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Tackling Complexity: Understanding the Food-Energy-Environment Nexus in Ethiopia's Lake Tana Sub-basin

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ABSTRACT: Ethiopia has embarked upon a rapid growth and development trajectory aiming to become a middle-income country by 2025. To achieve this goal, an agricultural development led industrialization strategy is being implemented which aims to intensify and transform agriculture, thereby boosting yields and, subsequently, economic returns. At the same time, the energy use which currently consists of more than 90% traditional biomass use is shifting towards increasing electricity production predominantly from large-scale hydropower plants, with the aim to improve access to modern energy sources. While the targets are commendable it is not clear that either all direct impacts or potential conflicts between goals have been considered. In this paper we evaluate and compare the impacts of alternative development trajectories pertaining to agriculture, energy and environment for a case-study location, the Lake Tana Subbasin, with a focus on current national plans and accounting for cross-sector interlinkages and competing resource use: the food-energy-environment nexus. Applying a nexus toolkit (WEAP and LEAP) in participatory scenario development we compare and evaluate three different future scenarios. We conclude that the two processes – agricultural transformation and energy transition – are interdependent and could be partly competitive. As agriculture becomes increasingly intensified, it relies on more energy. At the same time, the energy system will, at least in the foreseeable future, continue to be largely supported by biomass, partly originating from croplands. Two outstanding dilemmas pertaining to resources scarcity were identified. Water needed for energy and agricultural production, and to sustain ecosystem services, sometimes exceeds water availability. Moreover, the region seems to be hitting a biomass ceiling where the annual increments in biomass from all terrestrial ecosystems are in the same order of magnitude as biomass needs for food, fodder and fuel. We propose that a stakeholder-driven nexus approach, underpinned by quantitative and spatially explicit scenario and planning tools, can help to resolve these outstanding dilemmas and can support more consistent policy and decision making, towards improved resource productivities, lower environmental pressures and enhanced human securities.

KEYWORDS: Energy transition, agricultural intensification and transformation, WEAP-LEAP, participatory scenario development, Ethiopia

INTRODUCTION

Many countries in sub-Saharan Africa are currently undergoing rapid economic development commonly fuelled by two key processes: agricultural intensification and transformation (commercialisation, integration into world markets, etc), and energy transitions (moving beyond traditional biomass as the main source of energy, providing full access to electricity, meeting municipal and industrial demands). These transformative changes, in combination with population growth and changing consumption patterns, create increasing demand for natural resources and ecosystem services. Together with climate change, this in turn results in additional pressures manifested in resource degradation, whilst many millions of people continue to lack basic human (food, energy and water) securities. Development seems to be achievable only at the cost of the environment. A new approach is required to reconcile improvements in human securities and aspirations for better lives, with sustainable management of natural resources and ecosystems. In response to that quest, a nexus approach has been identified and discussed in a series of events and papers (e.g. Hoff, 2011, Bazilian et al., 2011, Howells et al., 2013) as a means to account for cross-sector interlinkages and competing resources use, in order to carve out an agreeable development trajectory for all stakeholder groups that not only meet human development targets but, at the same time, reduce environmental pressures.

Ethiopia has committed itself to reaching middle-income status by 2025. In order to achieve this ambitious goal, targets have been established for several sectors of the economy, including agriculture and energy. Building on a decade-long base of strong agricultural growth, Ethiopia's Growth and Transformation Plan (GTP) and the forthcoming Growth and Transformation Plan II (GTP II) targets cover a wide range of inputs (including improved seeds, fertiliser, mechanisation, land), energy use (hydropower), irrigation as well as conservation and land reclamation goals. For example, Ethiopia intends to increase cultivable land by 13%. This policy necessitates the conversion of grazing and/or forestlands into croplands. The country has also planned to increase irrigated land by more than 400% over the same period. Finally, in order to achieve dramatic productivity increases in agricultural output (30% increase in crop productivity of various crops) fertiliser use is expected to increase by approximately 100% (Ministry of Finance and Economic Development [MoFED], 2010). In addition to these traditional economic objectives of growth, GTP also outlines a National Resource Conservation Plan that seeks, among other things, to rehabilitate land and increase forest cover. These conservation targets are further detailed in Ethiopia's Climate Resilient Green Economy Strategy (CRGE) which seeks to achieve economic development in a sustainable way (Federal Democratic Republic of Ethiopia, 2012). While the targets are commendable it is not clear that either all direct impacts or potential conflicts between goals have been considered. For example, water for irrigation may put pressure on the ability to generate hydroelectric power. Understanding the conflicts is particularly important for understanding welfare impacts, coping mechanisms, and environmental feedback effects at the local level.

The aim of the paper is to evaluate and compare the impacts of alternative development trajectories pertaining to agriculture, energy and environment for a case-study location, the Lake Tana and Upper Beles regions in Ethiopia, with a focus on current national plans and accounting for cross-sector interlinkages and competing resource use. More specifically, the objective is to quantify cross-sector interlinkages and resource dependence of the energy and agriculture sectors and related environmental impacts. Moreover, stakeholder perceptions on the outcomes of different development pathways are assessed. Thirdly, the objective is to develop, test and apply a nexus toolkit in joint dialogue with stakeholders.

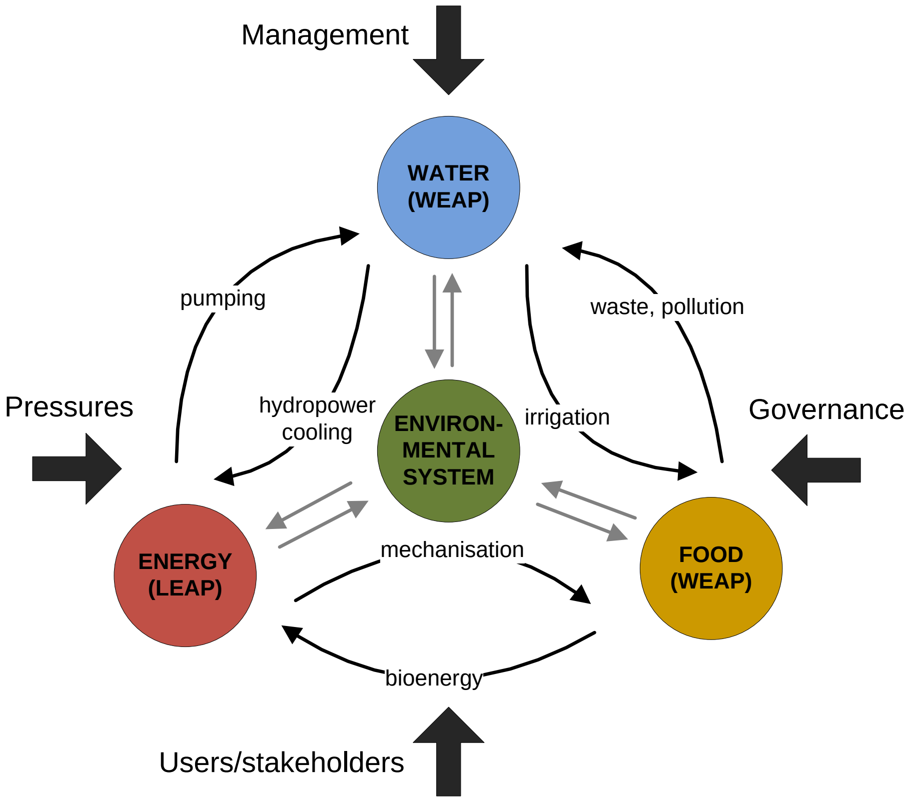
BACKGROUND

The word nexus simply means a connection or series of connections linking two or more things. Lately, the water-energy-food nexus has gathered a lot of attention internationally. What could be said to be novel about this concept is the focus on human securities and aspirations, and the bilateral nature of sector linkages. A wide array of conceptual models on the nexus has been produced. One way to illustrate these interlinkages is provided in Figure 1, which illustrates flows or impacts between sectors and interactions with the environmental systems. These inter-linkages are also impacted on by various pressures and drivers, governance, management and stakeholder actions.

The nexus concept emphasises interlinkages among and between environment (natural resources and ecosystems) and human development (food, energy and water security), and the need for coordination and integrated management and governance across sectors. For implementation of a nexus approach to be demand-driven, it needs to support and be 'mainstreamed' into ongoing processes, such as national development plans and strategies as well as institutions further connected to resource user groups.

These principles have been laid out in Hoff (2011) and subsequently elaborated in Mohtar and Daher (2012), Bleischwitz et al. (2012), ERD (2012), ADB (2013), Howells et al. (2013), Ringler et al. (2013), Rodriguez et al. (2013) and Flammini et al. (2014). Initial nexus assessments have been undertaken in various case studies around the world, e.g. in Burkina Faso (Hermann et al., 2012), Mauritius (Welsch et al., 2013), and USA (DoE, 2014).

Figure 1. Illustration of interlinkages within and between sectors and the environmental system.



Food, energy and environment – The situation in Ethiopia today

Out of the top ten fastest growing economies in the world since 2011 seven are African. With an average annual real GDP growth rate of 8.1%, Ethiopia ranks seven (The Economist, 2011). However, this figure does not tell the full story. The agriculture sector, which in 2010 accounted for 46% of national gross domestic product (World Bank, 2013), remains largely based around small-scale subsistence farming characterised by low levels of inputs and limited irrigation development. The energy sector continues to be predominantly biomass-based, with 88%[1] of the population lacking access to electricity (World Bank, 2009) and 84 and 99% of urban and rural households depend on biomass as their primary cooking fuel (Mengistu and Johnson, 2013). As such, it may be argued that development in Ethiopia is bypassing the rural population, as urban centres grow both in size and economic activity.

In order to translate impressive economic growth figures into development for a broad swath of the population, the Government of Ethiopia launched the Growth and Transformation Plan (GTP) in 2010 followed by the Climate-Resilient Green Economy (CRGE) strategy in 2012 (MoFED, 2010; Federal Democratic Republic of Ethiopia, 2012). These two documents claim to set out a pathway for Ethiopia towards modernising the economy and achieving the goal of becoming a middle-income country in a sustainable, climate-compatible manner by 2025.

[1] This is contrary to the ratio of 41% typically given by EEPCo (Ethiopian Electric Power Cooperation), which is based on the number of people within the reach of low-voltage distribution lines, not the actual number of consumers connected to the grid.

The five-year GTP builds on the government's previous five-year development plan, the Plan for Accelerated and Sustained Development to End Poverty (PASDEP), emphasising ambitious goals around agricultural and rural development, industry, infrastructure, social and human development, good governance and democratisation (MoFED, 2010: 1). For example, the GTP envisages increasing crop productivity by 30%, sugar production by 600% and power generation by 300% over a period of only five years, which in effect means an acceleration of several of the past and current trends in consumption and production, resource use, and environmental pressures, and which may yield unexpected results in the long term, e.g. related to resilience of the economy, society and environment, the basis for key production factors.

Meanwhile, the CRGE initiative was developed in response to growing concerns over climate change and how it might impact the country's ambitious development plans. It attempts to set out a pathway to 2030, in which Ethiopia can protect itself from and reduce the adverse effects of climate change by pursuing green growth, based on reduced greenhouse gas (GHG) emissions and sustainable use of natural resources (Federal Democratic Republic of Ethiopia, 2012: 1). Taking a sectoral approach, the CRGE initiative sets out over 60 initiatives that would allow the country to achieve its development goals whilst reducing GHG emissions. These 60 initiatives fit within four key pillars (Federal Democratic Republic of Ethiopia, 2012: 2):

- Improving crop and livestock production practices for higher food security and farmer income while reducing emissions.
- Protecting and re-establishing forests for their economic and ecosystem services, including as carbon stocks.
- Expanding electricity generation from renewable sources of energy for domestic and regional markets.
- Leapfrogging to modern and energy-efficient technologies in transport, industrial sectors, and buildings.

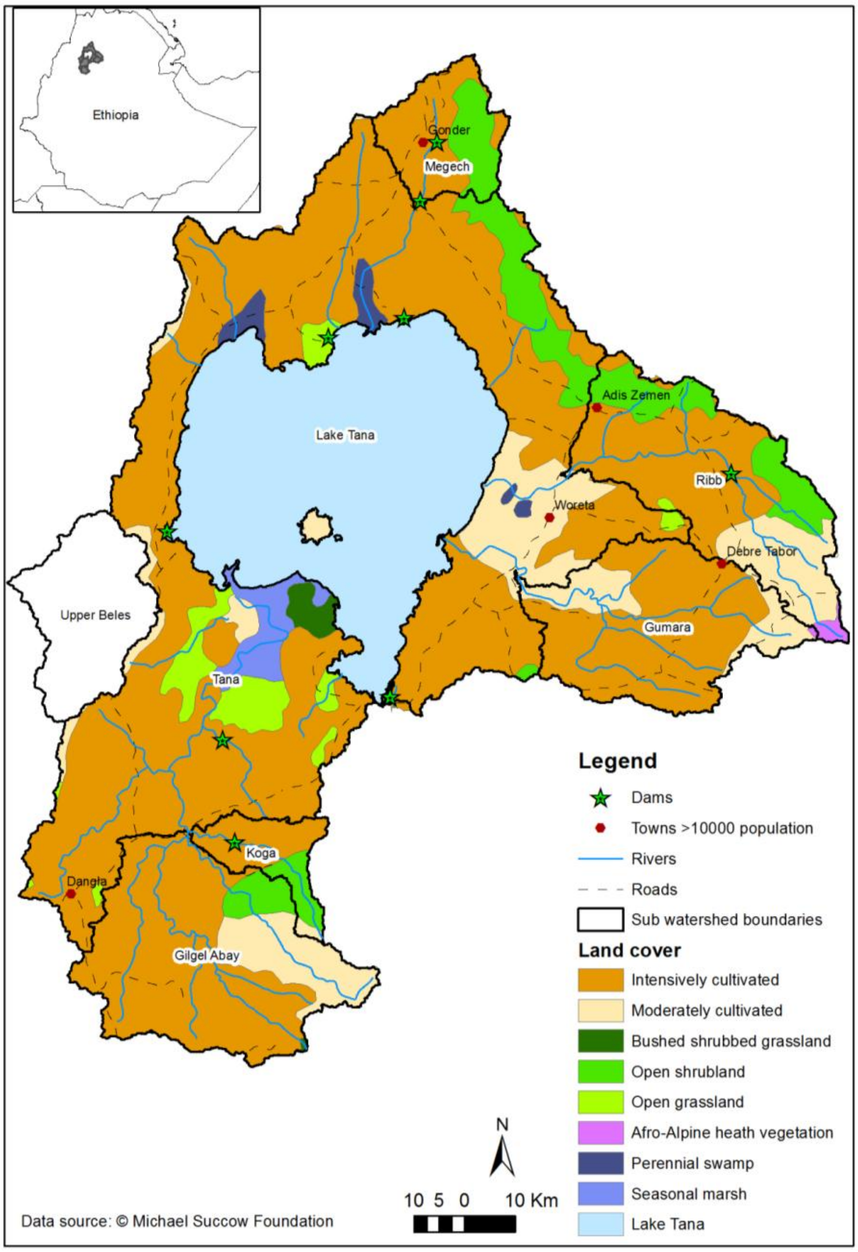
But whilst the country's development goals appear impressive, its ambitious national plans raise a number of concerns. Political opposition in Ethiopia remains weak (Kefale, 2011), leaving limited opportunity for democratic debate over the plans and the potential for alternative development pathways and framings of sustainability. Meanwhile, the rapid expansion of hydropower and irrigation infrastructure has heightened tensions with neighbouring countries that depend extensively on water resources originating from the Ethiopian highlands for household, agricultural and industrial consumption. Yet it also signals a changing geopolitical climate in which Ethiopia is becoming an important force in the Horn of Africa Region (Verhoeven, 2011; Rahmato, 2011). Given these related concerns, it is unlikely that all the goals of the GTP and the CRGE can be met simultaneously, particularly when following a conventional sectoral approach.

Case-study description – Lake Tana and Upper Beles

In our study, we focus on the Lake Tana (and Upper Beles) Subbasin, i.e. the uppermost part of the Blue Nile Basin. In our analysis, we first interpret national plans and goals (from the GTP, CRGE, etc) and then downscale them for the case-study region, shown in Figure 2. The Lake Tana Subbasin is situated in Amhara National Regional State in the northern part of the Ethiopian Highlands and consists of four administrative zones split into 21 *woredas* (districts) (IFAD, 2007).

With an annual mean surface area of 3156 km^2, Lake Tana is the largest lake in Ethiopia and one of the largest in Africa. It stretches roughly 84 km from north to south and 66 km from east to west, lies at 1840 metres above sea level (masl) and reaches a maximum depth of 14 m. It is a key source of the Blue Nile and has 40 tributaries (rivers and streams), of which the Gilgel Abay, Ribb, Gumara and Megech rivers account for 93% of the total inflow (Setegn et al., 2008). The region's high ecological value and unique wetlands, which attract many tourists, lie behind the recent application to UNESCO for a Lake Tana biosphere reserve (zur Heide, 2012).

Figure 2. Land-use map of Lake Tana (upper Beles) Subbasin.



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Key cities within the region include the historic city of Gondar to the north of the lake and Ethiopia's second biggest city and regional capital, Bahir Dar, on its southern shoreline. The region's population is estimated at around 20 million (25% of the country's total), with 16% living in urban areas and 84% living in rural areas. The regional economy is largely based around subsistence agriculture and focused on crop production and, to a lesser extent, livestock. Other livelihood activities include fishing, blacksmithing, carpentry, tailoring and weaving, and sale of goods such as papyrus and souvenirs. Of the population in the greater Amhara Region, 43% live in extreme poverty, and livelihood systems, particularly in rural areas, remain very traditional. Driven by a lack of options, poverty leads people to deplete natural resources through overfishing, deforestation to meet wood-fuel demand, papyrus reed harvesting and farming on slopes and in the wetlands during the dry season (zur Heide, 2012: 45).

In line with the GTP and CRGE national plans, there have been a number of recent developments in the Lake Tana Region related to intensifying and transforming agriculture and energy transitions. This includes, for example, the construction of a number of irrigation dams, which allow some farmers to plant a second and, sometimes, a third yearly crop, which allows them to increase their share of cash-crops. Following the national plans, significant growth in the use of tractors and fertilisers is expected, as agriculture is intensified (Federal Democratic Republic of Ethiopia, 2012). These trends cause additional energy demand for pumping of water, production of fertiliser, machinery use, etc.

Meanwhile, the completion of the Tana Beles transfer and hydropower plant in 2010 offers some hope of an energy transition in the region, together with national plans, which predict 100% grid coverage as early as 2020. Nonetheless, grid *coverage* may be substantially different from grid *access,* and historical trends will need to change substantially in the coming years if this target is to be achieved. On the issue of energy demands for cooking, it is assumed that efficient stoves, or those which use alternative fuels, will replace conventional wood stoves in greater numbers and that animal dung which may otherwise be consumed directly for cooking, is instead redirected into digesters for the production of biogas. Bioethanol (primarily for export) may also be produced in the region from sugarcane, adding to competition for agricultural land and water.

At the same time, there are a number of trends within the region that add increasing pressure to the development process. Between 2000 and 2010, the population of the Lake Tana Region increased at an average rate of 3.2% per annum, slightly faster than in the rest of the country. This correlates with greater urbanisation as the urban centres of Bahir Dar and Gondor develop. Land degradation is a persistent problem and induces topsoil loss and increasing siltation of the lake, with subsequent reduction in water-storage capacity of the lake. A large amount of biomass, such as manure and crop residues, is being removed for cooking purposes removing nutrients and organic matter from the soils with resulting soil degradation. Meanwhile, excessive recession farming in degraded wetlands, overgrazing and fuel-wood collection increasingly threaten wetlands and the few remaining forests. The low access to modern energy sources means that a lot of time is spent gathering fuel-wood, and health-related problems occur from traditional biomass burning. If traditional biomass continues to be the main source of energy, charcoal and fuel-wood prices are likely to increase, making it even more attractive to sow water-intensive eucalyptus for extra income. There are some associated environmental challenges including land degradation, periods of low lake levels and threats to specific habitats (e.g. forests and wetlands).

METHODS

The intrinsic complexity of the nexus approach shows the need for stakeholder engagement to illustrate perceptions connected to different actors in the system. The diverging views among stakeholders at different scales coupled with stakeholders representing different sectors needs to be considered while assessing opportunities for integrated approaches such as the nexus. In this study, we addressed the above listed challenges and opportunities in a systematic nexus analysis, i.e. engaging stakeholders and accounting for interlinkages between sectors, for three different plausible development trajectories for the region. The analysis focused on 1) agricultural intensification and transformation, and 2) energy systems transition, and related environmental impacts as they may play out in the Lake Tana Subbasin. Three development trajectories were defined and explored for the Lake Tana/upper Beles Sub-basin jointly by stakeholders and scientists. In a Story And Simulation (SAS) approach (Alcamo, 2001), initial narratives or qualitative scenarios were developed and translated into quantitative scenarios analysed in a nexus toolkit in an iterative process as described in this section.

A participatory scenario approach between stakeholders and scientists

A stakeholder mapping exercise was conducted in the initial face of the project to group stakeholders based on their link to the nexus. The stakeholder map was used to identify relevant persons to be interviewed. Semi-structured interviews were conducted with 30 persons to elicit information pertaining to their specific expertise to substantiate the initial scenario narratives. The interviews included a broad representation of stakeholders covering public and civil society including research institutes as well as government institutions from local to national levels. These included, for instance, the Bureau of Agriculture, Bureau of Energy and Mines, Bureau of Environmental Protection, Land Administration and Use, the Abbay Basin Authority, the Ethiopian Electric Power Corporation, the Amhara Regional Agriculture Research Institute, Bahir Dar University, and the Organization for Rehabilitation and Development in Amhara.

Based on these interviews, we developed a first scenario called 'business-as-usual' (BAU), in which all of the current resource management practices remain more or less the same, or continue to evolve in the same way as has been observed historically, but including an increasingly larger population sharing these resources. To provide contrast for this baseline development, a second scenario was generated based on the national policy framework (predominantly the CRGE and GTP plans). Stakeholder workshops were conducted to invite input from people who participated in the interviews on the two scenario narratives formulation. As a result, the interaction between stakeholders and scientists generated a revised set of narratives as well as a clearer understanding among the scientists on which data to include in the models. Thereafter, the researchers applied the nexus toolkit on the case study area for the two scenarios. In consecutive workshops, modelling was analysed and critiqued by the stakeholders, which led to a refinement of data and assumptions in an iterative process, until the results were deemed credible.

The stakeholder workshops were facilitated using the SWOT (Strengths-Weaknesses-Opportunities-Threats) analysis approach. The analyses were expanded to include questions aimed at identifying potential winners and losers under each scenario. The results from these SWOT analyses thus provided an assessment of the implications for different stakeholder groups under each development trajectory. Based on these assessments, a number of outstanding dilemmas, also under the ambitious national plans scenario, were identified. As a response to this, the stakeholders defined a third scenario (building on the National Plans scenario), which was initially termed the National Plans ++ scenario to indicate that it supports and adds to the national policy framework. Since this scenario addresses issues related to multi-sectoral use of water and biomass specifically, this scenario is hereafter called the 'nexus' scenario. Finally, an impact assessment using a SWOT analysis was done. The iterative process contributed to strengthen the relevance of the narratives for stakeholders within the system.

Scenario descriptions

Business-as-usual (BAU) scenario

In the BAU scenario the agriculture sector continues to develop slowly and remains dominated by small-scale farming, which is characterised by low inputs and declining productivity due to continued soil degradation. Agriculture tends to expand horizontally into grazing lands and wetland areas, although this expansion is rather limited in this specific area of Ethiopia, since most land is already used for cropping. Consequently, energy needs for agriculture remain low, and most of the biomass is removed from the fields after the harvest and used as fodder or for cooking purposes.

Most rural households remain unconnected to the national electricity grid, and traditional biomass will continue to be the major energy source in the region, supplied from wood-fuel, (including branches, leaves and twigs, or BLT), agricultural residues, cow dung, and charcoal, collected from farmland, homesteads, marginal areas, and communal land. Due to the increasing population, low grid connectivity and a low replacement rate of current inefficient cook-stoves, the demand for biomass will continue to increase. As a result, an expansion of wood-fuel tree plantations (e.g. eucalyptus) on farmlands can be expected, displacing food crops. As upstream irrigation development continues, albeit slowly, this may slightly decrease water availability downstream.

Continued extensive grazing, biomass-based cooking and expansion of farmland into other habitats, such as forests and wetlands, continue to result in undesirable environmental impacts (e.g. soil erosion, siltation and habitat destruction and fragmentation). No restrictions on water use for irrigation and hydropower production are imposed, and fertiliser use is low but unrestricted.

National Plans (NatPlans) scenario

In this scenario the agriculture sector develops quickly and by 2030 most farms are expected to operate as commercial enterprises, managed more intensively than today. Major irrigation plans will be successfully implemented, resulting in an infrastructure of drip-and-sprinkler irrigation in large parts of the area. Fertiliser use is high and many farms become mechanised. As a consequence, horizontal agricultural expansion is halted, and agriculture becomes more dependent on energy inputs for irrigation, tractors, and fertiliser production. Because of irrigation, farmers can harvest two to three consecutive crops per year. The concurrent commercialisation and increase in income will enable farmers to further invest in their farms. Issues with low soil organic matter persist, because of a large outtake of crop residues and manure for cooking and fodder, although the number of cattle heads is lower in this scenario.

Despite a successful cook stove replacement programme and more households being connected to the national grid, the demand for wood-fuel remains high due to high population growth. This biomass is provided by eucalyptus tree plantations and some other trees, such as acacia trees, which are used for charcoal production. Bioethanol will be produced from the sugar industry (as an agro-processing industries by-product). Biogas digesters are constructed and solar and wind capacity will be developed, while Ethiopia's geothermal potential continues to play a role in the power system.

Just like in BAU, biomass-based cooking and expansion of farmland into other habitats, such as forests and wetlands, result in undesirable environmental impacts (e.g. soil erosion, siltation and habitat destruction). In addition, the use of fertilisers and irrigation water is higher compared to BAU, and remains unrestricted.

Nexus scenario

The Nexus scenario assumes many of the same developments as the National Plans scenario, with a few additions and modifications. In the Nexus scenario, biomass use for fodder and fuel is being restricted, which positively impacts on soil conditions, and consequently increases in food production and sediment loss from croplands.

In the energy sector, an even larger share of the total energy supply is assumed to be provided from electricity, for residential cooking and other uses, as well as for other energy-consuming sectors. Specifically, in this scenario we assume that among biomass-consuming households, all traditional wood-stoves have been replaced by efficient biomass-fuelled stoves. At the same time, the number of households using biomass as their primary cooking fuel continues to decrease in favour of alternative fuels such as electricity and LPG.

Maintaining the water level of Lake Tana is made the highest priority in terms of water allocations, prior to both irrigation upstream and hydropower generation from the Tana-Beles hydropower scheme.

Quantitative analysis using SEI's nexus toolkit

Historical data are gathered for the year 2010,[2] with scenarios starting in 2011 and then following the three development trajectories until 2030. A nexus toolkit based on a water and biomass model called the Water Evaluation And Planning (WEAP) system dynamically linked with an energy and climate model called the long range energy alternatives planning (LEAP) system, was applied to quantitatively assess these scenarios and in particular the interlinkages ('nexus') between and within natural resources, agriculture and the energy systems, and related environmental impacts. On request, the authors can provide further details of the toolkit and of how the narratives were translated into scenarios, including the data and key assumptions used in the models.

Large variability in annual rainfall between years, and resulting fluctuations in water availability, mean that the results were in some cases analysed for 'wet', 'intermediate' and 'dry' years. Each year is deemed to be dry/wet if the average availability of the Tana Beles power plant in that year falls within the lowest/highest third of availability across all years in a given scenario. This means that there may be an unequal number of years in each category.

RESULTS

Quantifying interlinkages between sectors and resources

A comparison of food and energy production in the three development pathways shows that different land and water management practices do indeed significantly impact on the total amounts of commodities produced, as well as related environmental disturbances as exemplified by low water levels of the Lake Tana (Table 1). While food production is maximised in the Nexus scenario, hydropower production is substantially lower compared to the other two scenarios because maintaining the Lake Tana water level was given highest priority. While the National Plans scenario describes an intermediate level of food production coupled with high hydropower output from the Tana Beles station, the goal of maintaining the water level in Lake Tana appears to be heavily compromised. Finally, continuing along a business-as-usual development track results in low food production, which, because of rapid population growth, means that food production per capita would be lower than the current levels.

Table 1. Food and hydropower production, and environmental impacts (lake level) for the three different development trajectories.

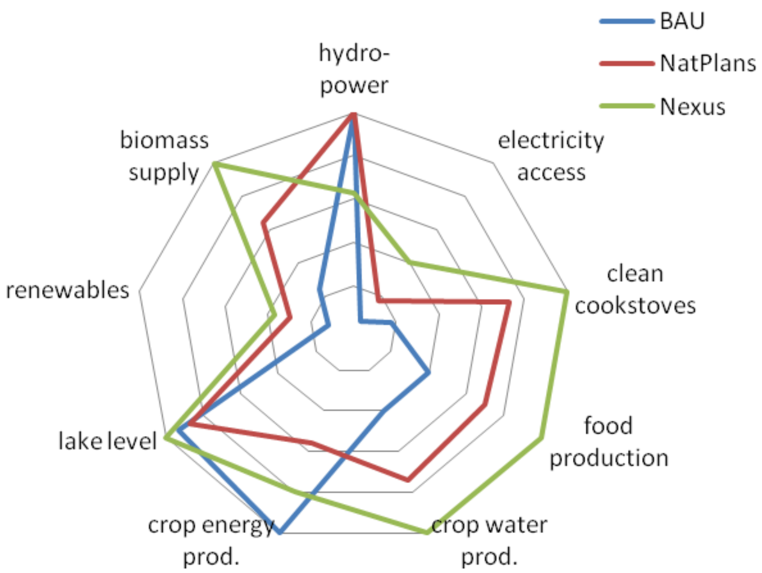
Scenario	Food production (tons)	Hydropower production (GWh)	Percent of the year with a water level below 1785 masl
BAU	790,000	1100	18
National Plans	1,510,000	1100	23
Nexus	2,130,000	610	12

The total food and energy production and also the resource-use efficiency entailed in the production of these commodities vary. To enable a comparison among the three development pathways, we selected three indicators for each sector – food, energy, and environment – and assigned them a score from zero to one (the latter indicates that a sector's needs are best satisfied among the scenario options). These

[2] In the energy model built using LEAP, historical data go back to the year 2000.

indicators are displayed together in Figure 3. In general, the Nexus scenario receives a high rating for indicators pertaining to all three areas (food, energy, environment) compared to the other two scenarios, except for hydropower production. In National Plans the water level and the biomass targets are compromised, while in BAU food and energy targets are not met, with biomass out-take of the system remaining large.

Figure 3. Total production of food and energy, resources use efficiency and related environmental impacts for the three different development trajectories.



Notes:

Food: 'food production' refers to total food produced in the area; 'crop water prod' is the crop water productivity, i.e. yields per unit water consumed (evapotranspired); 'crop energy prod' is the crop energy productivity, i.e. yields per unit energy spent in the production process.

Energy: 'hydropower' is the total production of hydropower; 'electricity access' is the total amount of the population connected to an electrical grid; 'clean cook-stoves' is the penetration of the cookstoves replacement programme.

Environment: 'biomass supply' is the ratio between biomass supply and biomass demand; 'renewables' is the amount of non-wood renewables of the total energy supply; 'water level' is the amount of time that the water level in the lake is above the critical lowest level.

Maintaining the environmental water requirements for Lake Tana leaves less water for other uses

Maintaining the water level of Lake Tana is important for navigation, for the fisheries industry, for the *Negede* people (i.e. the people whose livelihoods are based around making boats and baskets from papyrus), for tourism and not least for sustaining a healthy lake ecosystem. A critical minimum water level for navigation is defined as 1785 masl. The water level of the lake follows a seasonal pattern with an amplitude of around 3.5 metres, in which the largest risk for dropping below the critical lake level occurs during April-June just before the onset of the wet season. Looking at the consequences on the water level of the lake of upstream water withdrawals and regulations of outflows of the Lake Tana for hydropower generation, we find that the water level is below the critical level for around two months per year in BAU, and that this period increases to three months in the National Plans scenario (Figure 4a). The annual variations are large. During wet years the water level never drops below the critical level in the national plans scenario, while during dry years, the corresponding period is five months and the lowest level is around 0.7 m below the critical level (Figure 4b). In the nexus scenario the highest priority is assigned to maintaining the lake level above the critical level.

Figure 4a. Average annual fluctuations in the Lake Tana water level for the three scenarios.

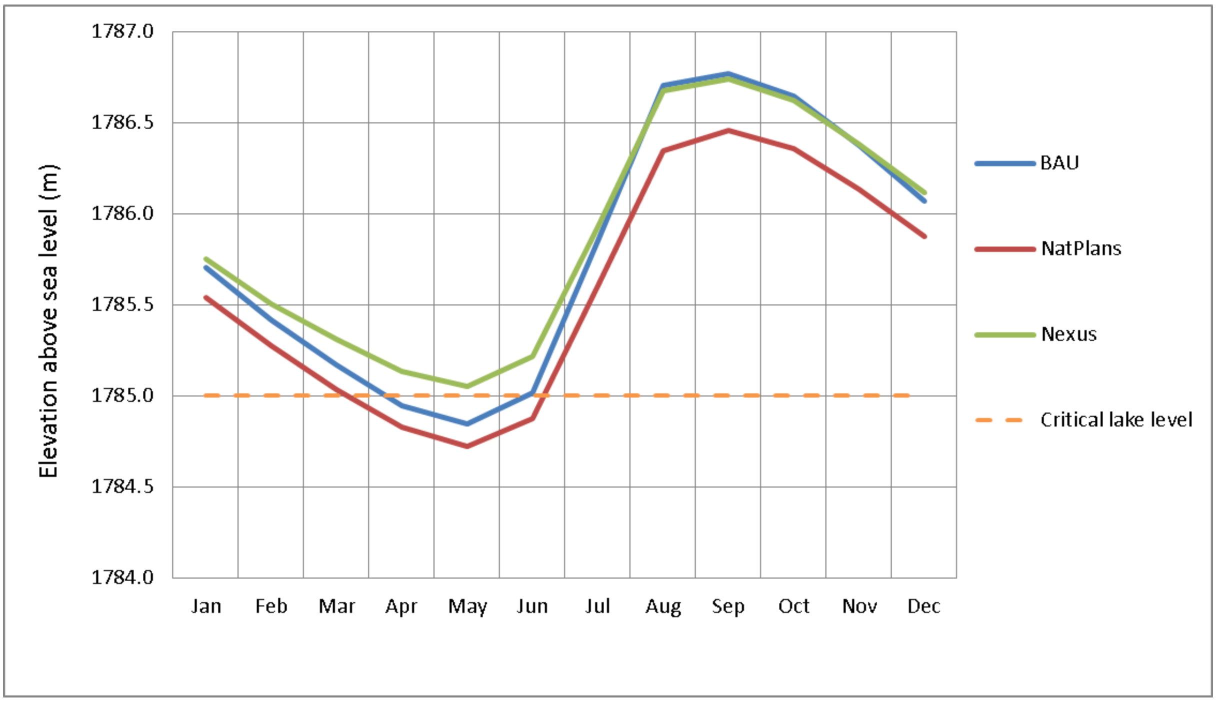
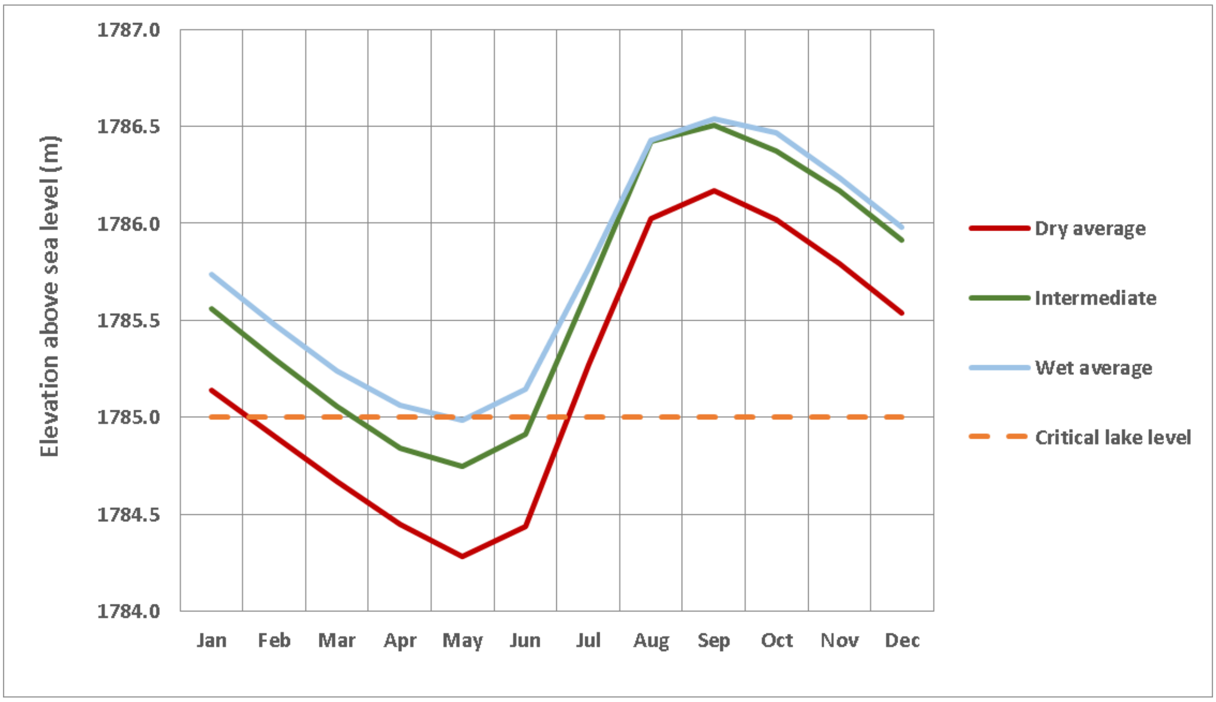


Figure 4b. Annual fluctuations in the Lake Tana lake level for three hydroclimatic years: 'dry', 'intermediate' and 'wet'. National plans scenario only.



Because of upstream water regulation in the National Plans and Nexus scenarios, in combination with improved soil water retention, the intra-annual variations in stream flow differ from BAU. Thus, the streamflow is more evenly distributed throughout the year compared with BAU in both the National Plans and the Neuxs scenarios. In our study, we show a reach of the Gumara River (see Figure 2 for its geographic location) downstream of the Gumara Dam. When the dam is present (i.e. in the National Plans and Nexus scenarios) water is stored during the rainy season and released during the dry season, causing a less variable flow of water from month to month when compared to the unregulated condition, although the total annual streamflow is lower.

Lower inflows into Lake Tana in the National Plans and Nexus scenarios could possibly result in less hydropower production from the Tana Beles hydropower plant. However, this is only observed in the Nexus scenario, in which hydropower production is reduced by nearly 50% (Figure 5a). In the National Plans scenario however, the Lake Tana buffers the water availability for hydropower production within the year, so that while power production is lower during the dry season compared to the wet season, it follows the same pattern as the BAU (Figure 5a). In the Nexus scenario, hydropower production ceases from March until July in order to maintain the water level in the lake above the critical level. At the onset of rains in July, the lake quickly overflows into the Blue Nile River. This results in a 'loss' of water for hydropower production. In the National Plans, it takes time for the lake to fill up again, and therefore less water leaves the system via the Blue Nile River or is lost, from a hydropower production point of view. To summarise, while the hydropower production is maintained in the National Plans compared to the BAU despite higher consumptive water use upstream, the Lake Tana level and possibly environmental flow requirements in the Blue Nile River become highly compromised in this scenario. On the other hand, while the Lake Tana water level is maintained, hydropower production is nearly halved in the Nexus scenario.

Lastly, focusing on different classes of hydroclimatic years, it is apparent that hydropower production is likely to vary between years (5b). Base production during the dry season remains the same for all years, but higher production levels are expected during the rainy season for wet years compared with dry years. Ambitious capacity expansion plans included in the National Plans scenario for Ethiopia as a whole mean that, even with restrictions on many hydropower plants, it appears there will be sufficient electricity generation to meet rising domestic demand and still export electricity to neighbouring countries. However, in the Lake Tana Region there continues to be a net import of electricity to meet the combined demands of households and commercial and industrial sectors, which are expected to grow with GDP.

Biomass continues to play an important role in energy transition

In the BAU scenario the predominant source of residential energy use is traditional biomass, which includes wood-fuel, crop residues, cow dung, branches, leaves, and twigs (Figure 6). By 2030, the use of traditional biomass for cooking is predicted to rise by around 50% in this scenario predominantly due to population expansion. Despite an ambitious programme to electrify the country, biomass is also predicted to remain the main source of energy for residential purposes in 2030 in both the National Plans and the Nexus scenarios (Figure 7). Indeed, this would appear to be the rationale behind national plans to replace traditional cook-stoves with more fuel-efficient stoves. A difference between National Plans and Nexus is a higher degree of electrification assumed in Nexus, as well as lower biomass use due to very successful implementation of the cook-stoves replacement programme.

There are marked differences in the energy consumption patterns of rural and urban households. In rural areas, the main source of fuel is wood, while in cities charcoal and electricity are other important sources of fuel, though fuel-wood is still dominant. It is worth noting that the degree of electrification in the rural areas is very low, which makes these areas dependent on either biomass or off-grid solutions to meet energy demands.

Figure 5a. Average hydropower produced by the Tana Beles hydropower plant in each month, during entire scenario period.

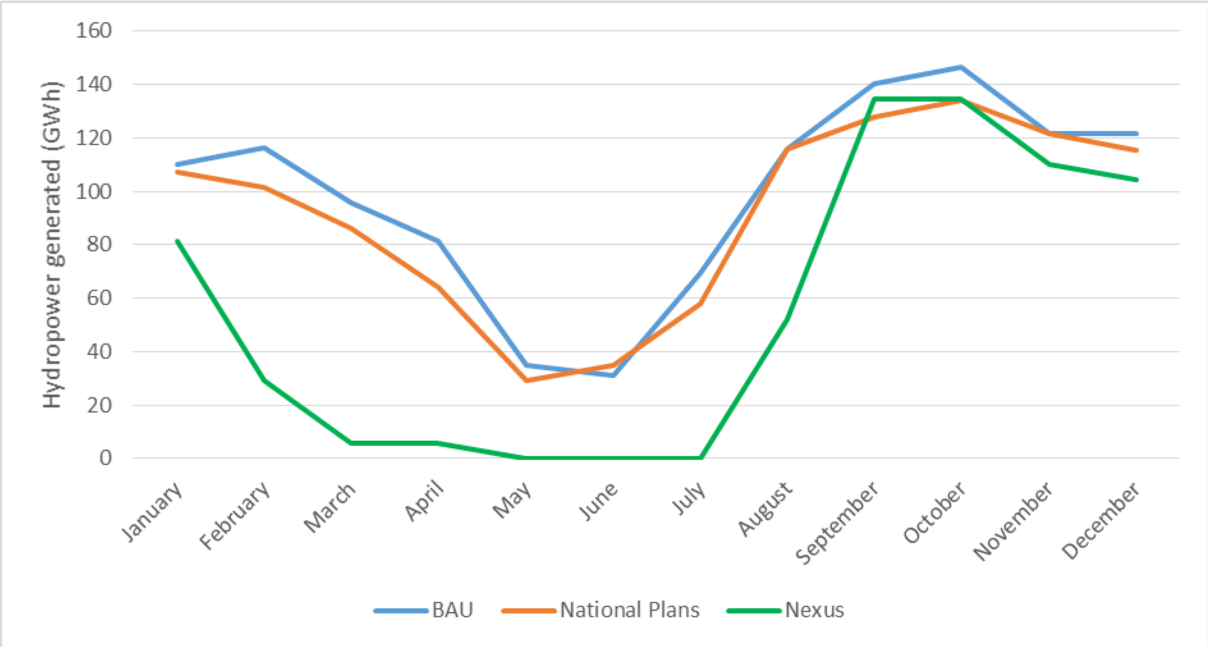


Figure 5b. Average monthly capacity factor of the Tana Beles hydropower plant for the National Plans scenario under different hydroclimatic years (dry, intermediate and wet).

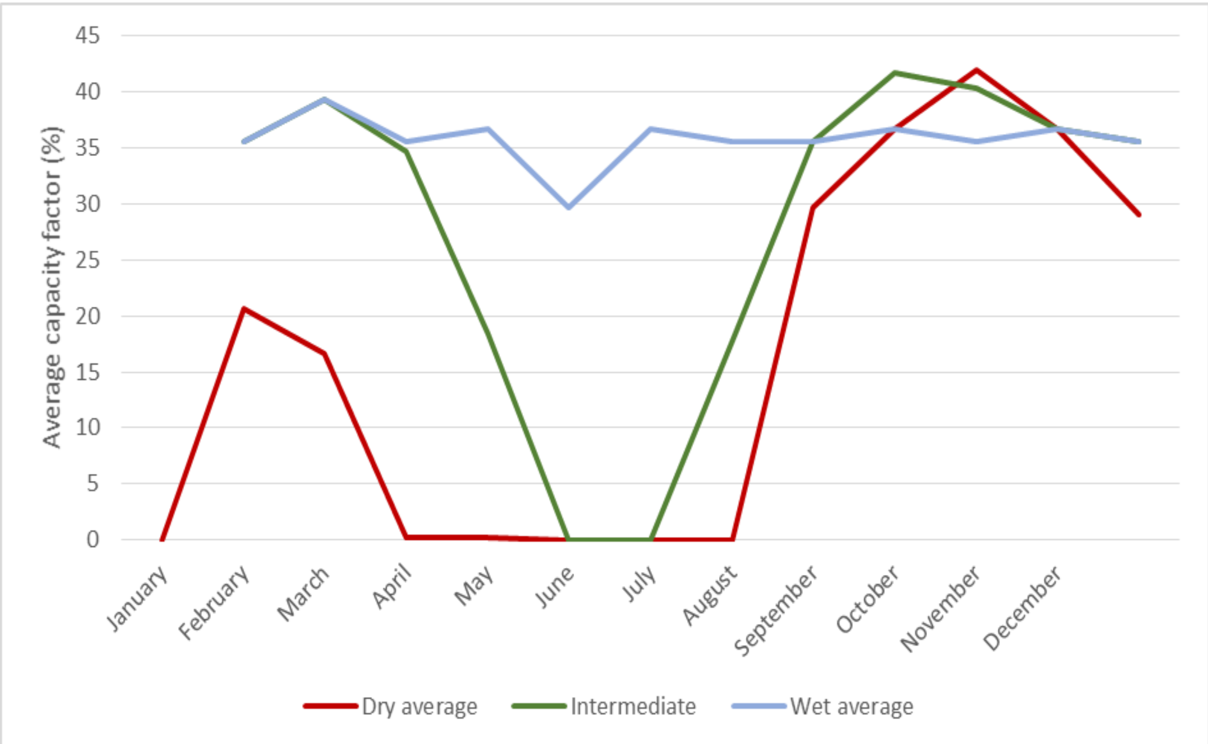
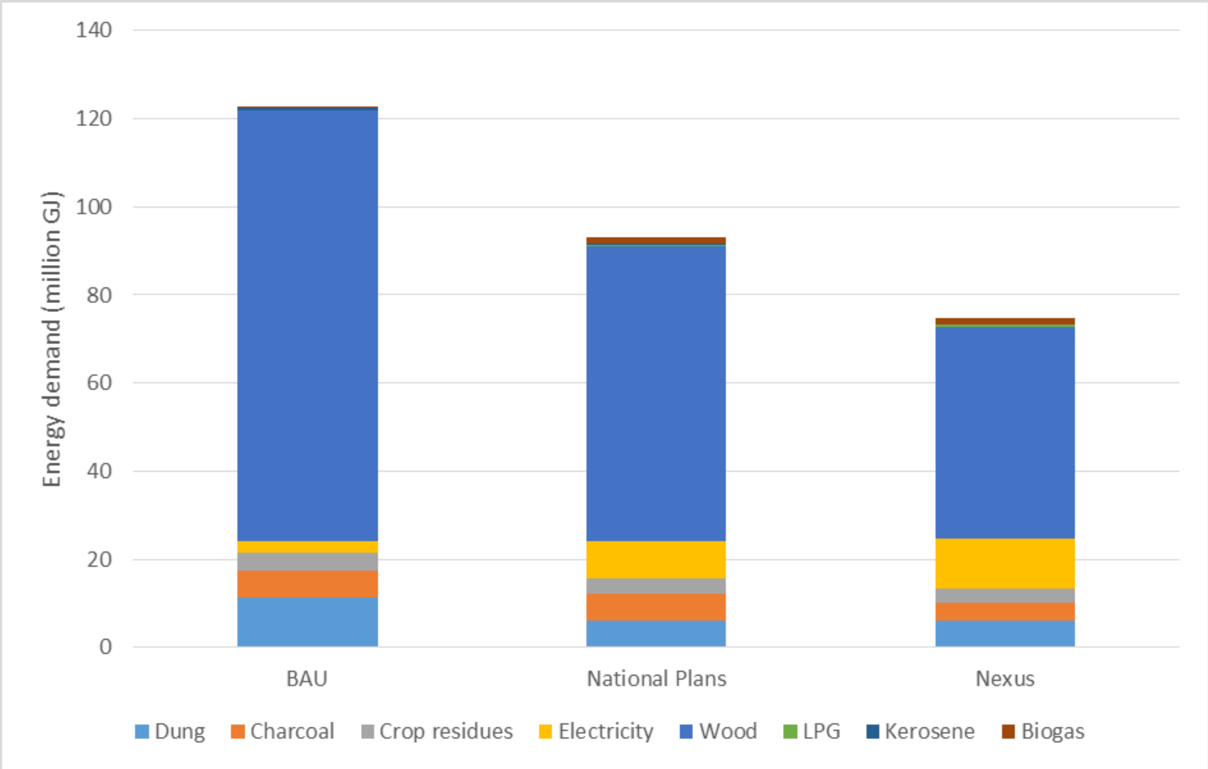


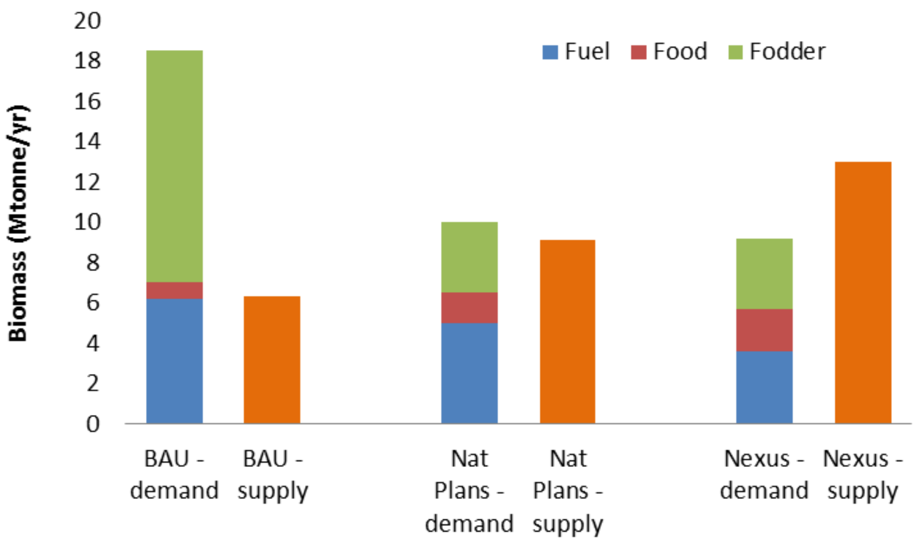
Figure 6. Household fuel energy demand in 2030, for all scenarios.



Notes: Full implementation of fuel-switching measures for household cooking, as described by the Growth and Transformation Plan and the Climate Resilient Green Economy plan which are included in the National Plans scenario, will be incorporated by 2030. Meanwhile, rising shares of electric stoves (as well as use of electricity for non-cooking purposes, not shown above) are assumed to be driven by the expansion of the national electricity grid, and by rising economic prosperity. Any rising shares of alternative fuel stoves described in the National Plans scenario is assumed to displace wood-fuelled stoves, while shares of highly efficient woodstoves continue to increase among those households which continue to use wood as their primary cooking fuel.

The implications of extensive use of biomass for energy purposes include deforestation and a depletion of soil organic matter and nutrients from agricultural soils. Figure 8 gives an indication of the order of magnitude of biomass use for fuel, food and livestock fodder purposes (demand) in relation to biomass production (net primary productivity, or supply). The analysis indicates that in the BAU scenario, the predicted use of biomass is more than twice that of biomass produced by 2030, which is clearly unsustainable. Productivity is assumed to be higher on croplands in the National Plans compared with the BAU, and both fodder and fuel needs for biomass is lower (the former is caused by a large reduction in livestock; see assumptions and data). In this scenario the net use of biomass is more or less the same as the annual increment in new biomass. Because biomass use from croplands continues unrestricted in the National Plans scenario, albeit at a lower rate due to reduced demand, it is still likely to hamper agricultural transformation by reducing soil productivity. Finally, in the Nexus scenario, use of biomass from croplands is restricted and a certain part of the croplands is allocated towards fodder production. However, as shown in Figure 7, despite the concurrent reduction in cropland area from fodder production, the resulting loss is superseded by higher cropland productivity from improved soil conditions. It is only in this scenario that the total annual increment in biomass is higher than biomass use.

Figure 7. Biomass use compared with net primary production of biomass from all ecosystems in the region for all scenarios. No numbers on fibre use could be found and this variable is therefore omitted from the demand of biomass.



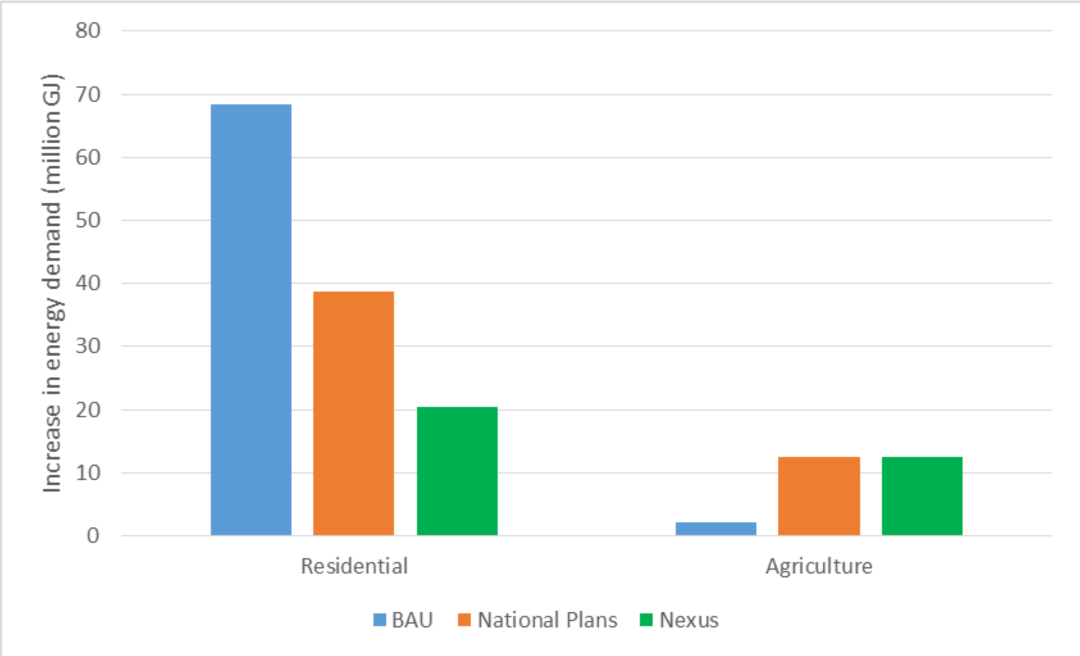
Agricultural intensification and transformation requires water and energy

The total amount of food produced in the case-study region is expected to increase in the future in all scenarios. Assumptions on crop growth are made for each scenario based on data generated from different management practices provided at Woreda level by agricultural experts. In the Nexus scenario, yields are expected to quadruple relative to 2010, based on improved land and water management, i.e. irrigation availability enabling two to three crops per year, high fertiliser inputs and the retention of soil organic matter through, for example, composting and agro-forestry practices. Compared with the National Plans scenario, the Nexus scenario restricts the use of organic matter from croplands. The net result is an increase in overall food production from the area.

The total amount of food is produced with different amounts of water and energy inputs. While crop water productivity increases with higher yields, energy productivity is actually lower at high yields (data not shown). Moreover, the resource-use efficiency of water and energy for food production also differs in the three scenarios.

In comparison with the total residential energy demand, the total agricultural energy demand remains small in all scenarios (Figure 8). In the national plans and nexus scenarios, assuming efficiency improvements for residential energy use in combination with a more energy-intensive agriculture, the energy demand for agriculture constitutes around a third of residential energy demands. Residential energy demand drops substantially in the National Plans scenario when compared with BAU, and even more in the Nexus scenario. This is due to aggressive targets for rural electrification levels, which enable the use of electric stoves, as well as penetration of biogas stoves, LPG stoves, and highly efficient woodstoves – each of which consumes less primary energy than a regular woodstove. The rise in non-cooking household energy demand, for electronics, refrigerators or lighting, is not sufficient to mask this decrease in energy consumption.

Figure 8. Absolute increase in total household and agricultural energy demand from year 2000 through 2030.



Notes: Compared to the BAU scenario, major drivers of increasing agricultural demand in both the National Plans and the Nexus scenarios stem from intensive crop irrigation and mechanisation, while falling household consumption is due primarily to the more efficient use of biomass for household cooking. The proliferation of alternative cooking fuels, despite being used more efficiently, plays a secondary role to efficient woodstoves.

Zooming in on the specific energy use for different purposes within the agriculture sector, it appears that the largest consumer of energy is for fertiliser production (around 60%), followed by the use of diesel for driving of tractors and other farm equipment (around 30%). In the case-study region, a lot of the irrigation is expected to be gravity fed, resulting in a relatively low energy demand for pumping of water.

Impacts of different development trajectories on stakeholder groups

The implications of the different development trajectories on stakeholder groups were assessed in SWOT analyses made on the results by the stakeholders themselves, and are presented in this section. The following descriptions are thus an interpretation of the modelling results into realities for people living in the case-study area.

Business-as-usual – Low agricultural production and energy access

Continued extensive grazing, expansion of farmland, and biomass-based cooking continues to have undesirable environmental impacts such as soil degradation and erosion, siltation, tree plantations on current croplands (eucalyptus) and habitat destruction. The latter will specifically threaten wetlands and the small remaining and partly connected natural forest remnants. Increasing sediment loads to the lake reservoir, together with regulations of river flows for hydropower production, impacts on wetlands, limnic ecosystems and adjacent land areas, may result in lower lake water levels, with concurrent negative impacts. For instance, stakeholders fear that fish species will be threatened, papyrus and other wetland grasses will diminish, the fisheries sector and tourism industry will be negatively affected, and rare endemic and migratory bird species will significantly decrease. Similarly, water regulation for hydropower production may affect traditional irrigation users downstream of Lake Tana.

Generally, stakeholders perceived that the extensive use of natural resources in agriculture (such as low energy, fertiliser and water inputs) as strengths in this development scenario. By developing agriculture slowly, there is a greater chance to maintain current good practices while avoiding being locked into new, possibly unsustainable management strategies. An ample labour force, good institutions, and a growing market for organic products were also considered opportunities in this scenario.

On the other hand, low crop yields, continued environmental degradation, inefficient use of resources, and low agricultural production deemed to result in continued problems with food security were considered to be the main weaknesses in this scenario. The largest threats according to the stakeholders were a continued high demand for (and hence higher price of) fuel-wood, high population growth, food and nutrition insecurity, low agricultural productivity, climate change, land degradation and the concurrent siltation of Lake Tana (i.e. low fish yields, low volume of water bodies, ecosystem destruction and lower hydropower production). In the end, this is likely to result in urbanisation, low economic development and possibly conflict.

In this scenario, the stakeholders considered that most people will lose out, because of generally low economic activity in the country, less access to food, and low tax revenues. In particular, rural farmers, fishermen, the *Negede* people and the navigation sector will be negatively affected, and there will be more landless people. However, some people may actually benefit slightly, including businesses and the private health sector, downstream land areas, urban sectors in need of cheap labour (seasonal migration), and NGOs.

National plans – High production but compromised environmental targets

The most positive outcome of this scenario is the improved agricultural productivity and the concurrent transformation of the agriculture sector, which not only ensures food security, but also contributes generally to the economic development and improvement of livelihoods in the region. A positive effect of the irrigation dams upstream of Lake Tana is that the flow of water in the rivers will be more constant over the course of each year. However, average flows will be lower due to the higher irrigation withdrawals. Also, improved land management upstream is likely to increase infiltration and reduce sedimentation. Meanwhile, the energy mix will be diversified as new and renewable sources of energy are exploited. Raised awareness is expected to result in more balanced and appropriate management of energy resources at household and enterprise level. The high level of political commitment behind this development and the high ambition levels in society in general are considered opportunities. Improved economic development may also result in more job opportunities. A high degree of urbanisation may be an effect of an increasingly mechanised agriculture sector and may facilitate electrification, improved water supply and other infrastructural development.

On the other hand, stakeholders identify biodiversity loss in and around the lake ecosystem due to large use of inorganic fertiliser and pesticides upstream as well as the modification of the hydrological regime as a major threat associated with this development trajectory. As a result, the tourism industry, the fisheries and the *Negede* people may be severely negatively impacted. Moreover, the fisheries industry, the wetlands and the lake ecosystem are likely to be negatively affected by lower water levels in the lake. Higher agricultural energy demands may compete with residential demands for energy, which is seen as a threat in this scenario. Excessive irrigation could possibly cause waterlogging, which could cause declining crop productivity over time, and would therefore have to be monitored.

Most people in the value chain will benefit from this development including farmers, seed producers, cooperatives, businessmen, agro-industries and government (more foreign currency and tax revenues); however, some farmers may also be displaced because of the dam construction. There is also a fear that the fisheries and the papyrus industry would diminish due to increasing problems of pollution and eutrophication (as is already manifesting itself in a strong infestation of water hyacinths along the lake shores). Some farmers may be outcompeted by others as the farming industry becomes increasingly commercial. Where there is a shift to electricity-based cooking, the indoor environment improves and subsequently the health, in particular, of women. An expanding agro-industry gives employment to people, and labour efficiency improves. On the other hand, labour availability in urban areas goes down. Malaria outbreaks impact negatively on people living around the lake.

Nexus – Agricultural transformation and energy transitions go hand-in-hand

In the Nexus scenario, limited water and biomass availability in the case-study area changes how each sector uses these resources. The energy sector relies less on biomass and more on electricity. Similarly, the agriculture sector shifts away from livestock use to mechanised agriculture, which reduces biomass needs for fodder. At the same time high energy (specifically for fertiliser use) and water inputs boosts crop yields. Water use is restricted to ensure environmental needs, which reduces hydropower production.

Stakeholders list high agricultural productivity and a maintained lake water level as the biggest strengths of this scenario. Maintaining the lake water level has positive impacts on fisheries, tourism and the lake ecosystem itself. Other benefits are reduced deforestation and land degradation, as well as improved indoor air conditions with the replacement of traditional cookstoves. Efficient resource use is considered an opportunity in this scenario, as is the potential development of the tourism industry.

The major weakness of this scenario is reduced electricity generation from hydropower production. Moreover, eutrophication of the lake from fertiliser leaching is thought of as a threat in this scenario. Resource and capacity limitations are considered to be weaknesses hampering implementation. Potential threats include resistance to use new technologies, political uncertainty and cross border water conflicts, to mention a few.

Farmers, fishermen, the tourism industry, other industrial developments, and the ecosystems are suggested winners in this scenario. However, eutrophication continues to be a major threat, and should be carefully monitored.

DISCUSSION

Agricultural transformation and energy transitions are interdependent

In this analysis we found that the processes of energy transitions and agricultural transformation and intensification are interdependent and sometimes compete for the same resources. An intensified agriculture sector needs more energy for pumping of irrigation water, mechanisation, and fertiliser production. At the same time, the large amount of biomass fuelling the energy sector partly originates from the agriculture sector, causing productivity losses as organic matter and nutrients are removed from the soils. While the former connection is likely to increase in the future, biomass use for energy production might decrease as the country embarks on a transition towards a higher electricity inclusion of the energy mix.

Our analysis hints towards a number of outstanding dilemmas in the current policy framework and its implementation. Firstly, if water use remains unregulated for both irrigation and hydropower production purposes, there is a risk of reducing the Lake Tana water level below a critical depth for extended periods of time every year. It is difficult to foresee the consequences of this. The risk is substantial damage to the limnic ecosystems including the wetlands surrounding the lake, the fisheries industry, navigation on the lake, and a number of indirect effects, for instance on the growing tourism industry. On the other hand, it may be possible to modify the operating rules of the upstream irrigation dams to let water through during periods of low water levels of Lake Tana. This potential opportunity would need further exploration.

The second dilemma is that of biomass use. Our analysis indicates that the region has hit a biomass ceiling where the demand for biomass for fuel, fodder and food is in the same order of magnitude as the annual increment of biomass production. The implication of this is an urgent need to reduce both fodder and fuel needs from biomass. Recent developments in the region, such as drying and burning of dung for cooking and eucalyptus plantations on croplands, indicate a response to general shortage of biomass in the area. Creating incentives for the livestock sector to reduce the number of livestock or to plant fodder on current croplands could be alternative options to respond to the biomass shortage that may be more sustainable in the long term. Similarly, reducing the biomass need for fuels could be accomplished by either improving cookstove efficiency or by switching to other energy sources. In this context, off-grid electrical options are interesting.

The analysis shows that both land (biomass) and water resources are in scarce supply in the region, that sectors interact, and therefore that there is a need to agree upon a development trajectory that is acceptable to all stakeholders and that take into account these interactions. Once this task is completed, new policies that support this development can be generated to complement the current policy framework in order to meet the development goals of the region and the country. This study did not focus on defining the barriers to implement a nexus approach to resources management which would be needed to define an effective uptake strategy of new policies and procedures.

The combination of 1) land degradation, 2) water scarcity, 3) a high dependence on biomass in the energy sector, multiplied by a growing population, is by no means unique to this case-study area. Therefore, although this study was done for one subbasin in Ethiopia, it is possible to imagine similar patterns in many other parts of sub-Saharan Africa. However, it is still difficult to tell how generalisable the findings from this project are, which warrants further studies in other areas to be able to make conclusions on a more general level.

Scientific assessment of the food-energy-environment nexus

The intention of the project was to support policy and decision making in Ethiopia by highlighting interactions between agriculture, energy, and environment issues, in the context of the country's national plans to develop the economy, sustainably manage resources and meet human-security needs. We applied a nexus toolkit (WEAP and LEAP) to the Lake Tana Region jointly with stakeholders. The process was iterative; discussion and evaluation of data, assumptions and results during several workshops informed continuous model development. In addition, information was derived from one-on-one stakeholder interviews at the onset of the project. Also, training on the nexus toolkit was provided to stakeholders by the research team, with the intention that the tool would continue to be applied and developed after project closure. Indeed, WEAP and LEAP are already widely used by stakeholders around the world, e.g. government ministries and authorities; hence the training aimed to facilitate their use in the case-study region.

The nexus toolkit helps to illustrate system-wide and cross-sectoral outcomes of different policies, interventions and development trajectories and allows an assessment of potential synergies of a nexus approach and remaining dilemmas that need to be agreed upon by stakeholders. The SAS approach allows validation of scenario assumptions, continuous refinement of data, and mutual learning throughout the process.

This approach ensured several things: that 1) the best possible available data were used in the tools (it is important to note that we identified some data that we were unable to access as they were not yet publicly available), 2) assumptions were realistic, 3) results were credible, and 4) the toolkit and methods remained in the hands of stakeholders. Involving stakeholders from the onset of the project provided a quality check of both inputs and outputs from the toolkit. Moreover, by involving stakeholders throughout the project process, local actors could impact on what results were derived from the toolkit, which increases the usability and relevance of results. Finally, training stakeholders to use the toolkit and methods meant establishing capacity to continue using a nexus approach within the region to support integrated planning as further issues arise.

To summarise, the project was characterised by joint learning about integrated analysis, assessments and management across sectors (nexus approach), where the research team gained knowledge about pertinent local issues in the case-study region and about necessary components to include when designing a toolkit and methods for assessing these issues (i.e. the nexus toolkit). At the same time, stakeholders gained knowledge about potential cross-sector issues that should be taken into account during future planning and policy processes, the needs and issues faced by other sectors, and a possible methodology for assessing these issues (i.e. the nexus toolkit).

With regard to the quantitative modelling, the recent linking of the two tools comprising the nexus toolkit (WEAP and LEAP) enabled a joint assessment of energy and agricultural production and related environmental impacts. Energy and climate impact models are rarely linked with biomass/land/water tools. Therefore, the nexus toolkit presented in this paper is special in this regard, and thus lends itself to integrated, cross-sectoral analysis. Moreover, the scenario functionality that is built into the tools was found useful when working with policy analysis, stakeholder dialogue, and scenario narratives. In general, we found that working with scenarios helped to formulate current strengths and opportunities, and also to identify dilemmas with different development trajectories that would have to be accounted for in the planning and policy-making process.

Implementing a nexus approach in the Lake Tana area

The formation of a multi-stakeholder working group around 'nexus' issues has been a first step towards implementing a nexus approach in the Lake Tana Region. The working group offers a platform for dialogue and exchange of ideas, aspirations, and concerns amongst different stakeholders, thereby raising the awareness amongst stakeholders of the needs and challenges of other groups.

However, as noted by Stein (2013) in his analysis of social networks amongst stakeholders within the nexus in the Lake Tana Region, networks and relationships largely follow administrative and sectoral boundaries. This reflects the state-driven and centralised governance system of Ethiopia as a whole, and suggests that the decentralised federal system may not simplify the process of achieving a nexus approach within the Lake Tana Region.

Hence, a next step in realising the potential of the working group would be to actually develop, in a multi-stakeholder consultation process, new policies and plans that take into account impacts on other sectors. Moreover, new innovations that target identified needs, such as local innovations for energy supply to replace traditional biomass use, or improved operating rules for irrigation and hydropower dams, remain to be implemented in the region.

In addition, there is a need to define barriers to the uptake of a nexus strategy, and options to overcome those. Currently, there is a gap between policy goals and strategies on the one hand, and their implementation, on the other, in the region. It is unclear what is causing this gap and therefore how to overcome it. In the stakeholder workshops the participants expressed their appreciation of a platform for cross-sector interaction for increased learning, which thus appears to be one key element of an implementation strategy.

Aspects for future research

In this study we identified the strong link between agricultural transformation and energy transitions. The current energy system is heavily reliant on traditional biomass, which leads to removal of biomass from a range of different habitats. A next step in the model development would be to link the demand for fuel-wood estimated by LEAP to an actual use of biomass in WEAP to supply the energy sector.

Secondly, a lot of land-use information currently derived from GIS-based information, such as land-use types, soils, potentially irrigated areas, and so on, was used in both tools. A GIS-based interface in WEAP, enabling a direct processing on spatial data, would speed up the parameterisation process and limit the risk or errors and inconsistency in spatially explicit data entered into the tools.

What is currently labelled 'environment' in this study's food-energy-environment nexus approach ought to be further developed conceptually. In the framework applied in this study, resources such as land and water, arguably part of the environment, are treated separately from what has been termed 'environment'. A number of other characteristics and dynamics of ecosystem need to be put into future consideration, such as the qualitative (and not only quantitative) aspects of water, the spatio-temporal dynamics of the hydrological regime, ecological parameters for crop growth, as well as the nutrient cycle with its major implications for land and water productivity (biomass growth). This is a limitation of this study and, in general, there is a need for an improved understanding of what the term 'environment' stands for in a nexus analysis and how that relates to natural resources. The current framework does not account for factors of ecological integrity, ecosystem interactions, ecosystem services in general, and the potential for integrated management.

Another important aspect that has not yet been included in the current framework is economics. Many changes in society are driven by economic factors such as pricing, affordability and access to markets and inputs. In the case of the Lake Tana Region, economic development is central to plans and policies. New innovations and new development pathways need to be analysed from a financial point of view to assess the impacts on business and, ultimately, on livelihoods. There is, for instance, a need to study the supply chain in agriculture in this context.

The current model application on Lake Tana does not incorporate climate change projections. This is due to the lack of reliable and high-resolution data. Including climate uncertainty in the quantitative assessment would increase the credibility of results.

Lastly, there is a need to better understand the institutional arrangement and the process for developing policies, to assess how a nexus approach could be embedded in the current institutional setup. Moreover, a more in-depth analysis of the current policy framework would shed light on the current policy coherence and identify inconsistencies, as well as a definition of barriers to the uptake of a new strategy.

CONCLUSIONS

This project has addressed several conflicting interests under the current policy framework and analysed outstanding dilemmas to achieve wise use of natural resources to maintain ecosystem services by reducing negative impacts on the environment, while at the same time meeting the development targets of these strategies and human aspirations in general, specifically focusing on the agriculture and energy sectors.

We found that the agriculture and energy sectors are interdependent and sometimes compete for the same resources. An intensified agriculture sector needs more energy for pumping of irrigation water, mechanisation, and fertiliser production. At the same time, the large amount of biomass fuelling the energy sector partly originates from the agriculture sector, causing productivity losses as organic matter and nutrients are removed from the soils.

To meet the objectives stipulated in the national plans, some outstanding dilemmas pertaining to resources scarcity need to be addressed. Firstly, water withdrawals for irrigation purposes would in all likelihood increase agricultural productivity. However, increased consumptive water use upstream will inevitably result in lower water availability downstream; in this case, for the Lake Tana itself or for hydropower production, depending on prioritisation. A possible opportunity that would need more exploration is to modify the operating rules of upstream irrigation dams to release more water during periods when there is an unmet demand of water.

Secondly, it appears that the region has hit a biomass ceiling where the out-take of biomass for food, fuel and fodder is in the same order of magnitude as the current annual increment of biomass summed up for all terrestrial ecosystems in the region. This is clearly not sustainable, and to resolve this dilemma, either a certain amount of the current croplands would have to be set aside for fodder or fuel production (e.g. eucalyptus), or the demand for biomass would have to decrease. The latter could be achieved by reducing the livestock population or by investing in off-grid energy solutions for rural electrification.

These interlinkages between sectors lead us to conclude that in order to achieve the sustainable development outlined in the national plans, cross-sector dialogue from local to national levels, will be key to decouple undesirable links between sectors, to avoid undesirable environmental impacts and to reap the benefits of synergetic effects between sectors. To underpin this dialogue, there is a need for quantifications of different development trajectories pertaining to the nexus. We found that the nexus toolkit WEAP-LEAP developed and applied jointly with stakeholders was useful for supporting such dialogue, in particular since the scenario approach incorporated in the toolkit enables comparisons of outcomes of different policies and plans, and impacts of new innovations. It can therefore also be developed into an efficient decision support system to be routinely used in local institutions. By involving multiple stakeholders in the model development process from the onset of the project, the quality of data, assumptions and results were improved and, at the same time, the relevance of the results was ensured. We propose that a stakeholder-driven nexus approach across sectors, underpinned by quantitative and spatially explicit scenario and planning tools, can support more consistent policy and decision making, towards improved resource productivities, lower environmental pressures and enhanced human securities.

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