriculture, vegetation harvesting) are based mostly on stakeholder and expert opinion. Through on-going PhD and MSc research, more empirical data on wetland ecology, hydrology and socio-economics are being generated. From hydrometric data collection, the description of the relationships between rainfall, river discharge, lake level, and the relative size of the perennial and seasonal wetland zones will be improved. Process models to describe these relationships are being developed and linked to the BN model (Khisa et al., unpublished data). Similarly, results from studies on household economics (e.g.
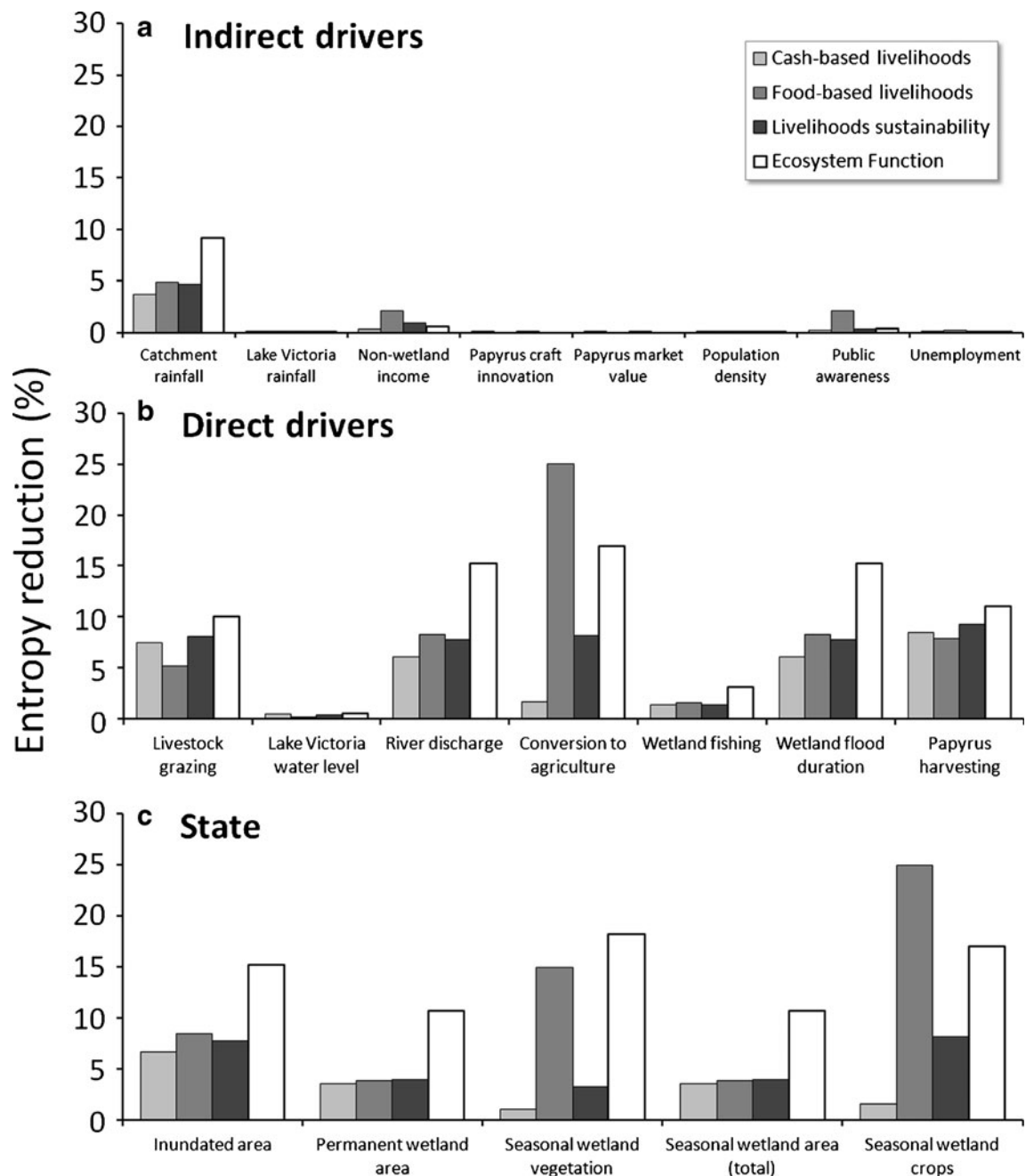
Fig. 6 Sensitivity analysis: the entropy reduction (the expected reduction in mutual information, measured in information bits) of the objective nodes "Ecosystem function" (*vertical axis*) and "Livelihoods outcomes" (*horizontal axis*) for various hydrology and exploitation-related decision nodes

data on household dependence on the wetland for income), governance and institutions will help to improve the model in terms of linking indirect drivers of change to livelihoods activities (Nasongo et al., unpublished data). This will enable the evaluation of policy scenarios, e.g. the impact of alternative livelihoods opportunities or regulation of wetland activities on wetland agriculture and papyrus harvesting. Similarly, data on livestock densities and plant diversity have been collected (Rongoei et al., unpublished data). Another area of

improvement is the quantification of ecosystem functions and services. Quantification of provisioning services is possible provided that regular monitoring of crop, fish and vegetation harvesting is done. Quantification of ecosystem functions, especially the biogeochemical and ecological functions, is more challenging because this requires more in-depth research and modelling.

One challenge for the present model are the spatio-temporal dynamics and feedback mechanisms of the

papyrus wetland driven by a combination of hydrology and livelihoods activities. Hydrology has daily (lake level), seasonal (rain) and longer-term (climate change) dynamics, while livelihoods activities have seasonal (driven by hydrology) and more long-term dynamics (based on population growth and economics). However, the BN model represents the wetland during a clearly marked period of time. Seasonal variability can be explored through seasonal settings for the input nodes and evaluation of the effect on the output nodes. This assumes that the output nodes for ecosystem function and livelihoods outcomes respond to changes in drivers at the same rate. This is not necessarily the case. People's responses to changes in flooding are rapid (within a season), leading to large differences in the extent of conversion to agriculture in different years. But the response of wetland biodiversity to flooding or cropping is slower. While a papyrus stand can grow back to maturity within one year, it is not clear if the full range of species belonging to the papyrus habitat will re-establish itself within that time. Similarly, the oxidation of the peat layer during cropping is likely faster than its formation.

Acceptance of the model as a tool for decision making can be enhanced by involving stakeholders in model development (Henriksen et al. 2007b). At the beginning of the workshop, most stakeholders were enthusiastic about the BN approach but had trouble understanding it. The DPSIR chains helped to overcome this problem as stakeholders easily understood and gave their opinions about variables and their relationships. The transformation of the DPSIR chains into a causal network (Niemeijer and De Groot 2008) was a useful step towards the construction of the BN. In this way, stakeholders' knowledge could be incorporated into the alpha-level model without troubling the stakeholders with the technicalities of BN models. For the alpha-level model, the CPTs were populated based on expert and stakeholder judgement. Feedback from the stakeholders led to not only updating of the CPTs, but also to substantial changes in the structure of the model nodes and links. The presence of multiple experts within each group reduced bias caused by individual preferences. Since then, the CPTs have been further improved as understanding of the relationships between the system variables improved. Model development thus is an iterative process of beta-level model (re-) formulation and stakeholder and expert consultation.

The current beta-level model is useful because it provides a framework for discussion and dialogue about options for sustainable management and provided an opportunity for stakeholders and experts to contribute knowledge to the research project. This framework can support policy and decision making as it allows incorporation of formal and informal knowledge about the functioning of the system and analysis of trade-offs between human and ecosystem well-being (which are some of the challenges identified for incorporation of

ecosystem services into decision making; Carpenter et al. 2009; De Groot et al. 2010). Nyando wetland does not have a special status (e.g., it is not a Ramsar site) and no integral management plan for the wetland presently exists. The immediate use of this BN model in supporting the policy process in Nyando wetland is therefore limited. However, the model structure based on DPSIR is sufficiently general to be used for other papyrus wetlands in the Lake Victoria basin. Seasonal flooding, conversion to agriculture, vegetation harvesting and a range of other livelihoods activities are common in papyrus wetlands (e.g. Ojoyi 2006; Namaalwa et al. 2013). In principle, the model is general and can be applied to other wetlands, provided that drivers, pressures, states and impacts are identified for the wetland under study.

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