Title:

The influence of water, land, energy and soil-nutrient resource interactions on the food system in Uganda

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Abstract

Food Security continues to be elusive in Sub-Saharan Africa (SSA), several decades after the first World Food Summit in 1974. The causes of food insecurity in Sub-Saharan Africa include among others; poverty, economic constraints, agricultural and agronomical challenges, rapid population growth, and the effects of adverse climate change. These causes however, are linked to complex interactions, constraints and dependencies amongst the key physical resources in food systems, namely – *Water*, *Land*, *Energy* and *Soil Nutrients* (WLEN). There is limited insight on the combined impacts of the resource nexus, and how this may constrain the performance of food systems in Sub-Saharan Africa. This understanding is essential if the food challenges in the region are to be tackled sustainably.

This study provides a detailed analysis of the Uganda's 2012 WLEN nexus resources vis-à-vis the country's current and potential food demand using calorific-demand analysis and source-to-service resource transformation modelling. The analysis determines estimates of the current resource stresses within Uganda's insufficient food system and the interconnected resource implications for the achievement of food security by 2050. The results are visualised using Sankey diagrams. The inferences highlight evident limits across all four resources. Overall, the analysis helps to inform food security policy and the resource context for the present and future management of Uganda's food system.

Keywords

Food Security, Food Policy, Sub-Saharan Africa, Water-Land-Energy-Nutrient Nexus, Resource Demand Analysis, Resource Sustainability

1. Introduction

1.1 Food Security in Sub-Saharan Africa

Each year, many people in Sub-Saharan Africa (SSA) endure severe famine. According to the United Nations Food and Agricultural Organisation [FAO] (FAO, 2012, p. 10) and the European Union's (EU's) European Court of Auditors [ECA] (ECA, 2012, pp. 9–10) *Annual Reports* on food security, the number of food insecure people in SSA increased from about 219 million in 2003 to 239 million in 2010-12. Proportionally, the percentage of food insecure people in SSA remained stagnant at 27% of the population between 2003 and 2012 – representing little progress towards the 20% population undernourished Millennium Development Goal (MDG) target for the same period (FAO, 2012, p. 10).

Regionally, by 2010 none of the five East African (EA) countries was on track to meet its Global Hunger Index (GHI) targets based on analysis of SSA annual food statistics (ECA, 2012, p. 21). All of them had varying degrees of food scarcity ranging from 'Extremely Alarming' in Burundi to 'Serious' in Kenya and Uganda (ECA, 2012, p. 21). In Uganda, over 700,000 people require direct famine relief annually according to statistics from the World Food Program (WFP, 2012) and the Uganda Bureau of Statistics (UBOS, 2012).

1.2 Food Security and the Interactions between Water, Land, Energy and Soil Nutrients

The European Union's report titled '*Confronting Scarcity: Managing Water, Energy and Land for Inclusive and Sustainable Growth*' (EU, 2012) examined the increasing global constraints on the Water, Land and Energy resources, and the connections to food security. They argue that one of the major challenges of existing policy efforts in SSA has been a limited understanding of the holistic resource considerations and interconnections within the food systems (EU, 2012, p.3). Policy efforts thus far have tended to focus on causal factors such as productivity/agronomic constraints, funding bottlenecks and climate change mitigation.
However interventions in one resource-use sector – for instance using limited energy supplies for large-scale fertilizer production, may have unintended adverse consequences elsewhere – such as irrigation water shortages. While discussing this challenge, the EU (2012, pp.3-4) proposes integrated resource analysis to help identify the critical points of

interconnected resource stress within SSA's food systems and the impact of different policy options.

In this light, the research reported here adopts a ***Food System*** approach to analysing Food Security in SSA as proposed in Ericksen (2008, p.238)'s and Ingram (2011, pp.420-422)'s Global Environmental Change and Food Systems (GECAFS) framework. The approach proposes system-level analysis across the broad-spectrum of food system components, namely: Production, Processing, Distribution and Consumption. Ingram (2011) and Ericksen (2008) identify nine food 'outcomes'. These nine outcomes are grouped under 3 main components of Food Security namely: *Food Availability* (Production, Distribution, Exchange); *Food Accessibility* (Affordability, Allocation and Preference) and *Food Utilisation* (Nutritional value, Social value, Safety). Definitions of these components as adopted in this paper are as follows:

Availability, is comprised of the net stock of food produced, procured or otherwise received within the country, and the variety of foodstuffs available (Ingram, 2011, p.420). Availability also includes the measures of physical proximity to food stocks including travel distance, efficacy of transportation. **Accessibility** consists of the drivers of Allocation and Preference (such as market efficiency and socio-cultural factors), as well as Affordability – which includes of the complementary aspects of Food Price and Purchasing Power (financial ability) (Ericksen, 2008, p.240). Finally **Utilisation** includes both the Health & Safety considerations during production and preparation, and the nutrient content of the food. The social value and access to food are dependent on its physical availability. The three components of Food Security are listed in ***Table 1***.

Table 1: Aspects of Food Security (adapted from Ericksen, 2008; Ingram, 2011)

Availability	Accessibility	Utilization
• Food Stock (Production, Distribution, Exchange) • Variety • Travel Distance • Transportation	• Allocation • Preference • Affordability (Price, Purchasing Power/Financial Ability)	• Nutritional Value, • Health and Safety • Social Value

The scope of this study is limited to understanding the interconnected physical limits of the Water, Land, Energy and Soil macroNutrient (WLEN) resources and their potential impact on functionality and outcomes of Uganda's Food System. The economic trade-offs and other social-political costs involved in translating the physical resource availability into productive application in the Food System are complementary aspects not looked at within the scope of this study. Figure 1 shows the links between the availability of the WLEN nexus resources and their interconnections with the *Food System* components and the different outcomes of Food Security. The study scope is indicated in the dashed boundary.

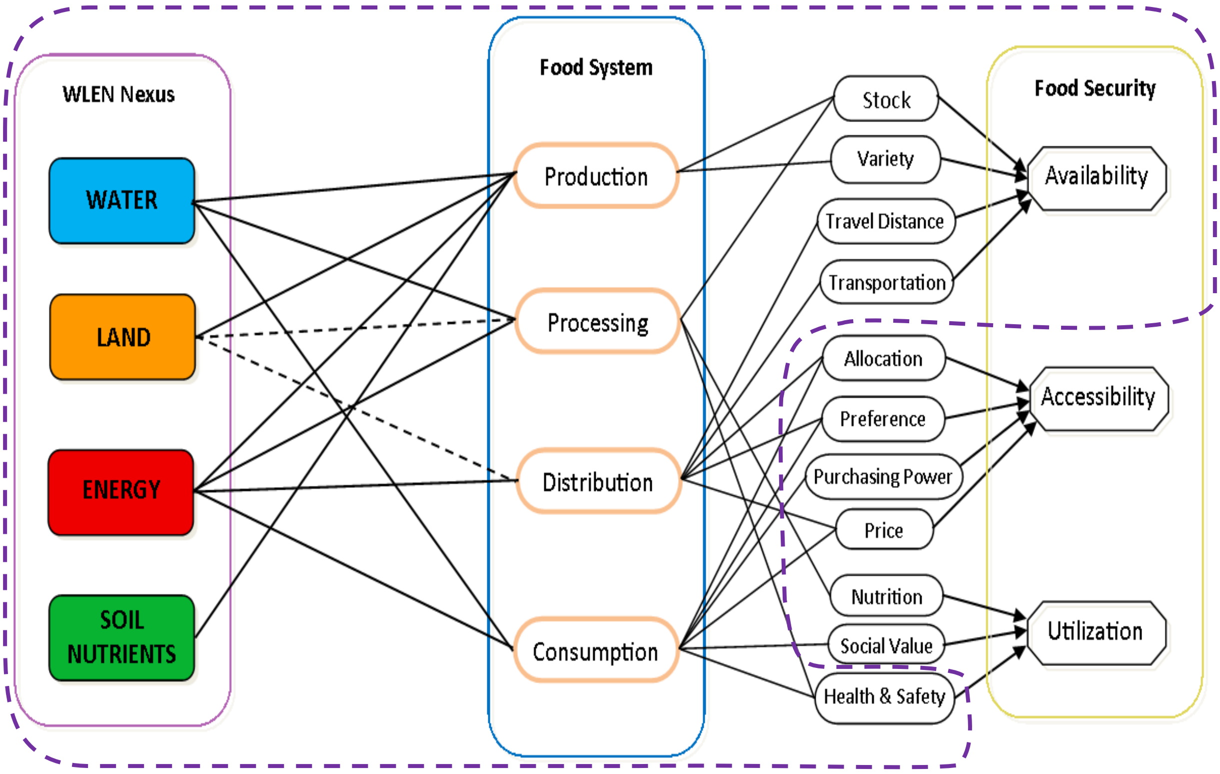


Figure 1: *Food System and WLEN Nexus Interconnections; Scope of the study.*

1.3 Understanding SSA's Resource Limits

Sub-Saharan Africa faces major challenges with the four resources of the Water, Land, Energy and Soil Nutrient nexus (WLEN nexus). SSA's interconnected WLEN resource stresses and trade-offs are discussed here below.

1.3.1 Water Stress

According to FAO statistics (FAOSTAT, 2013), over 90% of the agriculture in Sub-Saharan Africa is rain-fed. This leads to perennial food shortages on account of failing rains, as reported in the USAID monthly surveillance report on emergency food-aid requirements and supply statistics – USAID (2012), and the Australian Office of Development Effectiveness strategic report on food security in SSA, AusAID (2008). The challenge of unreliable rain-fed agriculture points to a need for major shifts towards managed agricultural water use.

Rockström (2003, pp.1999-2006) analysed 'green water productivity' in developing countries using a combination of evapotranspiration modelling, hydro-climatic modelling, and crop yield modelling assuming different cropping systems. The analysis suggests that consumptive dietary use of water in Sub-Saharan Africa will have to almost *double* by 2030 accounting for changes in land productivity, from 690 m^3/year to 1300 m^3/year, with a modest diet mix of 20% animal protein. This poses a significant water-stress challenge, considering the already formidable water concerns in the region and the likely adverse impacts of climate change.

In addition, there is also a competing demand for water for hydropower production, as evidenced by the increasing tussle between the Nile's riparian countries. McCartney & Girma (2012) analysed the likelihood of water stress as a result of agricultural and hydropower interventions on the Ethiopian Blue Nile, for the projection period 2100. Their analysis was based on a combination of Climate Change modelling (using IPCC climate scenarios), hydrological modelling and water resource modelling, calibrated using 30-year time-series weather data. Their findings indicate that the proposed irrigation and hydropower projects are likely to encounter serious water constraints. There is therefore a need for analysis of the trade-offs between agricultural water use and other water resource development objectives at the local, national and regional levels.

Importing food from the global market (virtual water) may be one way of resolving SSA's future water-stress challenges. Analysis by Dalin *et al.* (2012) of the global imports of 58 food items from 1986 to 2007 using FAO statistics, network theory and hydrological modelling, reveals that SSA (which includes Uganda) has relied disproportionately on the global virtual water market over the past few decades. However this trend may not be sustainable in the long-term considering SSA's relatively disadvantaged economic position and food sovereignty concerns. This was noted by Hanjra & Qureshi (2010, p.373) in their discussion paper highlighting the results of several regional agricultural-water studies done using the IFPRI's WATERSIM and IMPACT-WATER models. Their study identifies water-efficient agriculture as the alternative solution, using interventions such as rainwater harvesting, conservation irrigation, and increased use of water-efficient crop varieties and Genetically Modified (GM) crops.

Tadele and Assefa (2012, pp.242-3) specifically note the potential benefits of changing current crop mixes towards more water-tolerant crop varieties such as Cassava, Yam, Pearl Millet, Improved Rice and Cowpeas. Their study discusses various crop-improvement and genetic engineering techniques under investigation by different international and national organisations such as the *Consultative Group on International Agricultural Research* (CGIAR), the African Union's *Comprehensive Africa Agriculture Development Programme* (CAADP) (CAADP, 2013), and the *Alliance for a Green Revolution in Africa* (AGRA). They highlight low nutritional value and low productivity of these crops as some of major bottlenecks. Analysis of the potential crop-mix productivity options is beyond the scope of this study. Nevertheless, the coupled resource stresses identified in this study should form the basis for further examination of the likely potentials of the suggested crop-mix options.

1.3.2 Land & Soil Quality

Jayne *et al.* (2010, p.1386) carried out extensive household farm surveys in five countries in East and Central Africa in different periods from 1995 to 2004. Their findings revealed that agricultural land in SSA is heavily fragmented with average farm holdings at less than 3.5 hectares. The same is true in Uganda, where smallholdings account for over 95% of the cultivated land area according to nationals statistics by the Uganda Bureau of Statistics (UBOS, 2012). Rapid population growth in SSA continues to reduce the amount of land available per capita for food production. Kijima *et al.* (2011, p.82) note that increasing land fragmentation invariably compounds the challenge of implementing concerted food security efforts as it diminishes the economies of scale required for large-scale agricultural production, and shifts farmer priorities towards low-output subsistence agriculture. Kijima *et al.* (2011)'s findings are based on analysis of the adoption and performance of improved rice varieties and enhanced agricultural techniques, using data from 347 households in Central and Western Uganda.

With regard to soil quality, land degradation continues to plague Sub-Saharan Africa as a result of over grazing, soil erosion and nutrient depleting cropping methods. Access and use of fertiliser is very low, and where available, incorrectly applied resulting in further land degradation. WOCAT (2009, p.3) suggest that the solution may lie in the adoption of Sustainable Land Management (SLM). SLM involves the use of improved farming practices such as Conservation Agriculture (CA), Conservation Tillage (CT), Agro-forestry (AF) and Rainwater Harvesting (RH). Based on demonstration studies on smallholder farms in Central Kenya, Upper East Ghana, Tanzania, Togo, Ethiopia and Niger, WOCAT (2009) found that the application of SLM practices significantly improved soil quality and resulted in increases in land productivity of more than 200% in the same year. They highlight several challenges of up-scaling these technologies which include: climate uncertainties (for RH), associated operational requirements such as fuel and maintenance (for CT and CA equipment) and land constraints (for AF).

1.3.3 Energy Stress

Agricultural energy use in SSA is very low compared to energy consumption for similar uses in developed economies. In Uganda, an estimate of only 10 TJ (Terajoules, TJ equals 10^{12}J) of electricity was used for agriculture (mostly for large-scale irrigation) in 2012 based on UN energy balance statistics (UNSD, 2012). This is almost negligible when compared to the agricultural energy consumption in developed countries, which are in the order of thousands of TJ per year. Improving agricultural output in SSA may require major increments in energy-use irrespective of the adoption of Conservation Agricultural practices. WOCAT (2009) (discussed in the previous section) found that irrigation, fertilizer use and other productivity-enhancing agricultural techniques all require significant quantities of commercial energy. Food processing, transportation, and preparation for consumption, also carry unavoidable energy-footprints.

Kebede *et al.* (2010) investigated energy demand in SSA using an econometric model based on 1980-2004 statistics of 20 SSA countries from the International Energy Agency (IEA), US Department of Agriculture (USDA), World Bank, and FAO. Their study indicated that almost 90% of the households in SSA (Kebede *et al.*, 2010, p.534) rely on unsustainable biomass fuel to meet their present demand, the majority of whom are poor smallholder farmers. Purchasing major quantities of commercial energy is therefore most likely beyond the financial abilities of these smallholder farmers.

Government fuel subsidies could help to bridge this gap, especially where significant fossil fuel holdings exist. Uganda for instance, may rely on its recent oil discoveries to boost agricultural energy supplies. However, fuel subsidies often result in adverse economic effects, especially rapid inflation, as shown by Mmadu & Akan (2013) in their analysis of the socio-economic impact of fuel subsidies in Nigeria, using econometric modelling and household survey data. Therefore further research is required to establish the limits these energy related trade-offs could place on increasing the performance of SSA's food systems.

1.4 Uganda's Food Security Situation

In this study, a holistic analysis of the WLEN resources of Uganda's food system has been carried out as a test case for the analysis of SSA food security. Uganda has close cultural, historical, socio-economic, geographical similarity to the other SSA countries (excluding those in Southern Africa and the Sahel). Uganda also has a broad range of food security challenges (conflict-related, economic, and resource constraints) and has diverse agro-ecology that is representative of the agro-ecologies in the region. As of 2012, Uganda had a GHI classification of 16 – 20 indicating 'serious' food security challenges (IFPRI, 2012).

Uganda is located between latitudes 4°N to 2°S and longitudes 29° to 35°E. It is one of the 5 member-countries of the East African Community, the others being Kenya, Tanzania, Rwanda and Burundi. It is divided into 112 administrative districts and eight (8) hydrological sub-basins that are part of the Nile basin (MoWE, 2012; UBOS, 2012), along with 9 major cropping systems/agro-ecologies (FAO, 2006).

Uganda has one of the fastest growing populations in the world, currently standing at about 35 million people and growing at more than 3% per year (UBOS, 2012). Its land area is about the size of the United Kingdom, at 241,500 square kilometres, giving it a population density of about 140 people per square kilometre (UBOS, 2012).

Regular food crises occur in the north and eastern parts of the country, and a large percentage of the country's population is under-nourished (FAO, 2012; UBOS, 2012). In 2011, over 11 million people (about 40%) out of a total population of 35 million were food insecure (UBOS, 2012). Over 700,000 people require direct famine relief annually (UBOS, 2012; WFP, 2012). A significant proportion of these are urban-poor, which is compounded by rapid urbanisation at a national rate of over 4% (UN-HABITAT, 2013, p.166). Over 25% of children less than 5 years are seriously malnourished (ECA, 2012, p.10).

Food insecurity in the country can be attributed to several different factors, including poverty, and low agricultural output (UNECA, 2009; FAO, 2012). The low agricultural output is linked to the effects of erratic rainfall and drought, increasing land-degradation and fragmentation, and underdeveloped agricultural practices (MAAIF, 2012). Over 80% of the population are smallholder farmers carrying out rain-fed subsistence agriculture with limited access to, and application of, high-productivity resilient agricultural inputs and technologies (MAAIF, 2012). Key statistics of the study area are summarised in ***Table 2***.

Study Area – Uganda profile and summary statistics:

- East Africa (Latitudes 4°N to 2°S, Longitudes 29° to 35°E)

• GHI	16 – 20 [serious] (IFPRI, 2012)
• Total Land Mass (sq.km)	241,550 (UBOS, 2012)
• Agricultural land (sq.km)	139,620 (FAOSTAT, 2013)
• Arable (sq.km)	66,000 (FAOSTAT, 2013)
• Cultivable (sq.km)	41,406 (UBOS, 2012)
• Current Population (2012)	34,510,000 (UBOS, 2012)
• Population Annual Growth Rate	2.9% (UBOS, 2012)
• Total Annual Renewable Water	39 km^3 (AQUASTAT, 2013)
• Current Food Consumption 2012	1900-2200 kcal p.c.d (FAOSTAT)

Table 2: *Uganda Summary Statistics. (**Sources:** UBOS, 2012; IFPRI, 2012; FAOSTAT, 2013; AQUASTAT, 2013)*

2. Analytical Approach

This study provides a detailed analysis of the interconnected WLEN nexus resources vis-à-vis Uganda's current and potential food demand. The analysis is in two parts. The first part involves a combination of calorific-demand analysis and resource demand modelling. The methods are described in Sections 2.1 and 2.2 below respectively. This part gives the WLEN resources required to meet current and future food security whilst comparing it with existing resource potential and the physical limits constraining each resource sector. The second part builds on the first by examining the current competing demands on the WLEN resources and highlighting conflicting stresses that may arise in light of the demands identified in the first part. This is done by modelling Uganda's 2012 water, land and energy resource-flows from source to final service. Sankey diagrams are used to track and visualize the results of this analysis. The procedure for this is described in Section 2.3. As mentioned in Section 1.2, this study is only limited to the physical availability of the WLEN resources and their interconnected stresses with food system. It is recognised that the distribution of the resources may not accessible to corresponding demand centres.

2.1 Food Demand Scenarios

In this part of the WLEN nexus resource analysis, *estimates* of the quantities of the resources currently used within Uganda's insufficient food system are determined, as well as the resource implications for the achievement of food security. This baseline analysis helps to frame the resource policy context for any systems analysis of Uganda's food security.

The baseline analysis is done by calculating the resources required in five (5) food demand scenarios (numbered 1 to 5) based on the 2012 and projected 2050 population statistics obtained from the World Bank (WB), United Nations Population Division (UNPD), and Ugandan Bureau of Statistics (UBOS). Uganda's 2012 and 2050 populations are established as 34.5 million (WB, 2013) and 102 million respectively [calculated using the UNPD (2013) long-term average growth rate of 2.9%]. The population figures are multiplied by the current and projected per capita Daily Calorific Intakes (DCIs) (in kilocalories/capita/day –

kcal.p.c.d) obtained from the FAO's country food statistics database (FAOSTAT, 2013) and the FAO's report – *The State of Food Insecurity in the World 2012*. A similar approach is adopted in De Fraiture & Wichelns (2010) to compute food demand at global and regional scales. The scenarios considered are summarised in Table 3 below.

Scenario 1 is the current situation and 2 – 5 are projected scenarios. Scenarios 1 & 3 are based on developing country consumptions – current and 2050 projected according to the FAO (FAO, 2012). Scenario 5 is a developed-economy consumption scenario taken as the current USA dietary energy consumption (FAOSTAT, 2013).

Table 3: Uganda 2012-2050 Calorie Intake Scenarios

Scenario (No./ Acronym)	**Description**	**Year**	**Population** (Actual/ Projected)	**DCI** kcal.p.c.d	**Annual Calorific Necessity** (bn kcal)	**Colour**
1. 2012-DC	Uganda's 2012 developing country food consumption	2012	34,510,000 (WB, 2013)	1,900 (FAO, 2012)	23,932	
2. 2012-FRDCI	Uganda 2012 food consumption at FAO's recommended DCI	2012	34,510,000 (WB, 2013)	3,000 (FAO, 2012)	37,788	
3. 2050-DC	Projected food consumption at FAO's predicted 2050 DCI	2050	*102,265,000 (UNPD, 2013)	2,800 (FAO, 2012)	111,980	
4. 2050-FRDCI	Projected food consumption at FAO's recommended DCI	2050	*102,265,000 (UNPD, 2013)	3,000 (FAO, 2012)	104,515	
5. 2050-DECL	Projected consumption at developed economy (USA) DCI	2050	*102,265,000 (UNPD, 2013)	3,700 (FAOSTAT, 2013)	138,109	

*Estimated

2.2 Resource Limits Analysis

The WLEN resources required to meet the food demand in each of the five scenarios in Section 2.1 above are estimated as indicated in sub-sections 2.2.1 to 2.2.4 below. Data sources for the calculations include the Uganda Bureau of Statistics (UBOS) database, FAO's FAOSTAT, COUNTRYSTAT and AQUASTAT 2013 databases, the UN Statistics Division and International Energy Agency (IEA) Energy Statistics databases. This data was cross-referenced with other peer-reviewed sources as indicated in the corresponding sub-sections. The results are compared to Uganda's sustainable resource base of Water, Land, Energy and Soil Macronutrients in order to establish the likely sources of resource stress and the potential resource-stress interconnections.

In addition, where possible the resource demands have been compared with equivalent crop productivities and resource-use of Mexico. The Mexico-equivalent crop productivity and equivalent resource-use are used as benchmarks that could be achieved by Uganda in 2050 using enhanced 'Green Revolution' agricultural technologies. The 'Green Revolution' involves deploying a combination of genetically enhanced crop varieties, fertilizer and irrigation, along with corresponding stakeholder training and capacity building. Mexico-equivalent comparisons are adopted because of Mexico's success in eradicating hunger and achieving economic transformation as a pioneer of the 'Green Revolution' approach in the 1970's (de Graaff *et al.*, 2011). In addition, Mexico's situation in the 1970's shares similarities with Uganda's current condition as a developing country with a comparable rural population, rapid population growth and substantial food challenges.

2.2.1 Water

Based on Rockstrom (2003), the amount of water consumed per year to produce a typical diet in Sub-Saharan Africa is 690 m^3 (Scenario 1). The same is confirmed by bottom-up reverse calculations using the crop-water productivity and actual 2012 agricultural production figures for Uganda from UBOS (2012), WB (2013) and FAOSTAT (2013). The water-demand to meet the FAO recommended DCI of 3,000 kcal.p.c.d in Scenarios 2 and 4 is estimated using Rockstrom (2003)'s projected 2030 annual consumptive use of 1,300 m^3 assuming a 20% animal protein diet. The food-water required in Scenarios 3 and 5 is calculated using Hanjra & Qureshi (2010, p.369)'s approach, adopting a ratio of 1 litre per kcal for 365 days.

These water demands are compared with Uganda's total annual Internal Renewable Water Resource (IRWR) estimated at 39 km^3, calculated from precipitation recharge flows using evapotranspiration modelling (AQUASTAT, 2013; WB, 2013). This estimate may decrease in subsequent decades due to climate change given that although precipitation is predicted to rise over the target period 2050, so will evapotranspiration (Kigobe & Griensven, 2010). The results of the water demand calculations and the comparisons are given in Section 3.1.

2.2.2 Land

Uganda has a land area of 241,550 km^2 (UBOS, 2012). 66,000 km^2 of this is Arable land (FAOSTAT, 2013) with only 41,406 km^2 being cultivable (MAAIF, 2011, p.vii). The composite 12-year average annual grain productivity is estimated at 1.68 tonnes per hectare, calculated using grain production statistics from the UBOS (2012) and the FAOSTAT (2013) database. Data comparisons were also made with figures from Kraybill *et al.* (2012, p.3) and Kaizzi *et al.* (2012, p.109).

Allowing for a cereal-based diet and an Average Crop Calorific Content (ACC) per tonne of 3.9 x 10^6 kcal (Hollander, 2004, p.41), estimates of the amount of land required for each of the five scenarios are calculated using Equation 1. These values are compared with a Mexico-equivalent average grain productivity of 3.2 tonnes per hectare (De Fraiture & Wichelns, 2010, p.507; FAOSTAT, 2013) as a benchmark that could be achieved using enhanced 'green-revolution' agricultural technologies. Results are summarised in Figure 4 in Section 3.2.

$$Lr_i = \frac{(DCI_i \times P_i \times 365)}{ACC \times CP_i} \qquad \text{(Equation 1)}$$

i – Scenario number
Lr_i – Land required for Scenario i
DCI_i – Daily Calorific Intake per person
P_i – Population
ACC – (constant) Average Crop Calorific Content
CP_i – Average Annual Crop Productivity for a given scenario, Uganda & Mexico

2.2.3 Energy

The energy-use in Scenario 1 (current situation) is almost negligible. Out of a total estimated energy use of 423,000 TJ in 2012 in Uganda, only 10 TJ was used for agriculture

(UNSD, 2012). At present most of the agriculture in Uganda is rain-fed agriculture with low levels of mechanisation. Raising the country's agricultural output to Scenarios 2 to 5 will require the use of irrigation, fertilizers, and potentially greater mechanisation.

The amount of energy required to produce a given amount of dietary energy (calorific content) can be estimated using the 'Energy Use Efficiency' or 'Energy Ratio' which is the ratio of energy output to energy input (Houshyar *et al.*, 2012, p.674; Soltani *et al.*, 2013, p.56). Typical food production energy-ratios for developing countries using improved agricultural methods range from a minimum of 4 (Mushtaq *et al.*, 2009, p.3636), to a maximum of 12.74 (Houshyar *et al.*, 2012, p.678). Using these values, the minimum and maximum energy requirements for Uganda in Scenarios 2 to 5 with enhanced productivity are estimated using Equations 2 and 3. Figure 5 in Section 3.3 gives a summary of the results.

$$Er - min_i = \frac{(DCI_i \times P_i \times 365 \times 4.184 \times 10^{-9})}{EER_{max}} \quad \text{(Equation 2)}$$

$$Er - max_i = \frac{(DCI_i \times P_i \times 365 \times 4.184 \times 10^{-9})}{EER_{min}} \quad \text{(Equation 3)}$$

i – Scenario number
Er_i – Energy (TJ) required for Scenario i
DCI_i – Daily Calorific Intake
P_i – Population
EER_{max} – Maximum recorded Energy Efficiency Ratio (EER)
EER_{min} – Minimum recorded EER

2.2.4 Soil Macro-Nutrients

According to the FAOSTAT (2013) records, Uganda's current total chemical fertilizer consumption (2012-DC, Scenario 1) is 11,634 tonnes. The chemical fertilizer demands for Scenarios 2 to 5 are estimated using IFPRI recommended fertilizer input ratios. The Uganda Strategy Support Program (USSP) of the IFPRI suggests that a fertilizer input ratio of 60 kg N (Nitrogen), 19.4 kg P (Phosphorous), and 24.9 kg K (Potassium) per hectare would be sufficient to enhance Uganda's crop productivity to the benchmark level adopted in this study (Namazzi, 2008, p.1). Adopting this ratio along with the amounts of the land required for Scenarios 2 to 5 with enhanced crop productivity, the total quantities of N-P-K macronutrients required for Scenarios 2 to 5 are calculated accordingly using equation 4 below. The results of the analysis are summarised in Figures 6 and 7 in Section 3.4.

$$SN_i = UF_{nutrient} \times Lr_i \qquad \text{(Equation 4)}$$

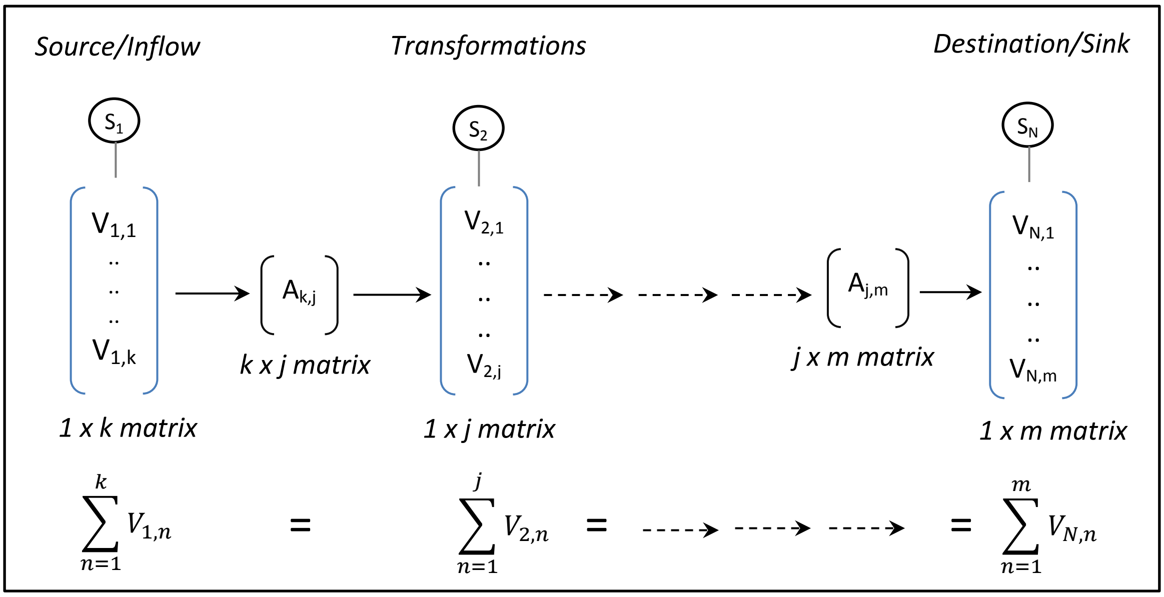
i – Scenario number
SN_i – Soil macronutrient quantity required under given scenario i
$UF_{nutrient}$ – Average unit quantity of nutrient required per sq.km for Uganda
Lr_i – Land (sq.km) required for Scenario i at enhanced crop productivity level

2.3 Modelling Resource Flows from *Source-to-Final-Service*

This second part of the analysis identifies and tracks the interconnected resource constraints as they occur along the various stages of the food system, through a series of three interdependent Sankey diagrams, with the focus specifically on the implications for food production, processing, distribution and consumption. Source-to-service analysis was not done for Uganda's 2012 chemical fertilizer consumption because of the relatively negligible quantities currently used and insufficient data (See Section 3.4; *Figures 6 & 7*).

The transformations of the WLEN resources in Uganda for the base year 2012 are traced from their primary sources through to the final services they provide. At each transformation stage (Sankey slice, S_i), a vector of data nodes is assembled ($V_{i,n}$) representing the resource fluxes at that stage. i is the number of the resource transformation stage from $i = 1$ to N; and $n = k, j, m$ *etc.* are the number of fluxes at stages $i = 1$ to N (see Figure 2 below). Allocation matrices (A) are also generated to map the resource fluxes between the transformation stage vectors. The resulting data points are verified for transverse and lateral consistency, across and along the Sankey diagram. The process is illustrated in Figure 2 below.

The vector and allocation matrix node data is sourced either from bottom-up analysis using primary data, GIS (Geographic Information System) modelling or secondary peer-reviewed publications (descriptions in Section 4.1-4.3). Data sources employed include the Uganda Bureau of Statistics database, FAO's FAOSTAT, COUNTRYSTAT & AQUASTAT 2013 databases, the UN and IEA Energy Statistics databases. In addition, ArcGIS geospatial image processing and geo-data modelling were employed for the IRWR evapotranspiration modelling, PNV and Land-use analysis, using UBOS/FAO Land-use geo-data (FAO, 2013) the Uganda Soil Map (Panagos *et al.*, 2011) and the University of Copenhagen Potential Natural Vegetation (PNV) model for Eastern Africa (Lillesø *et al.*, 2011).



S_i - Transformation stage (Sankey slice)
$V_{i,n}$ - vector of data nodes
n = k, j, m - number of fluxes
A - Allocation matrices
i is the stage number from *i = 1* to *N*;

Figure 2: *Resource Transformation Modelling and Source-to-Service Mapping*

The results of the source-to-service resource transformation modelling are visualised using Sankey diagrams for each of the resources as shown in Figures 8, 9, and 10 (Section 4). The structure of the Sankey diagrams is such that the total inflow fluxes match the outflows leaving the diagram (including change in ground water storage in the Water Sankey). Sankey diagrams possess unique features that make them well suited to the visualisation of the resource fluxes in the Food System. To start with, the relative sizes of the resource fluxes in the diagram represent their relative quantities, which provide an explicit visual aid. In addition, flux conservation is maintained across the slices (stages) of the system ensuring that data points are 'Mutually Exclusive and Collectively Exhaustive' (MECE) (Spencer, 2013). Similar resource mapping using Sankey diagrams can be found in the works of Curmi *et al*. (2013) (California Managed Water Resources), Bajželj *et al*. (2013) (Global Green House Gas Emissions) and Cullen & Allwood (2010a) (Global Energy Flows).

3. Resource Limits Analysis Results

The results of the resource demand modelling for each of the WLEN resources for the 5 food demand scenarios are given here below.

3.1 Water Resource Projections

The respective water resource-use and demands for scenarios 1 to 5 (2012-DC, 2012-FRDCI, 2050-DC, 2050-FRDCI and 2050-DECL) are estimated as **24, 45, 105, 133** and **138** km^3 respectively, as illustrated in Figure 3 below.

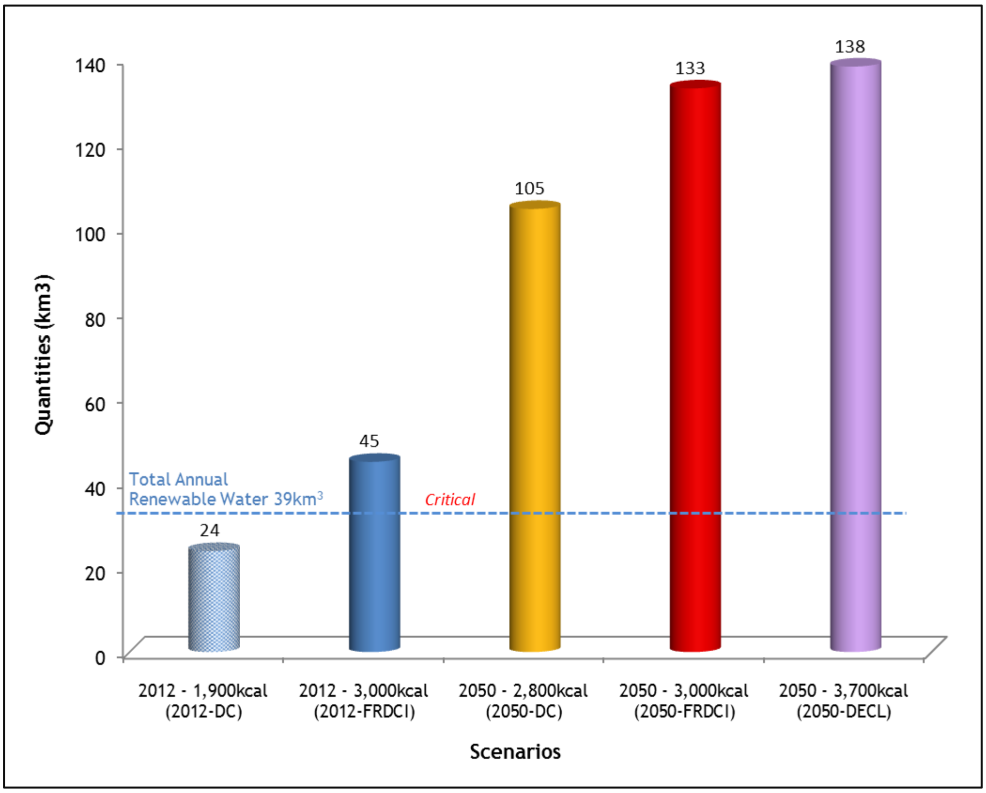


Figure 3: *Uganda water required for food production: Scenarios 1 to 5*

Most of the 24 km^3 in the current scenario (2012-DC) (*Figure 3*) is rain water/green water, used in Uganda's primarily rain-fed agriculture. Changing to irrigation agriculture in order to boost productivity and meet the FAO recommended 3,000 kcal.p.c.d dietary requirement (2012-FRDCI) would require an estimated **45** km^3 of water which **exceeds** the country's renewable water resource flow **by over 15%**. Moreover, producing sufficient food in 2050 (Scenarios 3 to 5) would require **more than 300%** of the country's renewable water resource. A significant challenge emerges when this demand is considered in light of other competing demands for water such as domestic access, industrial use, and hydropower production.

3.2 Land Analysis

As the graph in Figure 4 shows, of the 41,406 km^2 of Uganda's land mass that is cultivable, an equivalent area of about 36,379 km^2 is already used to produce the current food supply (Scenario 1, 2012-DC) leaving **only about 12% more** for expansion assuming ready access.

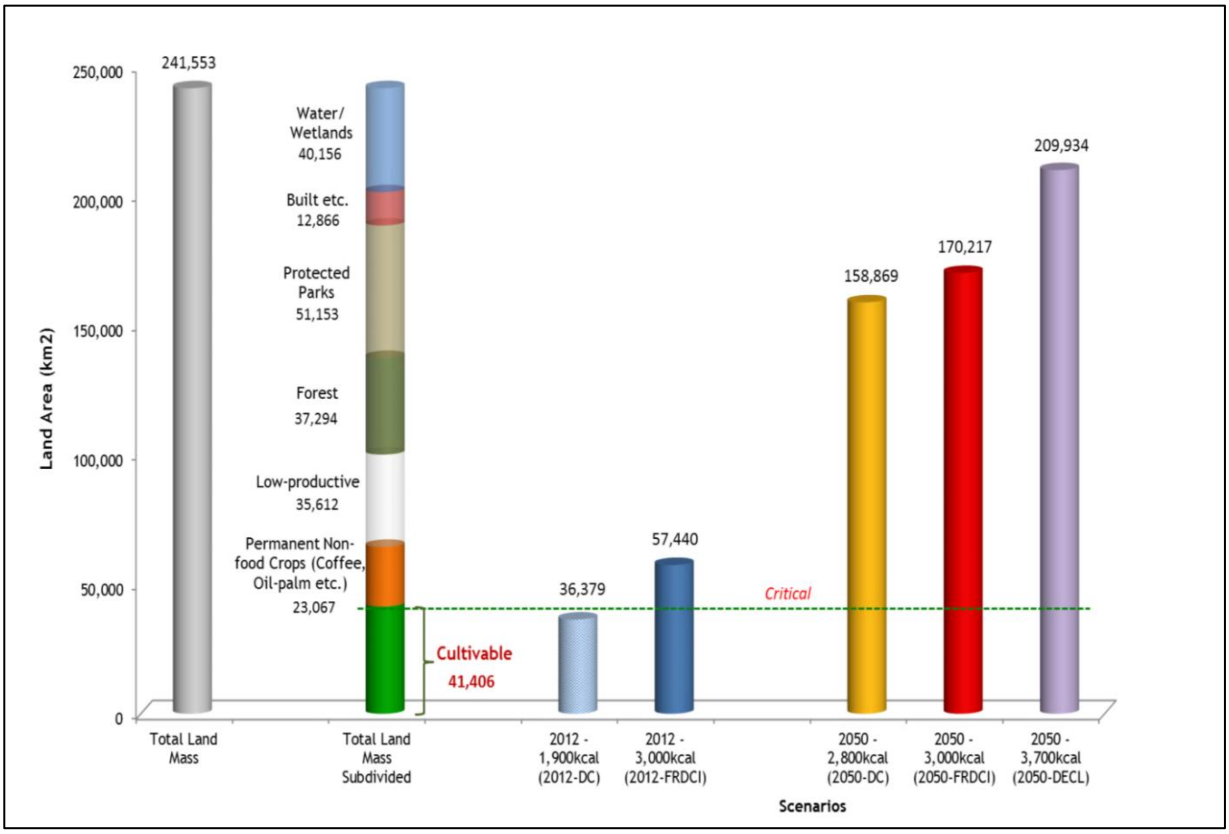


Figure 4: *Uganda land required for food production: Scenarios 1 to 5*

However the land required to meet the current food demand at the 3,000 kcal.p.c.d dietary intake level (Scenario 2, 2012-FRDCI) with Uganda's current level of productivity is estimated at 57,440 km^2. This is **almost 40% more** than the country's total cultivable land area.

Raising the average agricultural productivity to a Mexico-equivalent of 3.2 tonnes per hectare for Scenario 2 would help to reduce the land area required to 30,678 km^2 (a 47% reduction) which would be within the cultivable land limit. Nevertheless, with the population projected to grow almost threefold by 2050 (Scenario 2050-FRDCI) the amount of land required to meet the recommended 3,000 kcal dietary intake rises to 170,217 km^2 at current levels of productivity (Figure 4), and 90,911 km^2 at an enhanced (Mexico-equivalent) productivity level. Both are **well beyond** Uganda's cultivable or even arable land area. The implications of adopting different crop mixes and more advanced and energy-intensive agricultural practices remain undetermined.

3.3 Energy Demand

Uganda has an estimated verified renewable energy potential of 5,300 MW or 167,141 TJ per annum comprised of Hydro: 2,200MW, Solar: 200 MW, Biomass: 1650 MW, Geothermal: 450 MW, and Peat: 800 MW (Buchholz & Da Silva, 2010, p.57; SE4ALL, 2012, p.23). The minimum energy required for agricultural production in scenarios 2050-DC, 2050-FRDCI and 2050-DECL is estimated at 34,000 TJ, 37,000 TJ, and 45,000 TJ per year respectively, while the maximum required for the three scenarios is 109,000 TJ, 117,000 TJ, and 144,000 TJ respectively (*see* Figure 5). This amounts to a minimum of **20% – 30%** and a maximum of **65% – 86%** of Uganda's total annual renewable energy potential. Given a target of a totally-renewable energy mix for Uganda by 2050, these figures are considerably high when compared to the global food-energy percentage of about 18% (Cullen & Allwood, 2010a, p.80).

Uganda recently discovered significant deposits of oil (over 3.5 billion barrels) in the Lake Albertine region, some of which will be used for energy production (MEMD, 2012). The current plan is to dedicate a portion of this oil to generate 100 MW of electricity, which would supplement the country's energy mix by 3600 TJ/year (MEMD, 2012). This resource however is unsustainable, would increase the country's (albeit miniscule) carbon footprint.

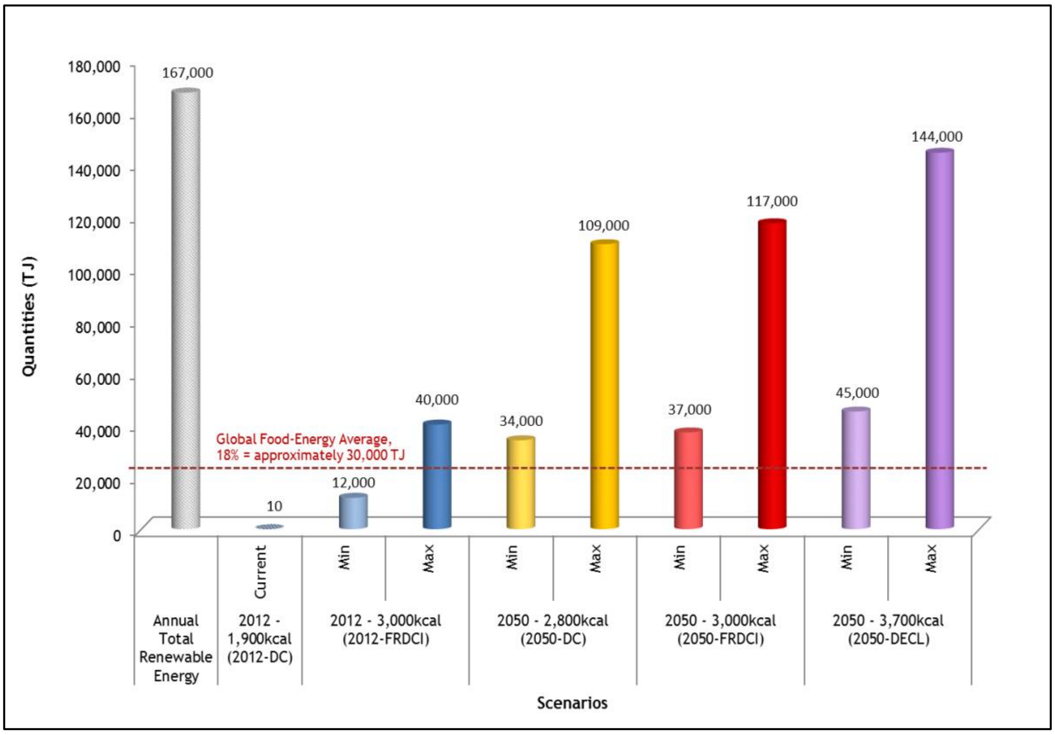


Figure 5: *Uganda Energy Demand for food production, Scenarios 1 to 5*

3.4 Soil Macro-Nutrient Analysis

The results of the analysis of Uganda's chemical fertilizer demand for Scenarios 1 to 5 are summarised in Figures 6 and 7. Figure 6 gives the total tonnage of soil macro-nutrients required and Figure 7 is a break-down of the required quantities of each of the N-P-K nutrients.

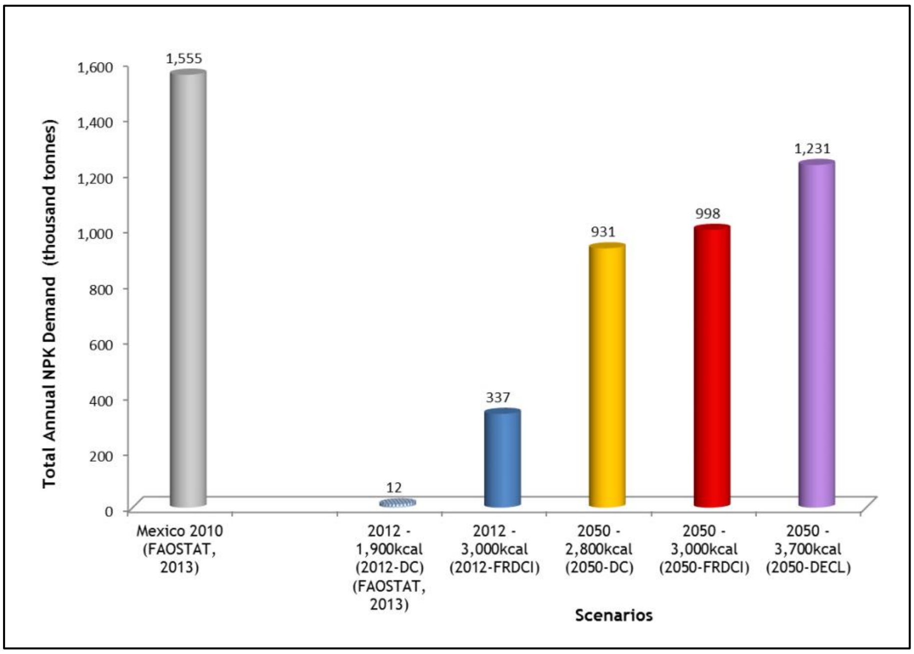


Figure 6: *Uganda – Total fertiliser required for food production in Scenarios 1 to 5*

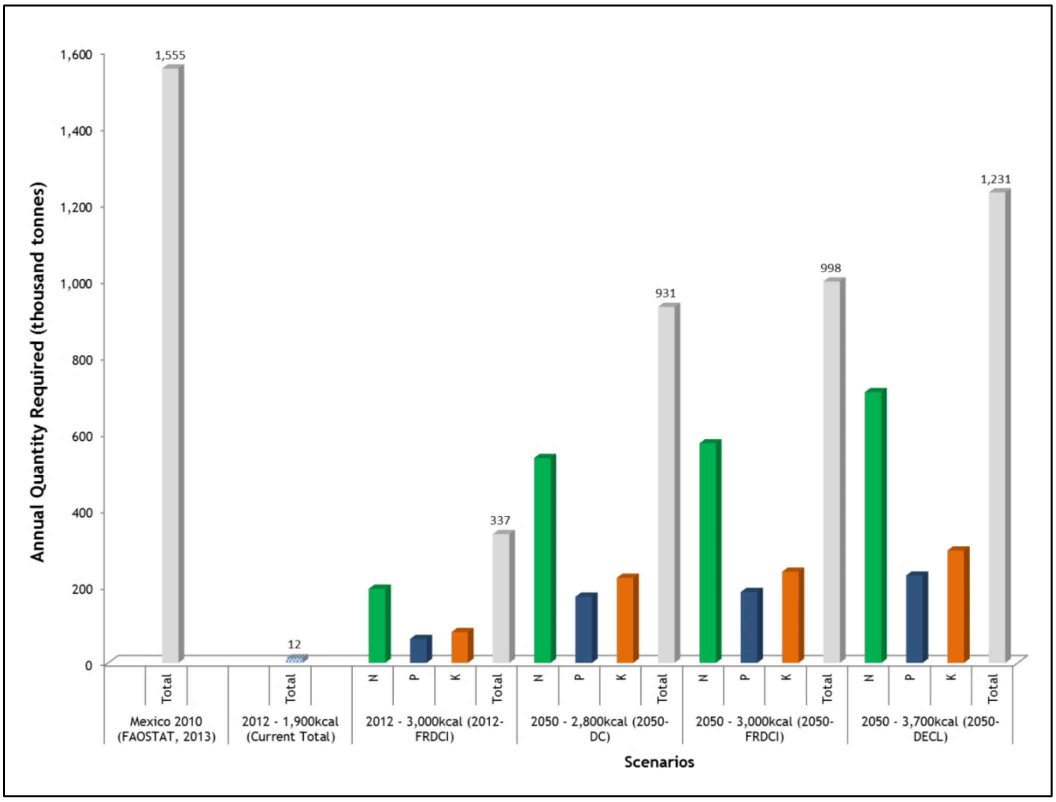


Figure 7: *Breakdown of nutrient quantities required in Scenarios 1-5.*

As with Uganda's currently low agricultural energy-use, most of Uganda's agriculture at present employs very low inputs of chemical fertilizer (Scenario 1). The country currently averages less than 2 kg fertilizer per ha per year compared to recommendations of over 120 kg/ha (Bayite-Kasule, 2009; Namazzi, 2008). Uganda previously had a production capacity of 25,000 tonnes of chemical fertiliser per annum, which was destroyed during the civil war in the 1970s-80s (UIA, 2013; van Straaten, 2002, p.303). Consequently all the chemical fertilizer inputs are now imported, with recent figures showing an annual total of about 12,000 tonnes (FAOSTAT, 2013). This quantity of fertilizer consumption is almost negligible when compared with the over 1.5 million tonnes used in Mexico in the year 2010 (FAOSTAT, 2013), as illustrated in Figure 6 & 7. Fortunately, Uganda has about 240 million tonnes of confirmed Phosphate deposits (13.4 million tonnes of P) contained within an ore complex in Sukulu in the East of the country (van Straaten, 2002, p.303). These deposits, which are comprised of amongst others: apatite, magnetite, goethite, and pyrochlore residual soils, would be enough to satisfy the P fertilizer demand at peak scenario 2050-DECL for over five decades. However, the implications for N and K macronutrients are yet unclear, as their potential quantities remain undetermined.

4. Resource Flow Analysis – Sankey Diagrams

The second part of the analysis involved source-to-service resource transformation modelling of Uganda's Water, Land, and Energy Resource Flows for the year 2012. The results of this analysis were visualised using Sankey diagrams as shown in Figures 8, 9 and 10 below. As mentioned earlier, source-to-service analysis was not carried out for Uganda's 2012 chemical fertilizer consumption because of the almost negligible amounts (*Figures 6 & 7*).

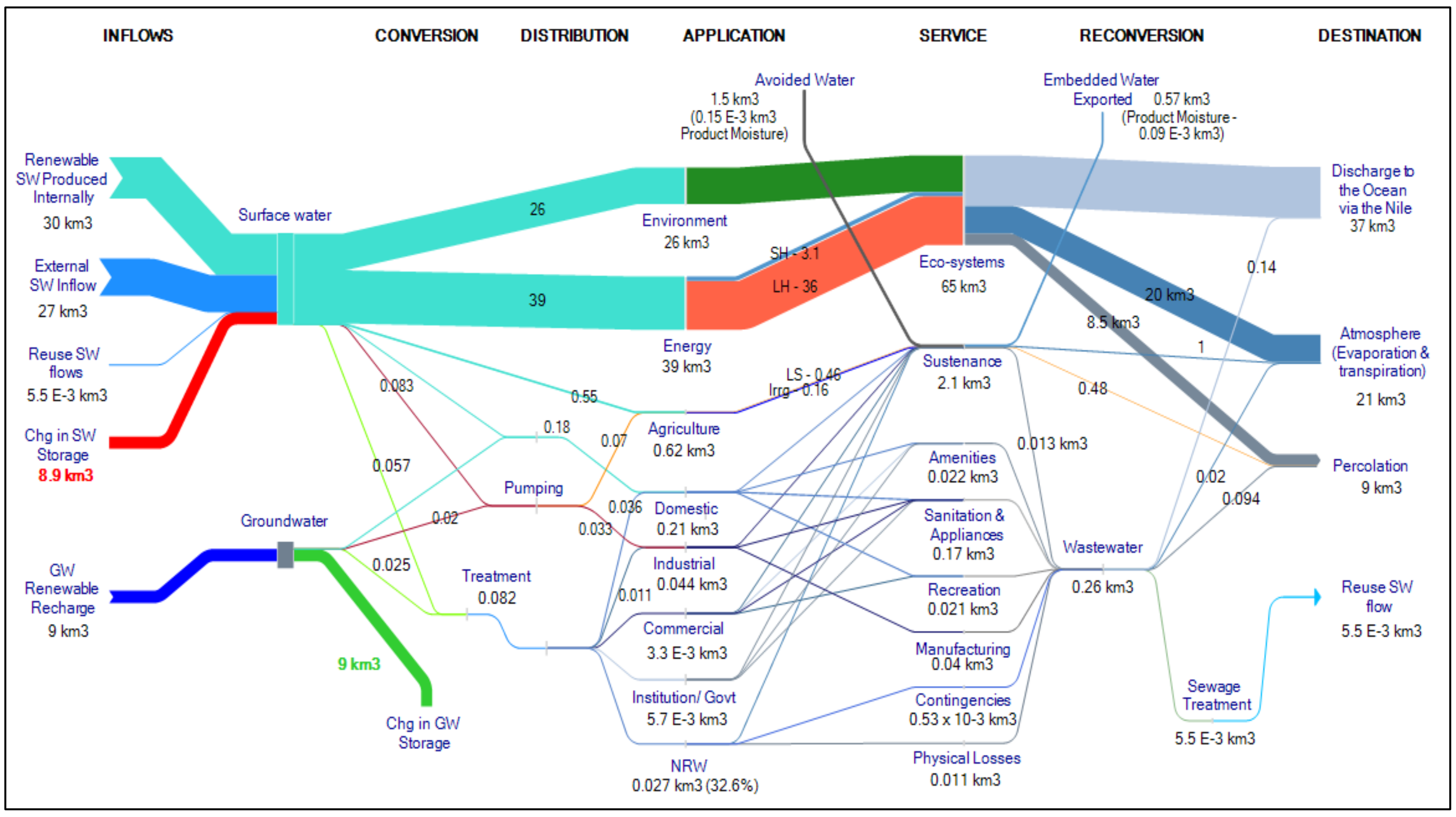


Figure 8: *Uganda Managed Water Sankey 2012 (km³): Source-to-Service Snapshot of Uganda's 2012 Renewable Water Resource.*

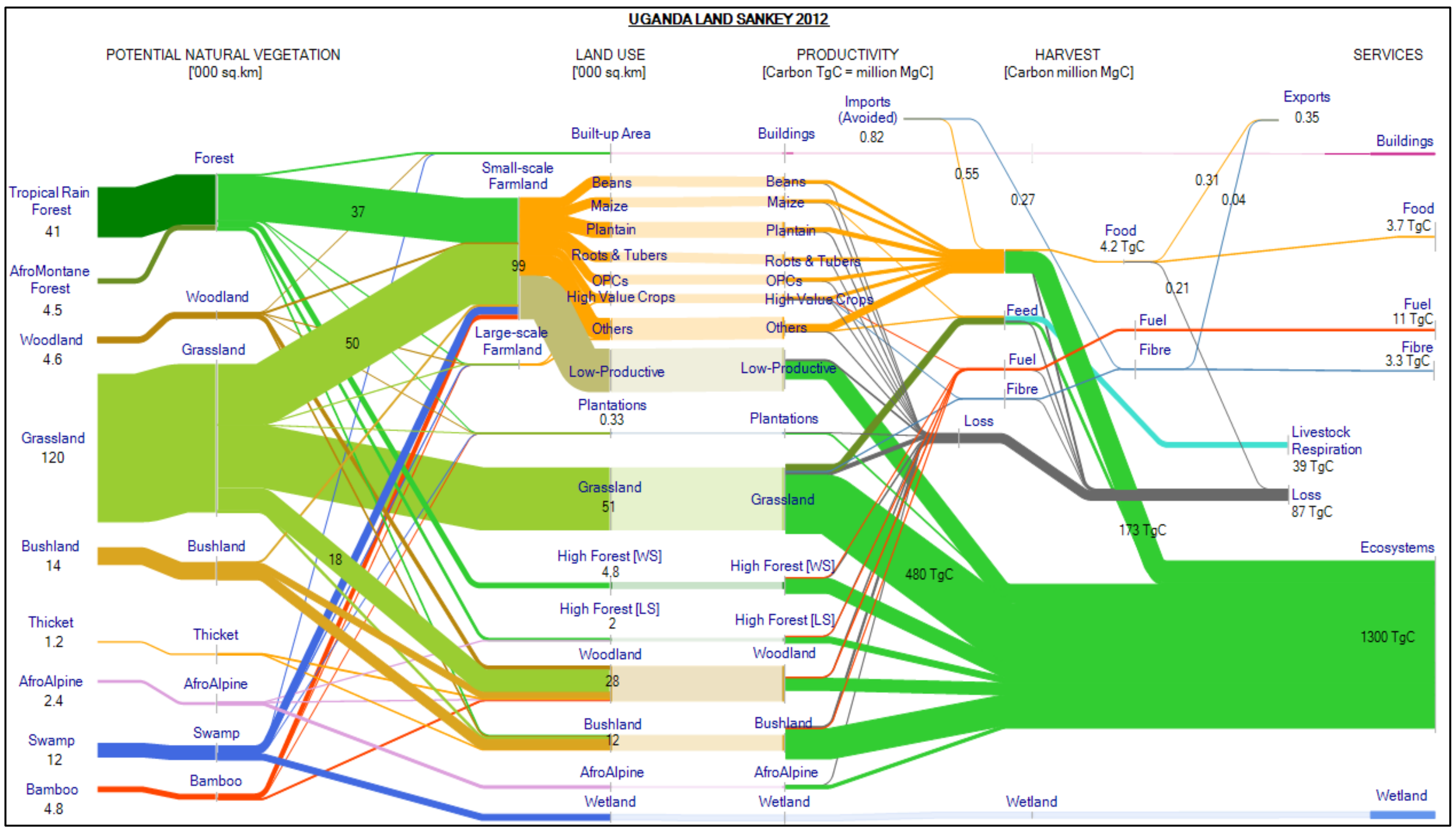


Figure 9: *Uganda Land Sankey 2012 (km² and TgC): Source-to-Service Snapshot of Uganda's 2012 Land Resource Area and Productivity*

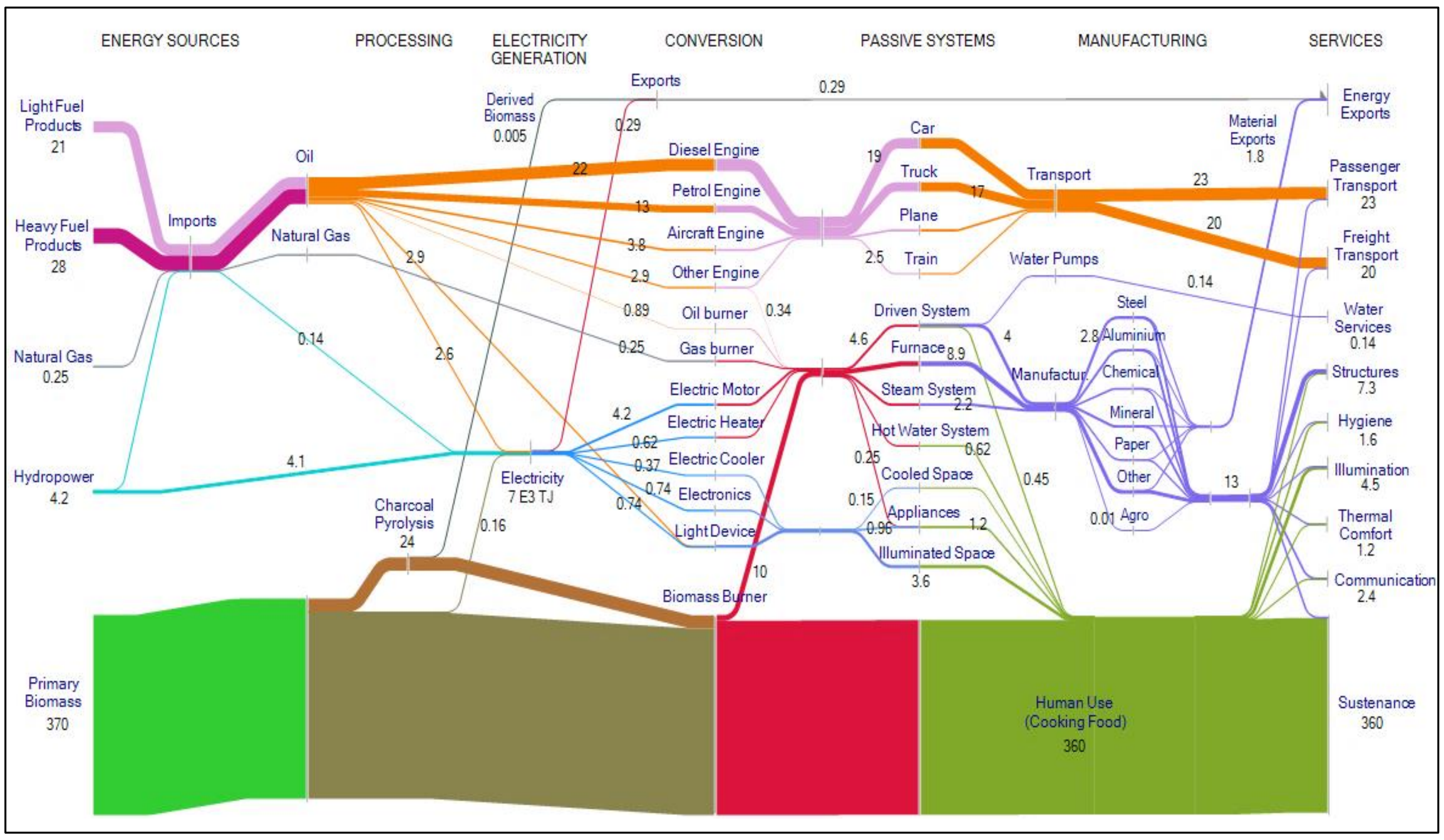


Figure 10: *Uganda Energy Sankey 2012 ('000 TJ): Source-to-Service Snapshot of Uganda's 2012 Energy Use*

4.1 Managed Water Sankey 2012

The summarised approximate stage vectors of the 2012 Uganda Managed Water Sankey (*Figure 8*) are: Stage1 (1.5, 30, 27, 9, 9) [76.5]; Stage2 (1.5, 26, 39, 1, 9) [76.5]; Stage 3 (0.5, 65, 2, 9) [76.5]; and Stage 4 (0.5, 37, 21, 9, 9) [76.5]. The components of the Water Sankey are as follows: As of 2012, Uganda's estimated long-term total annual Internal Renewable Water Resource (IRWR) is 39 km^3 (AQUASTAT, 2013; WB, 2013), computed from the average precipitation of 1,180mm/year (WB, 2013). External inflows are 27 km^3 giving total Renewable Water Resources of 66 km^3 (AQUASTAT, 2013). The net IRWR flux to ground water is estimated at 9 km^3 (Kyosingira *et al.*, 2011, p.14) and the rest apportioned to surface water (Figure 8). Hydropower accounts for 39 km^3 of surface water flows (AQUASTAT, 2013) with 36 km^3 used to power the Nalubaale and Bujagali Hydropower Stations as of 2012, which is an aggregate of the average annual flow of 1125 m^3/s (Zaake, 2006, p.13-14). The rest of the surface water for energy (3.1 km^3) is used to power small hydropower projects spread out around the country, such as Buseruka, Bugoye, and Nyagak (MoWE, 2012).

Potable water fluxes were calculated using data from the National Water and Sewerage Corporation (NWSC) customer database. Treated potable water is the smallest flux at 0.082 km^3 (Figure 8) used for domestic, industrial, commercial and industrial consumption (MoWE, 2012 p.89; NWSC, 2012, p.11). 32.6% of the treated water is lost as non-revenue water comprising of 0.011 km^3 of leaks & bursts, emergency use for firefighting (0.0053 km^3) and illegal consumption (MoWE, 2012, p.89; NWSC, 2012, p.11). Seventy per cent and ninety per cent of the water used for sustenance and industry respectively is obtained directly from the IRWR without conventional treatment (AQUASTAT, 2013; NWSC, 2012). Flows to the environment are estimated at 26 km^3. Of particular relevance to Food Security are the flows to Agriculture, which are less than 1% of the total IRWR at 0.62 km^3. About 1.5 km^3 is avoided water that would otherwise be exploited to produce the food that is imported (FAOSTAT, 2013; UBOS, 2012).

4.2 Land Sankey 2012

The Land Sankey (*see Figure 9*) highlights the extensive deforestation that has occurred in Uganda over the years. Over 90% of Uganda's forest PNV is currently used for small-scale farming (about 37 thousand km^2), which is a product of decades of rapid deforestation (almost 2% p.a.) (UBOS, 2012, p.2). The rest of the small-scale farmland is sourced from Grassland PNV (50 thousand km^2). Over 20,000 km^2 of farmland is degraded non-productive land generating relatively low amounts of biomass as shown in Figure 9. The cultivable land produces the equivalent of about 187 million tonnes of carbon biomass equivalent (TgC) inclusive of soil biomass; of which 9 TgC is lost and 173 TgC remains in the environment. The difference is combined with imports of 0.55 TgC (avoided biomass that would otherwise need to be generated in Uganda) giving a total available food supply estimate of 4.2 TgC. About 10% (EU, 2012) is lost post-harvest food losses (0.4 TgC). Of the total available food supply, 0.31 TgC is exported, 0.21 TgC (5% approximated) lost during consumption and the rest 3.7 TgC comprises the country's food consumption biomass. Also noteworthy is the 11 TgC of fuel biomass, mostly wood and charcoal, that is taken from eco-sensitive forests and woodlands. Particularly disconcerting is the estimated 4.7 TgC of the tropical forest biomass, which contributes to Uganda's serious 2% deforestation rate (UBOS, 2012, p.2).

4.3 Energy Sankey 2012

Figure 10 illustrates Uganda's 2012 Energy Flows. The total energy use is about 420,000 TJ (UNSD, 2012) with over 90% derived from unsustainable biomass fuel (370,000 TJ) (UNSD, 2012). In comparison, this total is equivalent to about 3% of California's energy use, and 5% of Mexico's (UNSD, 2012). The bulk of the biomass use is for cooking food (360,000) while 10,000 TJ is used in industry and a tiny amount 160 TJ is used for thermal power generation (Buchholz & Da Silva, 2010, p.57). 24,000 TJ is converted biomass in the form of Charcoal. The overall biomass burner efficiency is very low (less than 10% - Okello *et al.*, 2013, p.55), which translates into unnecessarily high biomass use.

The bulk of Uganda's electricity mix of 7,000 TJ is generated using renewable hydropower (4200 TJ) sourced from the hydropower stations described in section 4.1 (see *Figure 8*). 2,500

TJ is generated using oil powered thermal power plants Aggreko I, III and Namanve (UBOS, 2012). All the country's oil-consumption is imported, which places a major strain on the country's foreign exchange reserves and thus economic performance (WB, 2013; Kebede et al., 2010, p.533).

Overall, domestic use (cooking) accounts for an estimated 90% of the country's gross energy flux (Figure 10). Gas energy is an almost insignificant 250 TJ used mostly for cooking by the urban dwellers in the capital city – Kampala. Transport accounts for 5% with 23,000 TJ used for passenger transport and 20,000 TJ for freight transport. Notably, this includes the distribution of food throughout the country from the major production centres in the south west and central regions. Agricultural energy use is an almost negligible 10 TJ that is mostly energy used to facilitate the tillage and irrigation in the country's few plantations (UBOS, 2012; UNSD, 2012). The agriculture energy figure specifically represents commercial energy use (electricity and oil-fuels). It does not account for other energy forms not included in this study such as the human manual labour used in primary agriculture, ox-plough energy, or the sun's energy used in crop photosynthesis.

5. Discussion

The first part of the analysis (Section 3) has shown the extent of the WLEN resource developments needed to satisfy possible future food demands up to 2050. The second (Section 4) shows how these resources were constrained between different uses as well as the connections to the other WLEN nexus resources as of the base year 2012. The implications of these constraints on resource developments towards 2050, and the nexus interactions and their policy implications are discussed below.

5.1 Water Resources and Policy Implications

As discussed previously, over 95% of Uganda's agriculture is rain-fed, that is **23** km^3 of a total 24 km^3 (Scenario 2012-DC, Section 3.1). To improve the productivity of agriculture in the country, Uganda's agriculture would need to shift from predominantly rain-fed to managed water irrigation. This irrigation water would ordinarily be sourced from the country's IRWR. By 2050 over 100 km^3 of irrigation water is likely to be required (Scenario

2050-FRDCI, Chapter 5). However as observed earlier, about 60% (39 km^3 of 66 km^3) of Uganda's total water resources is currently used for hydropower production. While technically this water should be available for agricultural use downstream, current government Energy Policy is to increase dam construction all along the Nile upstream towards the country's outfall point (MEMD, 2012; Zaake, 2006), as illustrated in Figure 11.

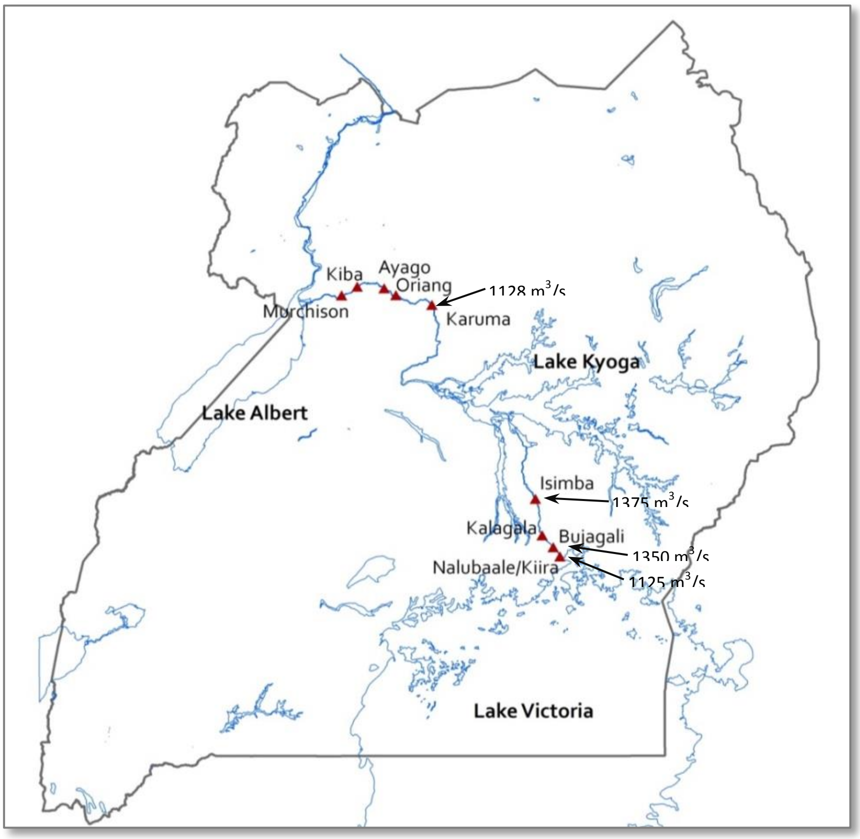


Figure 11: *Planned Hydropower Projects in Uganda.*

These dams are primarily for hydropower and thus are not optimised for multipurpose irrigation use (MEMD, 2012; Zaake, 2006). According to Uganda's official irrigation policy master plan – *A National Irrigation Master Plan for Uganda* (2010 - 2035) (MoWE, 2011, p.69) no comprehensive studies have yet been undertaken on the use of these hydropower dams as multipurpose irrigation schemes. As a result, their construction may lock the bulk of the Nile's flow in hydropower production, constraining the possibility for large-scale irrigation use. Moreover, most of the productive agricultural land is currently in the south of the country given the country's semi-arid northern/north-eastern corridor (MoWE, 2011). Appropriating the Nile's water for irrigation upon completion of the Karuma Dam may require energy-consuming pumping to transfer the water back south (Figure 11). This may have a significant adverse impact on the country's energy mix and carbon-footprint.

A likely casualty of this resource challenge could be the current flow of 26 km^3 to Eco-system services (*see Figure 8*) which would result in serious environmental repercussions. An alternative approach would be to harness more rainwater into IRWR for irrigation. However, this would require more land for valley dams and energy to pump the water to the farms. Future water resource policy should therefore in addition examine the prospects of converting the existing and planned hydropower projects into multipurpose schemes optimised for irrigation.

5.2 Land Discussion

The 2050-FRDCI scenario would require anywhere between 90,911 km^2 and 170,217 km^2 of land (*Figure* 4), well beyond the 41,406 km^2 of Uganda's available cultivable land area. Therefore, meeting Uganda's potential food demand by the year 2050 at current growth rates would require radical shifts in land use, calling not only for the restoration of the degraded arable lands but also the drastic appropriation of sensitive ecological and high economic value lands, amidst competition from rapid urbanisation. This could be through converting the 23,067 km^2 of land under permanent/cash crops such as coffee, cotton and oil-palm plantations (UBOS, 2012), which are a key source of both individual and national income, or appropriating the 51,153 km^2 of permanent meadows and grasslands that currently serve as protected reserves, wildlife sanctuaries and grazing areas (UBOS, 2012).

As shown in the Land Sankey (*Figure* 9), Uganda required an estimated 4.5 TgC of food biomass as of 2012 (Scenario 2012-FRDCI) to feed its current population, which is about 20% more food than the inadequate 3.7 TgC currently consumed. The projections for the 2050 scenarios are anywhere from 12 – 16 TgC, almost 3 to 4 times the current quantities. The Land Sankey analysis shows that the eco-sensitive Grasslands currently produce over 1.3 thousand TgC (see *Figure 9*), which would easily meet the potential food demand of 16 TgC by 2050. This makes them the primary candidate for further encroachment in the 2050-FRDCI scenario. Protecting these areas may therefore become increasingly difficult as the demand for productive agricultural land grows towards 2050. Opening these areas up for agricultural use could result in major environmental degradation to the eco-system services they provide. This would lead to the loss of key services such as natural biodiversity and eco-system resilience, watershed services, and carbon sequestration services.

5.3 Energy Discussion

Uganda could require an estimated 1.2 billion tonnes of fertilizer annually (*Section 3.4*) and over 100 km^3 of irrigation water in the year 2050 (*Section 3.1*) to achieve the 'green-revolution' level of crop productivity. The combined energy footprints of the required irrigation and fertiliser use, as well as the increased freight transport for food distribution are likely to conflict with the country's other development energy priorities. The 2050-FRDCI and 2050-DECL food demand scenarios would require 117,000TJ and 144,000 TJ of power per year respectively for food production, which is over 70% of Uganda's annual renewable energy potential of 167,141 TJ (*Section 3.3*).

In addition, the increased road transport necessary to improve the distribution component of Uganda's food system may generate anywhere in the order of 60% - 150% more traffic (Kamuhanda & Schmidt, 2009). From the Energy Sankey (*Figure* 10), this may increase the 2012 freight transport demand of 20,000 TJ to up to 50,000 TJ by 2050. The combined production and distribution demand would exceed Uganda's annual renewable energy resources potential. This would make it impractical to hope for a totally renewable energy mix target, given that food-energy as of 2010 accounted for only about 18% of the global energy mix (Cullen & Allwood, 2010a, p.80). These scenarios reveal that policies aimed at increasing Uganda's agricultural productivity and distribution-efficiency are likely to face serious energy constraints, coupled with increased competition for both land and managed water resources to produce the required fuel energy resources.

The Energy Sankey (*Figure 10*) illustrates in vivid detail that the largest impact on energy policy could be made by improving the efficiency of biomass use in the country. The environmental footprint of Uganda's biomass energy consumption is staggering. The result has been the rapid deforestation witnessed in the country (SE4ALL, 2012, p.25). This is the basis of the concerted efforts by the Uganda government with support of German Agency for International Cooperation (GIZ), to disseminate improved biomass stoves throughout the country (Okello *et al.*, 2013, p.59). A similar observation is made in Cullen and Allwood (2010b) who looked at global energy efficiencies and found that improving biomass burning in developing countries would have the single biggest impact that could be made, to reduce wasted energy and CO_2 emissions (Cullen and Allwood, 2010b, p.2066). Uganda's food-energy policy must therefore be coupled with comprehensive biomass conservation interventions to meet the 2050 food security energy demand.

6. Conclusion

This study has provided a detailed baseline analysis of the WLEN nexus resources in Uganda, highlighting their interconnections and dependencies in relation to the current and potential food demand. The inferences reveal evident limits across all four resources that appear to worsen towards 2050 (Scenarios 3 to 5, *Section 3*), with P fertilizer having the least constraint given the country's large ore deposits (S*ection 3.4*). In particular, 2050 food security would require almost 3 times Uganda's long-term annual Internal Renewable Water Resource (IRWR), 4 times the available cultivable land area, and over 70% of the country's annual renewable energy potential. Moreover, interconnections between the WLEN resources compound the food security challenge for Uganda. In particular, increased managed water use and fertilizer production may be constrained by hydropower production for other development priorities. As a consequence, achieving food security in 2050, even with enhanced agricultural productivity and 'green-revolution' techniques, may still come at a cost of the coupled depletion of water resources for eco-system services, destruction of eco-sensitive protected lands, and the disproportionate consumption of the country's renewable energy potential. Given the co-dependent nature of the stresses identified in the analysis, it is imperative that Uganda's food and WLEN resource policies be integrated to give holistic remedies to achieving 2050 food security. There is a need for co-optimisation of resource use and the associated dependencies between the different resources demands. An example would be pursuing innovative methods of waste-water re-use and nutrient recovery to avoid the energy demands associated with commercial fertilizer. The analysis also points to the need for demand-side interventions such as population growth management and the reduction of post-harvest food losses towards 2050.

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