
Title:

Scale variability of water, land, and energy resource interactions and their influence on the food system in Uganda

Authors:

Feriha Mugisha Mukuve^{a,*}, Richard A. Fenner^b

* Corresponding Author

^a Centre for Sustainable Development, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, E-mail: fmm32@cam.ac.uk, ferihamm@gmail.com

^b Centre for Sustainable Development, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, E-mail: raf37@cam.ac.uk

Abstract

Despite efforts to achieve food security in Sub-Saharan Africa (SSA) since the 1970's, food insufficiency continues to plague the region. As of 2014 more than a fifth of Sub-Saharan Africa's population - remain food insecure according to the United Nations Food and Agricultural Organisation (FAO). The food security challenges in Sub-Saharan Africa are linked to economic, agro-ecological, technological/agronomic, institutional and related factors. These causes however overlay complex interactions and constraints within the key physical resources of Water Land and Energy (WLE), which are necessary for food production, processing, distribution and consumption. The relationship between the WLE interactions and the performance of SSA's food systems, and the impacts of interventions at different scales are not yet fully understood, particularly in light of the need to maintain essential ecosystem services.

This study employs an integrated multi-scale Food System resource analysis approach to examine Uganda's WLE resource constraints vis-à-vis 2012 and 2050 agricultural resource demand at national, district and local scales, as a test case for Sub-Saharan Africa. The analysis identifies where the competing WLE resource constraints are and the variations from local (sub-county), regional, to national scale so that potential policy interventions can be appropriately targeted. The approach involves a combination of geo-spatial analysis, calorific-demand analysis and Source-to-Service resource transformation modelling. The results are visualised using coupled Sankey diagrams and resource stress maps. The analysis reveals the current competing demands and constraints at different scales, and helps to identify key resource intervention areas to resolve resource stress in Uganda's food system. The inferences highlight variations in the significance of resource stress at different analytical resolutions and constraints at different locations for the WLE 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, Resource Demand Analysis, Sub-Saharan Africa, Water-Land-Energy Nexus, Multi-scale modelling, Resource Sustainability

1. Introduction

Despite efforts to achieve food security in Sub-Saharan Africa (SSA) since the 1970's, food insufficiency continues to plague the region. Over 220 million people – more than a fifth of Sub-Saharan Africa's population – remain food insecure according to the United Nations Food and Agricultural Organisation [FAO] (FAO, 2014, p.8) and the European Union's (EU's) European Court of Auditors [ECA] (ECA, 2012, pp. 9–10). The food security challenges in Sub-Saharan Africa are linked to economic, agro-ecological, technological/agronomic, institutional and related factors. Underlying these factors are complex interactions and constraints on the key physical resources necessary for food production, processing, distribution, and consumption, that is: Water, Land, and Energy (WLE).

The relationship between the WLE interactions and the performance of SSA's food systems is not yet fully understood, particularly in light of the need to maintain essential ecosystem services. This is highlighted variously in authors such as EU (2012), Funk and Brown (2009) and Sage (2012). Interventions in one resource-use sector may result in harmful consequences in the other sectors; an example being the use of first generation biofuels resulting in upward pressure on food and land prices, as highlighted in Molony & Smith (2010) in their examination of biofuel energy policy in several African countries including Nigeria, Tanzania and Mozambique. Moreover priorities for resource allocation are further complicated by climate change challenges on the one hand, and policies to spur economic growth on the other such as increased energy production (hydropower and biofuels) and industrialisation, which may conflict with the overarching food security objective. Crucially however, policies to address these interconnected challenges are often evaluated at the national or regional scale, which misses out anomalies and variations at the local scale. This calls for a *multi-scale* integrated systems approach to these resource interactions and their effects on food systems in Sub-Saharan Africa, in order to establish where the competing WLE resource constraints are and the variations from local (sub-county), regional, to national scale and ensure that potential policy interventions are appropriately targeted.

1.1 Water-Land-Energy nexus impacts on the *Food System* in SSA

Several other authors have proposed ways of looking at the analysis of the physical resources nexus and food security from the systems perspective. Conceicao *et al.* (2011), specifically consider food systems in Sub-Saharan Africa in their discussion of the strategic considerations for food security in the region. Their study assessed key trends and challenges for attaining food security in Africa using FAO data, World Bank statistics and other peer-reviewed literature. They highlight in particular, the need for *Food System* analysis with emphasis on the interconnections beyond the agricultural sector, for instance the social and health influences on productivity and accessibility. They also identify the need for multi-scale system analysis linking the local scale to the regional and global scales.

Focusing on the physical resource nexus, in contrast to the social and health dimensions raised in Conceicao *et al.* (2011), Bazilian *et al.* (2011, pp.7899-902) discuss the challenges of energy and water resource stress in relation to the *Food System*. Their analysis uses case studies from developing countries, notably energy stress in Uganda, Kyrgyz Republic, Uzbekistan and South Kazakhstan. They propose an integrated *Food System* modelling framework based on the World Economic Forum's (WEF) risk analysis of the global water-food-energy nexus and the International Atomic Energy Association's (IAEA) Climate, Land, Energy and Water (CLEW) modelling framework (WEFWI, 2011). Their framework highlights the links within and across the WLE resource pathways and also emphasizes the need for integrated multi-scale analysis given the need for context specific interventions.

With emphasis on the energy implications of fertilizer use in agricultural intensification, Sage (2012, pp.4-8) discusses the links between food, energy, fertilizers, climate-change, and changing diet trends across contrasting time periods ('food regimes'). Based on UK government statistics, as well as evidence from field studies in Malawi and South Africa, Sage's study reveals the close connection between energy and food stress especially in light of currently energy-intensive fertilizer production. The study argues for integrated analysis of the interconnections between the *Food System* and 'environmental support systems' (Sage, 2012, p.8). They note the adverse consequences of the trend towards more energy-

intensive agriculture, particularly harmful climate change effects namely: erratic weather patterns, extreme temperatures and changing rainfall regimes.

EU (2012) examined the increasing global constraints on the Water, Land and Energy resources and their interconnections, providing a broad discussion on the challenges of managing the world's natural resources. They note the complexities of the resource nexus, highlighting the trans-boundary challenges of river water exploitation particularly in Africa. Their report also underscores integrated resources analysis and management as key to addressing the challenges of food security amidst the current rapidly changing global socio-economic and environmental realities. A significant WLE nexus challenge in SSA is the likely competition between water-use for agricultural purposes versus hydropower production to meet energy objectives. McCartney & Girma (2012) investigated the trade-offs between hydropower production and irrigation water use for the Nile's riparian countries. Their study analysed water stress links to agricultural and hydropower interventions on the Ethiopian Blue Nile up to 2100. Their analysis was based on a combination of Climate Change modelling (using IPCC SRES-AR4 A1B climate scenario), hydrological modelling and water resource modelling, calibrated using 30-year time-series weather data. Their findings indicate the increasing likelihood of water constraints to proposed irrigation and hydropower projects, hence the need for multi-scale analysis of the trade-offs between agricultural water use and other water resource development objectives at the local, national and regional levels.

Ericksen (2008, p.238) and Ingram (2011, pp.420-422) articulate the *Food System* approach to the analysis of food security and physical resource interactions in their proposed Global Environmental Change and Food Systems (GECAFS) framework, based on an extensive literature survey of over 40 high quality peer-reviewed studies, workshops and analyses undertaken by European Cooperation in Science and Technology (COST) and the Consultative Group on International Agricultural Research (CGIAR) between 2006 and 2011 in Europe, the Caribbean, Africa and Indo-Asia. Notably, they propose system-level analysis across the broad-spectrum of food system components, namely: Production, Processing,

Distribution and Consumption. They particularly argue for emphasis on the analysis of environment and natural resource implications in the *Food System*. This is important in light of several harmful ecological effects of both 'traditional' and 'modern food systems' such as water pollution, land degradation/exhaustion, biodiversity loss and habitat destruction. Ingram (2011, pp.420-422) also suggests tools and innovations that could facilitate system modelling, such as Geographical Information Systems (GIS) modelling, mobile-telephony and web-based data crowdsourcing and monitoring.

In setting out a framework for Food System analysis, Ingram (2011) and Ericksen (2008, p.240) also identify 3 main components of Food Security namely: **Availability** (the net stock of food produced, procured or otherwise received within the country; the variety of foodstuffs available; and measures of physical proximity to food stocks and transportation), **Accessibility** (drivers of allocation and preference such as market efficiency and socio-cultural factors, and affordability including the complementary aspects of price and financial ability), and finally **Utilisation** includes both the health & safety considerations during production and preparation, the nutrient content of food, and social value and access to food, all of which are linked to its physical availability (Mukuve & Fenner, 2015). **Figure 1** illustrates the links between these different outcomes of Food Security, their interconnections with the *Food System* components, and their utilisation of the interlinked Water, Land, Energy (WLE) nexus resources. To start with, each of the 3 food security **outcomes** shown on the far right of the diagram is linked to the different **components** of the food system. The **components** of the food system involve different **activities** (such as irrigation, post-harvest processing, fertilizer application etc.), each of which makes use of a combination of **WLE resources** along the nexus continuum as illustrated on the left of the diagram. The WLE resource nexus consists of interlinked **physical systems** that provide services that support the activities (*Figure 1* left).

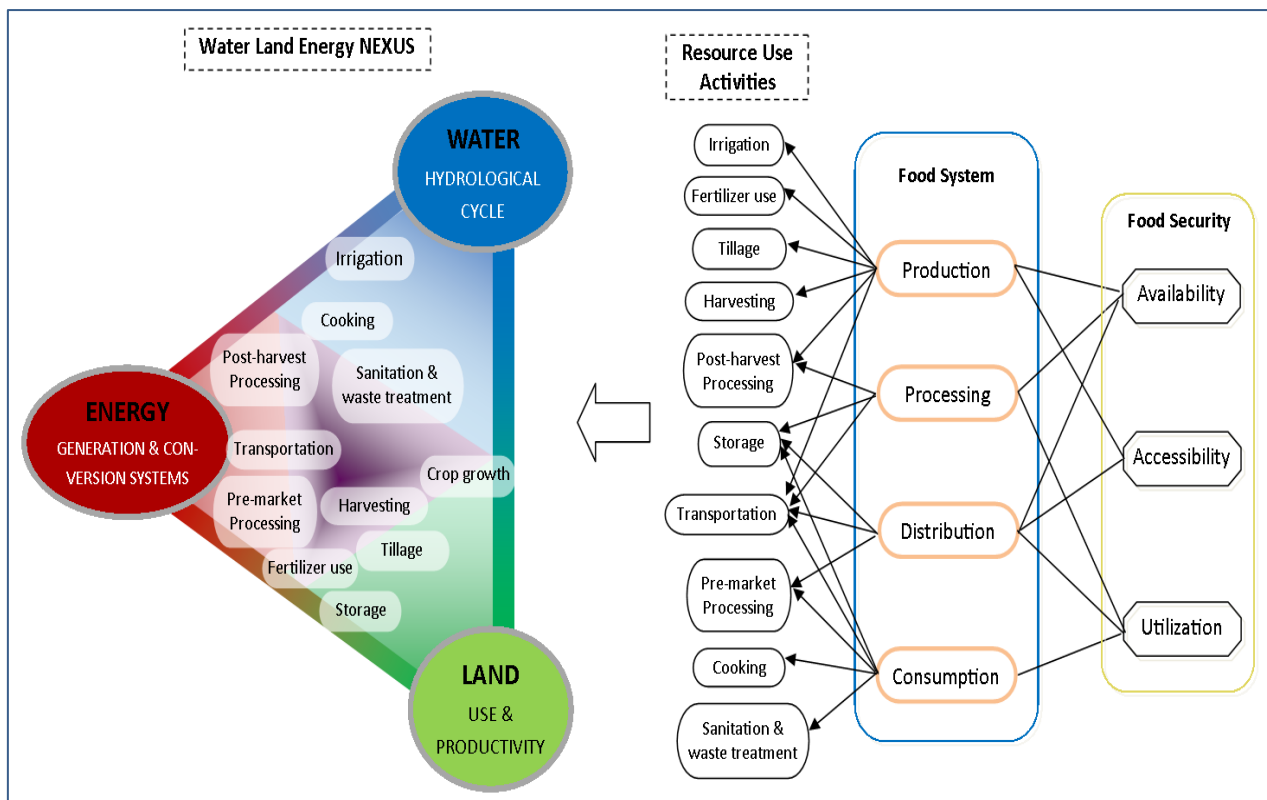


Figure 1: Food System, Key Activities and the Water Land Energy Nexus (**Source:** authors' own illustration developed from concepts from amongst others Mukuve & Fenner, 2015; Ingram, 2011; Ericksen, 2008, p.238).

1.2 Scale Variability of Water, Land, Energy interactions in the Food System

The WLE resources typically require analysis at different scales, to ensure that policies which are often set nationally do not have perverse or unintended outcomes at local scales. For instance, energy resource planning is often carried out at national scale while water stress is often a local challenge. Moreover, crop productivities vary spatially due to various factors including: climate variability, land suitability, external agronomic factors etc., and the influence of these factors also varies at different spatial scales. Therefore analysing resource constraints for homogenous geographic areas may not provide sufficient resolution to identify and test relevant policy solutions at different scales. In a comprehensive review of over 110 peer reviewed studies on agricultural land-use systems, Verburg *et al.*, (2013) specifically argue for the need for integrated multi-scale analysis.

They note that success of interventions at local scale often disproportionately influences policy development at the national level regardless of agricultural technologies adopted and conversely success at the national level often masks large variations at the local scale.

Examples of studies that demonstrate the challenge of scale variability and the need for integrated multi-scale analysis include: Curmi *et al.* (2013a) who modelled the variations in managed water resources flows in California at state and catchment levels using Sankey visualisation. Their analysis showed that state scale water resources analysis gives generalised results that do not adequately reflect local realities (Curmi *et al.*, 2013a, pp.3041). Analysis reported in Yu *et al.* (2012, p.54) showed that the effects of climate variability on wheat productivity in China were weaker for precipitation variability and stronger for temperature variability, showing that the influence of climate variability also varies at different spatial scales. Lawford *et al.* (2013) considered the water-energy food nexus from the perspective of river basins including those of Lake Winnipeg, the Yangtze River in China and several smaller basins in India under the Global Water System Project (GWSP). Their review showed that even within a single resource system (in this case – water resources), the interactions of the different components also vary at different spatial scales adding another layer of complexity (Lawford *et al.*, 2013, p.608). They therefore emphasise the need for multi-scale analysis of the food system WLE resource interactions at different analytical resolutions.

The paper builds on research reported by Mukuve & Fenner (2015) who analysed at the national level, Uganda's 2012 food system physical resources vis-à-vis the country's current and potential food demand. Mukuve & Fenner (2015) used the *Source-to-Service* resource transformation modelling concept developed by the Cambridge University Engineering Department *Foreseer*TM Project (see www.Foreseer.org) [Curmi *et al.*, 2013a, b], to analyse Uganda's food system resource requirements and competing WLE resource demands at different stages of the food system, as a test case for Sub-Saharan Africa. The research reported in this study undertakes integrated multiscale WLE analysis by incorporating *geo-spatial analysis* and geovisualisation with the *Source-to-Service* modelling concept and

calorific demand analysis employed in the previous paper, to analyse Uganda's food system resource constraints at *multiple scales*. In particular the focus here is on the spatial dimension to understand where the competing WLE resource constraints are and the variations from local (sub-county) to national scale so that potential policy interventions can be appropriately targeted. The multi-scale analysis from local to national scales helps to determine i) where the key resource constraints are, ii) at what stage of the food system along and across the WLE resource pathways, and iii) how the constraints will change in the future. The focus of the paper is on the systems perspective hence the analysis is limited to the national, regional, and local district/sub-county levels. Nevertheless the findings from the study form the basis for further micro-scale/household level analysis within the systems context.

1.3 Study Area – Uganda

Uganda has been selected as the test case for this study as a template for the multi-scale integrated food system resource analysis of food systems in Sub-Saharan Africa (SSA). Uganda is located between latitudes 4°N to 2°S and longitudes 29° to 35°E. It is divided into 112 administrative districts and eight (8) hydrological sub-basins that are part of the Nile basin, along with 9 major cropping systems/agro-ecologies (UBOS, 2013; MWE, 2013). Uganda has a broad range of food security challenges similar to the other SSA countries including: economic, conflict-related, and resource constraints; and has diverse agro-ecology that is representative of the agro-ecologies in the region. 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, 2013), with a rapid urbanisation at a rate of over 4% (UN-HABITAT, 2014). In 2014, nearly 11 million people (~26%) of a total population of about 36 million were food insecure (FAOSTAT, 2014). A significant proportion of these are urban-poor. Over 25% of children less than 5 years are seriously malnourished (ECA, 2012, p.10). As of 2014, Uganda had a GHI classification of 16 – 20 indicating 'serious' food security challenges (IFPRI, 2014).

Water stress

Unreliable rain-fed agriculture remains the most prevalent source of food in Sub-Saharan Africa. In Uganda, subsistence-farmer households who rely on rain-fed agriculture for their livelihoods form over 80% of the population, a large proportion of whom are food insecure (UBOS, 2013). According to HLPE (2012) and Kigobe & Griensven (2010), although precipitation is projected to rise in most parts of the country, any gains will probably be countered by rising temperatures, inhibiting weather extremities, and droughts, leading to a reduction in crop yields. HLPE (2012, p.42)'s findings were based on analysing the effect of climate change on global crop yields using the CSIRO and MIROC General Circulation Models – GCMs (CSIRO – Australian Commonwealth Scientific and Industrial Research Organisation; MIROC – Model for Interdisciplinary Research on Climate). Kigobe & Griensven (2010, pp.2101-2) made a similar finding for Uganda in their hydrological simulation of the impact of climate change in the Uganda/Upper Nile region over the next century. Their study involved statistical downscaling of three GCMs using Generalised Linear Modelling. Other studies by Moore *et al.* (2012, p.835)'s Regional Atmospheric Modelling System (RAMS) and Thorton *et al.* (2010, p.77)'s MarkSim weather model, the DSSAT crop model and the WATBAL water-balance model show that yield declines in East Africa and Uganda in particular could exceed 30%, with Uganda in particular experiencing mainly negative effects. In order to close the yield gaps in Uganda, over 110 irrigation projects covering a total of 241,671 hectares have been planned in the country for period up to 2030 as contained *the National Irrigation Master Plan for Uganda, 2010 – 2035* (MWE, 2011). These planned projects should help to eliminate the yield gaps. However, further investigation is required to examine the effects of these planned agricultural water withdrawals in relation to competing water demands and the other resource dependencies.

Energy stress

Uganda's current Energy Development Index is very low at only 0.07 (IEA, 2012), with very limited access to gridded energy. Over 90% of Uganda's current energy use comprises unsustainable biomass fuel used for food cooking (IEA, 2012). Currently energy consumption for agricultural production in Uganda is only 10 TJ (UNSD, 2012), which is low with compared to agro-energy consumption in thousands of TJ in developed economies.

Most of Uganda's current electricity production is sourced from two main power stations along the Nile, namely Kiira/Nalubaale and Bujagali which together have an installed capacity of ~630MW. However, Uganda faces a rapidly growing electricity demand at a rate of 10-12% per annum with electricity demand by 2040 expected to reach over ~41,000MW, representing a growth in demand of over 40 times the currently installed generation capacity (ERA, 2014). The agricultural intensification required to eliminate yield gaps and achieve food security is likely to form a major proportion of the growing energy demand. Current energy policy in Uganda is targeted at further renewable hydropower development to meet these energy requirements. However, given that Uganda's hydrological system is dominated by the Nile river system which has transboundary implications, there is need for analysis of both the energy requirements to meet the growing demand, and the interconnected trade-offs that may arise from competing water demands such as: irrigation, industrial use, municipal uses, and ecosystem conservation.

Land & Soil Quality

Uganda faces several land and soil quality pressures related to amongst other factors, rapid population growth and subsistence agricultural practice. Smallholdings account for over 95% of the cultivated land area according the national statistics by the Uganda Bureau of Statistics (UBOS, 2013). This land fragmentation diminishes the economies of scale required for high intensification agriculture, and shifts farmer priorities towards low-output subsistence agriculture, as highlighted in Kijima *et al.* (2010, p.82). Kijima *et al.* (2010)'s findings are based on analysis of the adoption and performance of improved rice varieties and enhanced agricultural techniques, using a data from 347 households in Central and Western Uganda. Rapid population growth projected to reach over 108 million people by 2050 (UNPD, 2014; medium variant) continues to further reduce the amount of land available per capita for food production on one hand, while increasing the rate of deforestation on the other due to growing demand for primary wood fuel. Unsustainable agricultural practices remain prevalent including over grazing, detrimental tillage methods leading to soil erosion, and other nutrient depleting cropping methods (WOCAT, 2009). Moreover, access and use of fertiliser is very low at less than 2kg per hectare (kg/ha), and

where available, incorrectly applied resulting in further land degradation (Bayite-Kasule, 2009; Namazzi, 2008). These challenges call for in-depth analysis of the implications of continued population pressure on land-use, soil quality, ecosystems depletion and future land resource availability.

In this paper, integrated resources analysis of Uganda's WLE resources and 2012-2050 food demand has been carried out for multiple interconnected scales. The scales considered are: national – at Uganda country level; regional – for the selected Central 1 region; and district/local – for Uganda's capital, Kampala city. Kampala city and Central 1 region were selected because they comprise the economic centre of Uganda and the likely location of most of the anticipated rapid urbanisation and corresponding growth in food demand. Kampala's population growth rate is the second highest in Eastern Africa region at 6.75% and it hosts the largest proportion of Uganda's total urban population at 31.2% (UN-HABITAT, 2014, pp.149-150). *Figure 2* gives a summary of the key statistics of Uganda as discussed in this section, indicating the location of Kampala city, the Central 1 region and the other regions of Uganda.

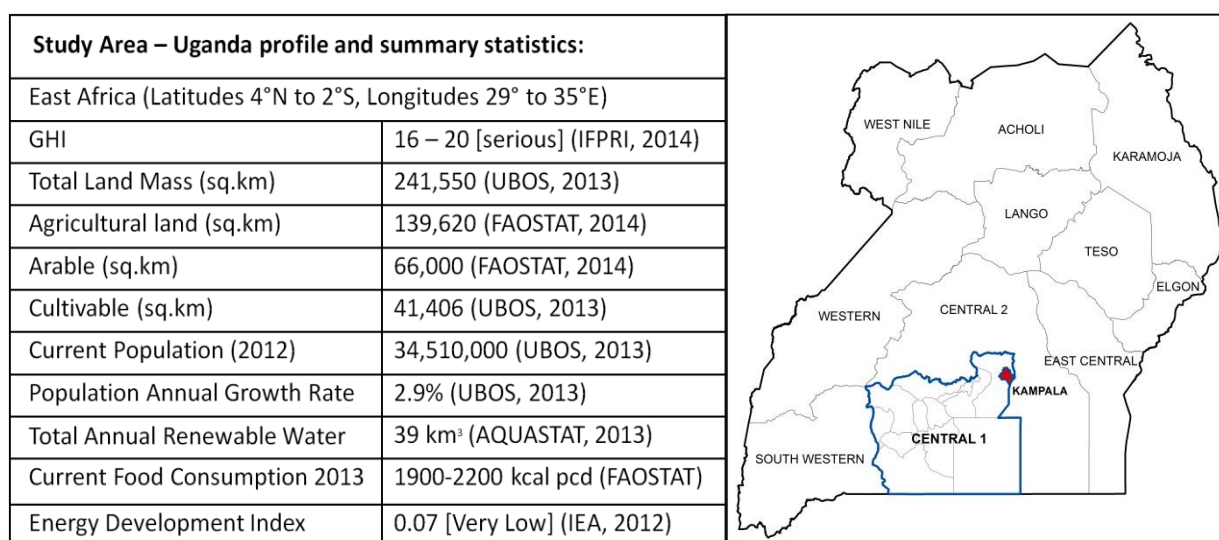


Figure 2: Study area – Uganda Summary Statistics and Map showing Central 1 region, Kampala City

2. Analytical Approach

The analytical approach in this paper consists of two parts. The first part involves spatial analysis using ESRI's ArcGIS geo-processing to examine the agricultural resource deficits and surpluses (WLE resource thresholds) in Uganda at national, district and local resolutions for the base year 2012, and the target year 2050. This involves geo-processing and mapping of the results of 2012 and 2050 calorific-demand analysis and resource demand modelling. A synopsis of these methods is provided in Section 2.1.

The second part involves detailed examination of the interconnected WLE *Source-to-Service* resource fluxes and transformations at the national (Uganda), regional (Central 1) and district scales (Kampala city) for the base year 2012 and projected to the year 2050. This part enables the comparison of the current competing WLE demands and constraints in Uganda's food system at the different scales in order to identify key resource intervention areas to resolve the resource stresses identified in the first part. The technique employed for the second part is *Source-to-Service* resource transformation modelling using Sankey diagrams to track and visualize the results of the analysis. The procedure for this is described in Section 2.2.

2.1 Geospatial Analysis of Uganda's Resource Limits

The first part of this study involves geospatial analysis of the agricultural resource deficits and surpluses in Uganda at national, regional and district/local scales resolutions for the base year 2012, and the target year 2050. The analytical approach for this includes *calorific-demand analysis* and *resource demand modelling* as follows. National, regional and district statistics on Uganda's 2012 and 2050 populations and projected growth rates were computed using data from the Uganda Bureau of Statistics database (UBOS, 2013), and validated using United Nations Population Division (UNPD, 2014) database and FAO's COUNTRYSTAT database figures. The computed population figures were then multiplied by the FAO recommended 3,000 kcal per capita Daily Calorific Intakes (DCIs) (in

kilocalories/capita/day – kcal.p.c.d) [FAO, 2014] to give annual calorific demands which were in turn converted into food system resource demands using methods summarised in Sections 2.1.1 to 2.1.3 below. A similar approach is adopted in De Fraiture & Wichelns (2010) to compute food demand at global and regional scales. The difference between the calculated agricultural resource demands and the sustainable WLE resource endowments for each area gives the resource deficit or surplus. The 2050 projections are based on the UN Medium Variant population projection for Uganda; Uganda's 25-year average GDP growth rate (from 1989 to 2013), which is 6.8% calculated using data from the World Bank (WB, 2014); and the *IPCC SRES B2 – RCP 6.0* climate change scenario which is the midway scenario corresponding to business-as-usual. The projections also include all the planned irrigation projects as contained the *National Irrigation Master Plan for Uganda, 2010 – 2035* (MWE, 2011) and planned energy projects in MEMD (2012), including domestic petroleum production anticipated to commence in 2018. Energy consumption and access are computed based on projected GDP growth rates, and include projected biomass burner efficiency enhancements and projected growth in grid sourced energy consumption. The results of the analysis were then mapped using ESRI ArcGIS for spatial analysis and geo-visualisation. Data sources for the resource calculations include the Uganda Bureau of Statistics (UBOS) database, the University of Copenhagen Potential Natural Vegetation (PNV) model for Eastern Africa (Lillesø *et al.*, 2011), FAO's FAOSTAT, COUNTRYSTAT and AQUASTAT 2013 databases, the UN Statistics Division and International Energy Agency (IEA) Energy Statistics databases.

2.1.1 Water

The agricultural water resources requirements were analysed vis-à-vis the internally generated water flows (IRWR) to avoid the trans-boundary complexities and uncertainties surrounding external water inflows. The agricultural water resource demands at the different scales in Uganda's food system were calculated using Hanjra & Qureshi (2010, p.369)'s approach, adopting an approximate ratio of 1 litre per kcal for 365 days, less Uganda's 2012 average DCI of 2,100 kcal (FAOSTAT, 2014). These values were compared with figures obtained using Rockstrom (2003)'s projected 2030 annual consumptive use of

1,300 m³ per capita per year (m³ pca) assuming a 20% animal protein diet. The normalised net per capita food water surpluses/deficits for the different scales were then mapped.

2.1.2 Land

The cultivable land demand for the different scales for 2012 and 2050 were estimated using (Equation 1. 17 crop types were considered in the analysis as extracted from UBOS (2013) and the FAOSTAT database (FAOSTAT, 2014) namely: banana/plantain, potatoes, cassava, yams, beans, maize, oil palm, rice, sorghum, coffee, sugarcane, cotton, vanilla, fruits, vegetables, other legumes and pulses. The different crop calorific contents were converted into cereal-equivalents, and the analysis carried out using an Average Crop Calorific Content (ACC) per tonne of 3.9×10^6 kcal (Hollander, 2004, p.41). The composite crop yield and yield growth rates were calculated using 12-year yield and production statistics from the FAO's FAOSTAT 2014 database and Uganda Bureau of Statistics database UBOS (2013). Comparisons were also made with figures from Kraybill *et al.* (2012, p.3) and Kaizzi *et al.* (2012, p.109).

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

i – Year

Lr_i – Land required for given year *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

The computed land requirements were compared with Uganda's cultivable land area computed using reclassified and validated spatial data from the FAO's Globcover geodatabase (FAO, 2013). Future land use change rates (urban, agricultural and deforestation) were calculated using data from the FAO's Globcover geodatabase, UBOS database, and published sources including the FAO – Uganda National Forestry Authority (NFA) Forest Resources Assessment 2010 (NFA, 2010) and MAAIF (2011, p.vii). The normalised net per capita cultivable land surpluses/deficits for the different scales were then mapped using ESRI's ArcGIS.

2.1.3 Energy

The agricultural energy consumption was estimated using the 'Energy Use Efficiency' or 'Energy Ratio' (EER) which is the ratio of energy output to energy input (Houshyar *et al.*, 2012, p.674; Soltani *et al.*, 2013, p.56). An EER of 12.74 was adopted from Houshyar *et al.*, (2012, p.678) representing an enhanced energy efficiency ratio for developing countries using improved agricultural methods such as mechanised tillage, post-harvest processing and irrigation. The minimum agricultural energy requirements for Uganda at the different scales were then calculated using (Equation 2).

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

i – Year

Er_i – Energy (TJ) required for year *i*

DCI_i – Daily Calorific Intake

P_i – Population

EER_{max} – Maximum recorded Energy Efficiency Ratio (EER)

The computed energy requirements were compared with estimates of Uganda's 2012 and 2050 energy supplies calculated using energy balance statistics from the UN Statistics Division and International Energy Agency (IEA) Energy Statistics database (UNSD, 2012), assuming a potential food energy mix of 18% which corresponds to the global food energy mix in Cullen & Allwood (2010, p.80). The 2050 projected energy mix considered in this study is the likely 'Business-As-Usual' scenario which assumes the complete development of all planned renewable power stations (mainly hydropower) supplemented by Uganda's internal oil production and imports of petroleum products from the world market by Uganda's growing economy (MEMD, 2012). The net agricultural energy availability was mapped for the different scales using ESRI's ArcGIS.

2.2 Modelling Food System Resource Flows and Thresholds

This second part of the analysis looks at the WLE resource transformations and conflicting demands in Uganda's food system at country, regional and district/local scales to understand the dynamics of the WLE transformations at the different analytical resolutions. The method used involves modelling and tracking the resource interactions as

they occur along the various stages of the food system, that is: production, processing, distribution and consumption, and visualising the resource fluxes using Sankey diagrams. The transformations considered are not *food transformations* but rather the *WLE resource transformations* that map onto the food system stages. The construction and features of Sankey diagrams are described in Riehmman *et al.* (2005).

The WLE resource transformations in Uganda for the base year 2012 are traced from their primary sources through to their final services and projected to the year 2050. 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 3 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 (Riehmman *et al.*, 2005). The Sankey diagram components are designed correspond to the production, processing, distribution and consumption stages of the *Food System*. The process is illustrated in *Figure 3*.

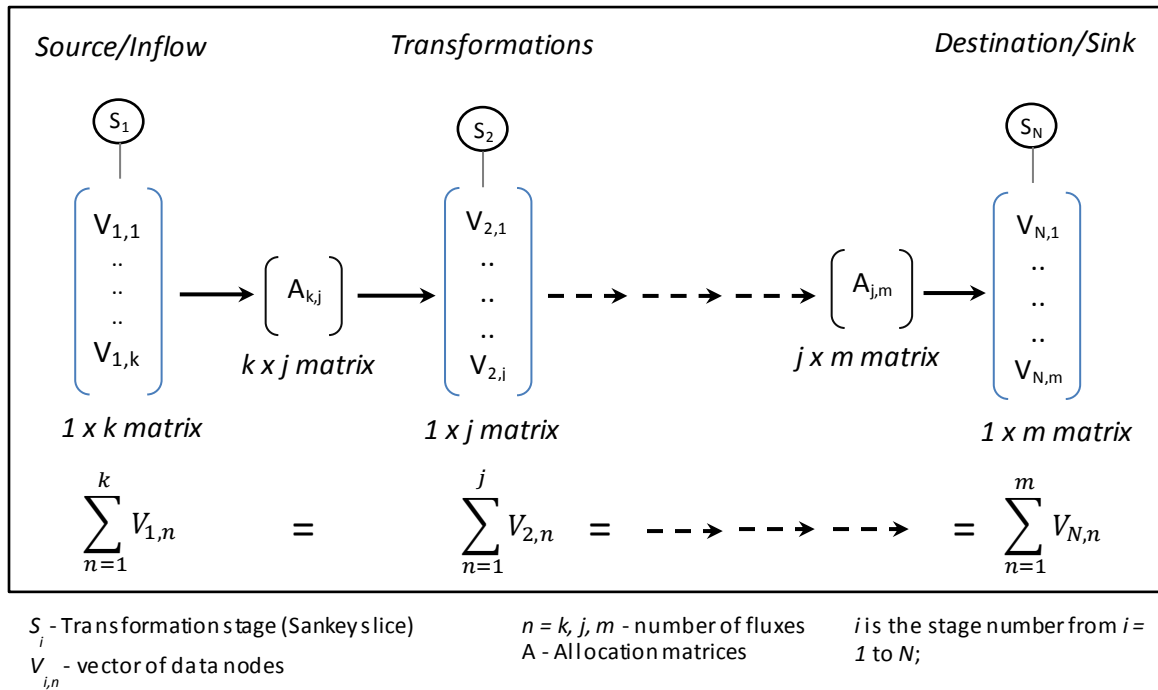


Figure 3: Source-to-Service Resource Transformation Modelling (Source: Mukuve & Fenner, 2015)

3. Multi-scale Resource Limits Results

The results of the resource demand modelling and geovisualisation for each of the WLE resources for the baseline year 2012 and the projected year 2050 are given in *Figure 4a, b, c* and *Figure 5a, b, c* below. The maps show the Water, Land, and Energy food resource surplus or deficit geovisualisation from left to right, with regional, district and local (sub-county) shown from top to bottom.

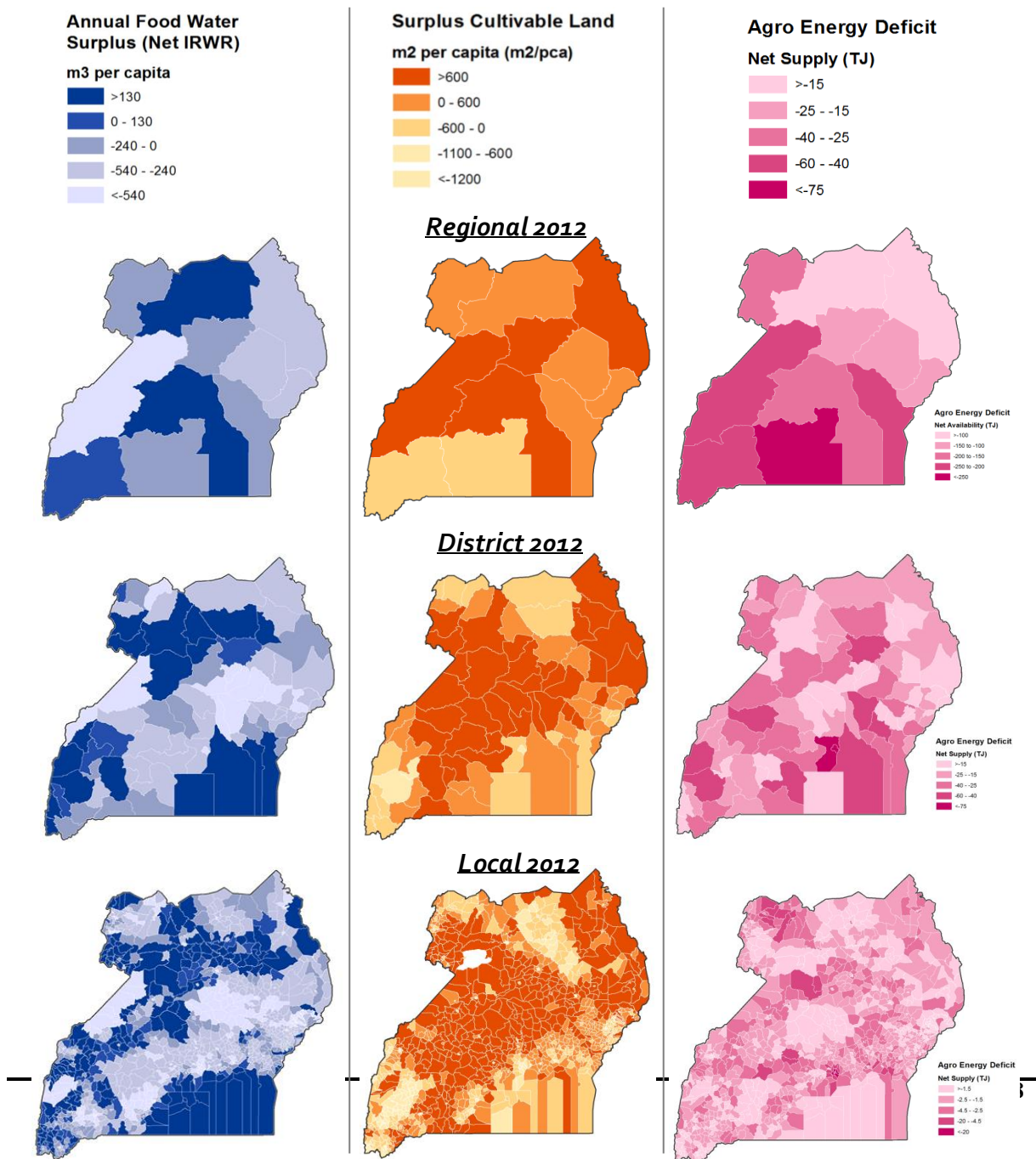


Figure 4a, b & c: 2012 annual WLE Food Resources surplus/deficit geovisualisation

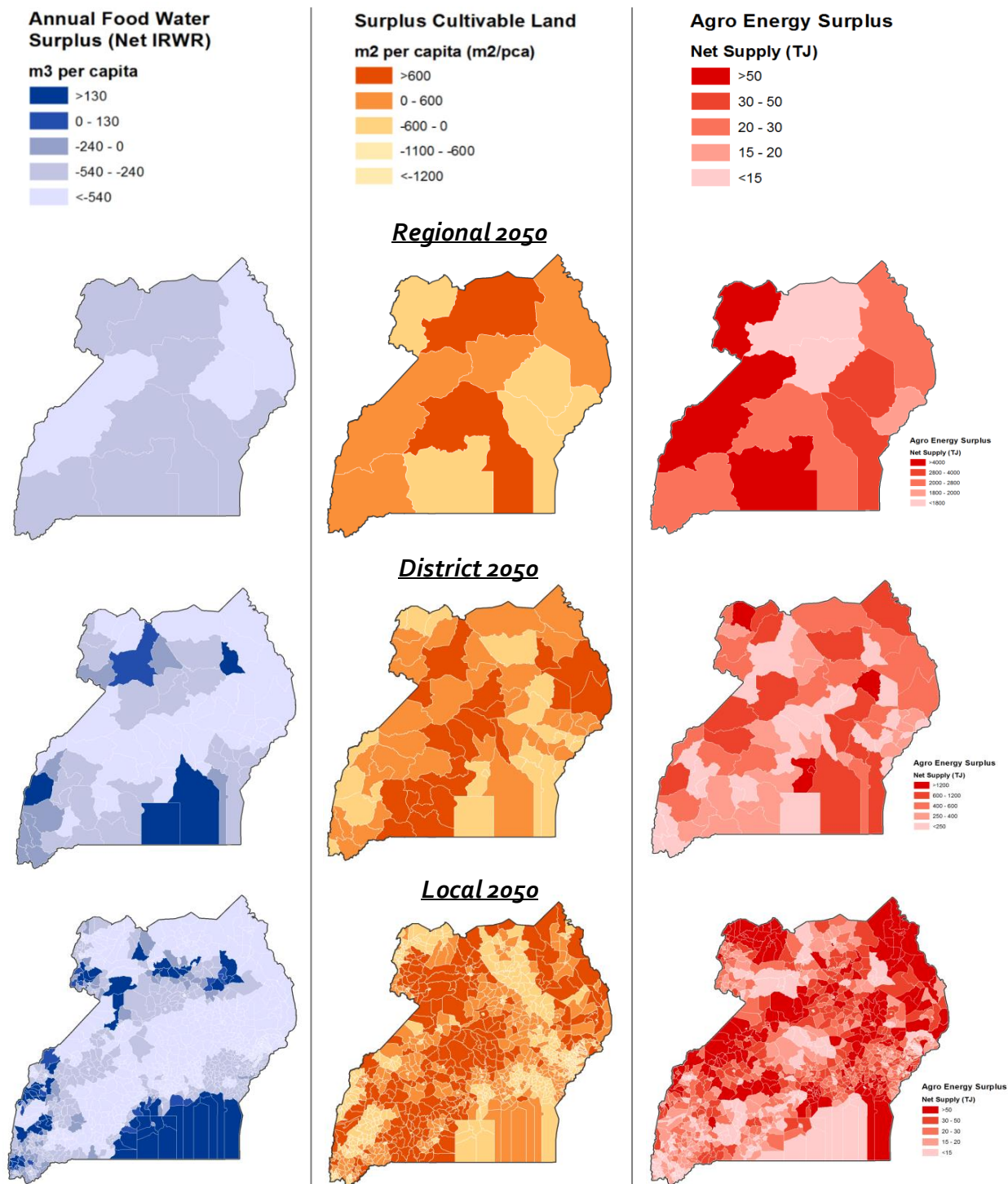


Figure 5a, b & c: 2050 annual WLE Food Resources surplus/deficit geovisualisation

3.1 Water Resource Limits Analysis 2012–2050

The analysis shows an estimated overall national per capita food water deficit of about -184 m³ per person for the year 2012 when compared with national IRWR flows. However, analysis at the regional level (*see Figure 2 for region locations*) reveals surpluses in the South Western region and Central 2 region (180 m³ pca), with the largest surplus in Acholi sub-region in the north (480 m³ pca) [*see Figure 4a top*]. These surpluses are however negated by deficits in the other regions ranging from about -180 m³ pca in the East Central sub-region to -720 m³ pca in the Western region. Moreover, the food water surplus in the Central 2 region masks net deficits at the local and district levels with net deficits shown in constituent districts such as Luwero (-470 m³ pca), Nakasongola and Mityana (*Figure 4a middle*). The Central 2 regional surplus only arises as a result of the lake water IRWR availability in the lower half of the region as shown in the district and local level food water maps (*Figure 4a middle & bottom*).

The 2050 food water projection results show even greater food water stress with over the 2012 national average annual per capita food water deficit (-490 m³ pca). Regional analysis shows projected food water deficits in 2050 in all the regions (

Figure 5a top). The rapidly urbanising Central 1 region is projected to have an average food water deficit of -410 m³ pca by 2050. The district and local level food water analysis reveals some exceptions to the general trend. Five districts are projected to have food water surpluses by 2050 (

Figure 5a middle). And apart from Abim district (in Acholi region, *shown in Figure 2*), the other districts with food water surpluses have access to lake water IRWR. Notably the analysis shows that these five districts have surpluses in both 2012 and 2050 and therefore should be focal places for future food policy planning.

3.2 Land Resources 2012–2050

In contrast to the water analysis, the 2012 land resource analysis indicates a net cultivable land surplus at the national level, though marginal, with an estimated average surplus of about 440 m² (0.11 acres) pca. The regional land geovisualisation also shows contrasting resource availabilities in the different regions. Agricultural land deficits appear to occur in the regions where water surpluses exist and vice-versa (*Figure 4b*). The agricultural land resource analysis at the district and local levels shows the composition of the deficits and surpluses. Notably, cultivable land deficits appear to occur in the South Western districts where agro-water surpluses currently exist, the mountainous Elgon sub-region districts in the East, and some Northern districts (*Figure 4b*). As expected, land deficits also occur in the areas around the capital – Kampala city.

The results for 2050 show a projected drop in cultivable land surplus at the national level of over 60% to only 170 m² pca by 2050. Regional analysis shows consistent drops in land availability in most regions of country (*Figure 5b*). The exceptions include the Central 2 (see *Figure 2*), which is projected to retain a land surplus (albeit diminished), and improvements in the South Western and Acholi sub-regions. However further analysis shows that this would come at the cost of near complete depletion of land for eco-system services (Section 4). District and local scale land analysis shows that the 2050 land surplus in Acholi region would be due to significant change in Kitgum district (320 m² pca from -60 m² pca in 2012) which currently has considerable uncultivated land as well as eco-sensitive grasslands that would be converted to agricultural use, although a proportion are protected. A similar trend would occur in Amuru district in Acholi sub-region and Abim district in Karamoja sub-region which are also projected to have cultivable land surpluses.

3.3 Agricultural Energy Resources 2012–2050

The analysis suggests that energy resource stress was the most prevalent constraint throughout the country in 2012 with the largest agricultural energy shortage occurring in the Central 1 region (*Figure 4c*) with an average energy deficit of -55 MJ pca. Agricultural energy consists of energy required for irrigation, mechanisation, tillage, post-harvest processing. Districts with the largest agro-energy deficits include Kampala–the capital city

(-95 TJ), and the surrounding districts of Wakiso (-76 TJ) and Mukono (-57 TJ) that are witnessing rapid urbanisation, resulting in limited energy availability for increased agricultural production (*Figure 4c*).

In line with anticipated economic growth and anticipated oil production, the energy analysis shows agricultural energy surpluses throughout the country by 2050 (

Figure 5c). Given this energy growth scenario, the largest regional agro-energy surpluses are projected to occur in the anticipated oil producing Western region (5,130 TJ), the West Nile region (5,360 TJ) and the Central 1 region (4,720 TJ) which should experience the bulk of the anticipated commercial and industrial growth. The district and local level analysis shows the distribution of the projected surpluses, with potential agro-energy surpluses ranging from 26 TJ in Abim district to 1790 TJ in Kampala city corresponding to the highest level of access and urban purchasing power.

4. Resource Flow Analysis – Sankey Diagrams

The second part of the analysis involved source-to-service resource transformation modelling of Uganda's national, regional and district/local Water, Land, and Energy Resource Flows for the year 2012 and 2050. The results of this analysis were visualised using Sankey diagrams as shown in *Figure 6*, *Figure 7*, and *Figure 8*. The figures respectively show Uganda's 2012 and 2050 WLE resource flux transformations and interactions at National, Regional (Central 1 region) and District/Local scales (the capital city – Kampala) (top to bottom). The main emphasis of the diagrams is on the relative shapes of the WLE fluxes, with the numerical results as complementary detail. Hence the Sankey diagrams have been scale-normalised by population ratio to highlight the changes in the resource flux proportions at each geographical level. The national, regional and district/local Sankey diagrams are arranged from top to bottom, and the 2012 and 2050 are on the left and right respectively.

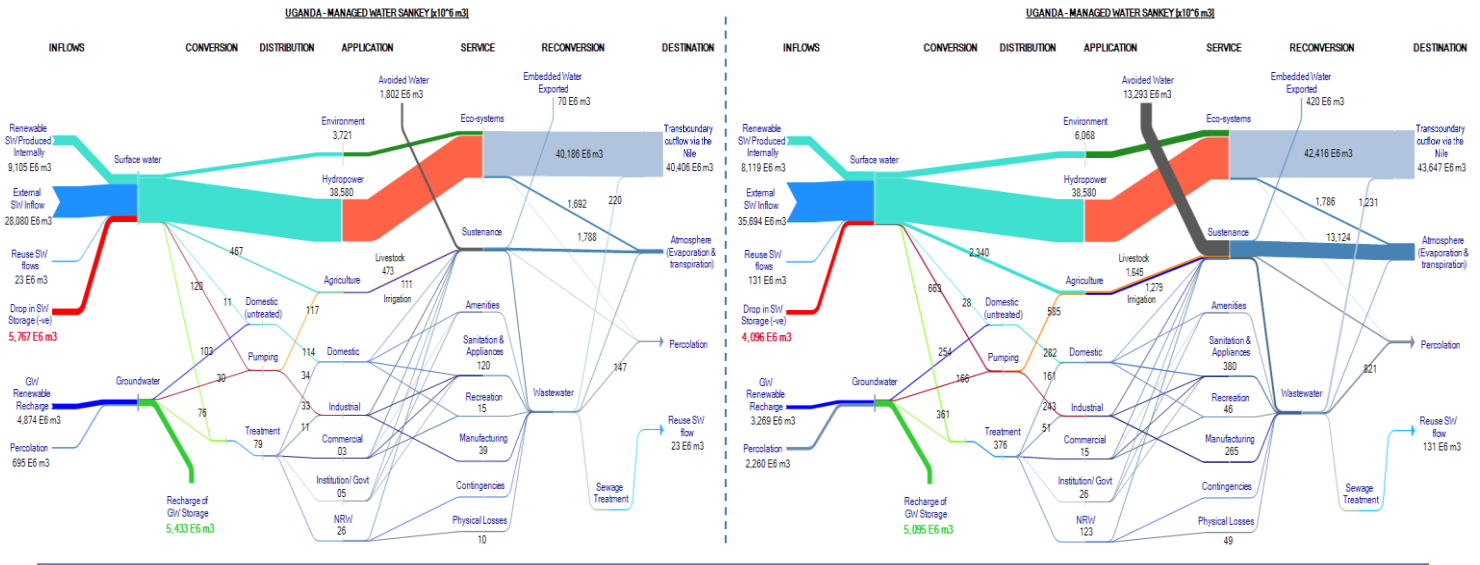
Figure 6: 2012 - 2050 (left to right) Water resource Source-to-Service fluxes, from national to local scale (top to bottom)

WATER FLUXES

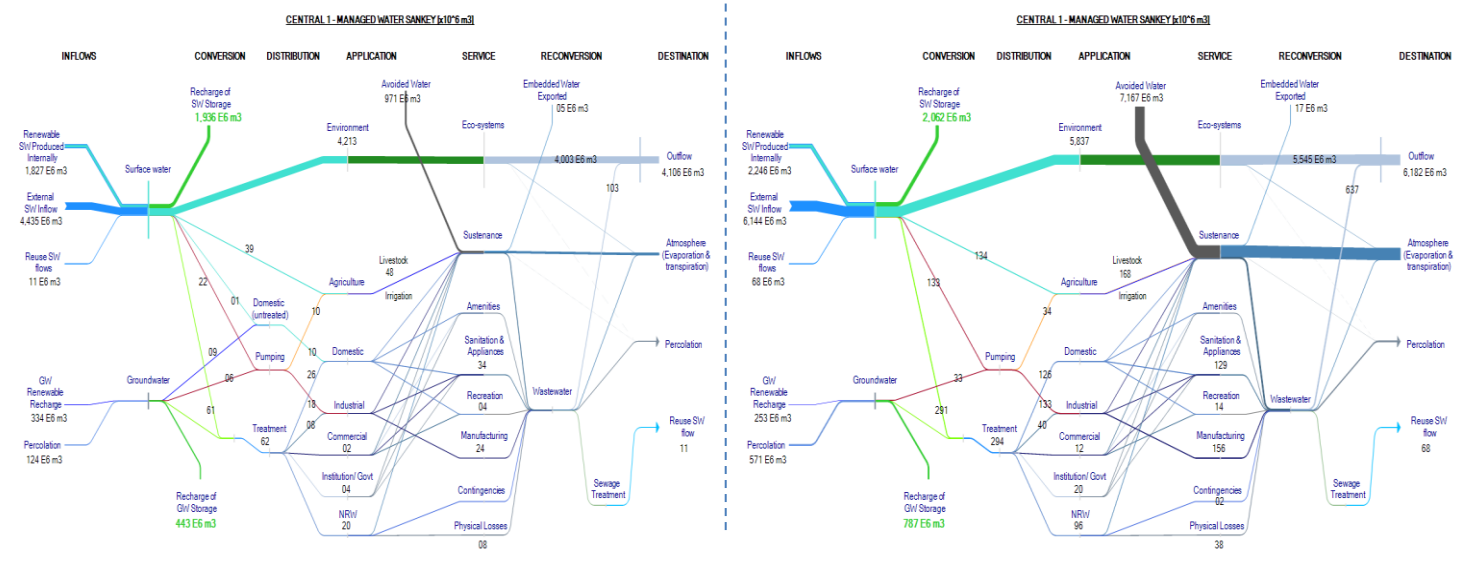
2012

2050

National



Central 1 Region



Kampala City

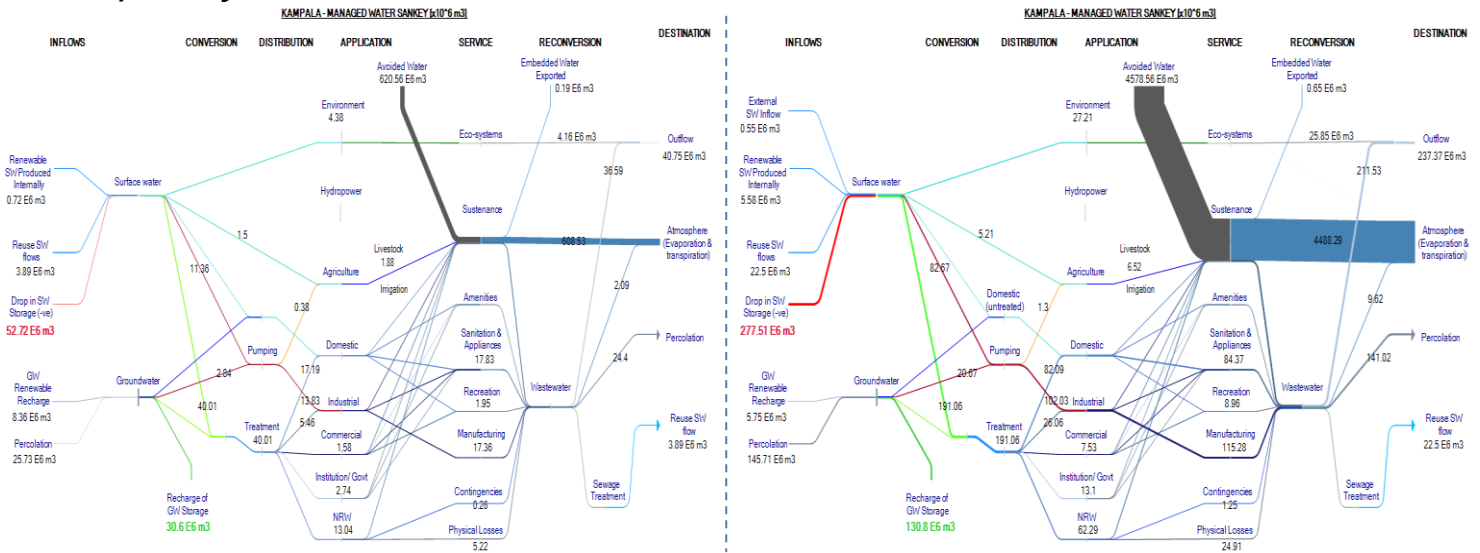


Figure 7: 2012 - 2050 (left to right) Land resource Source-to-Service fluxes, from national to local scale (top to bottom)

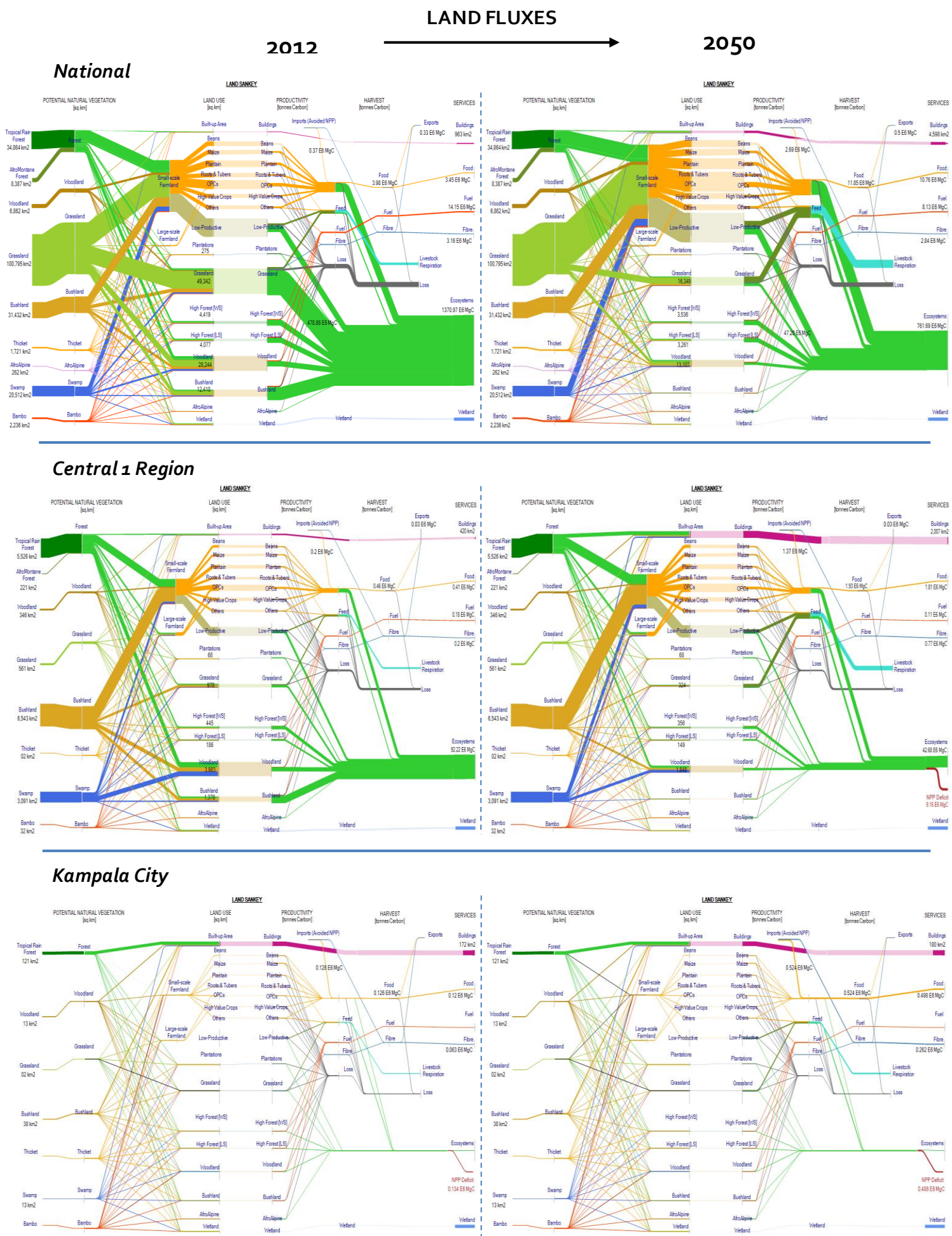


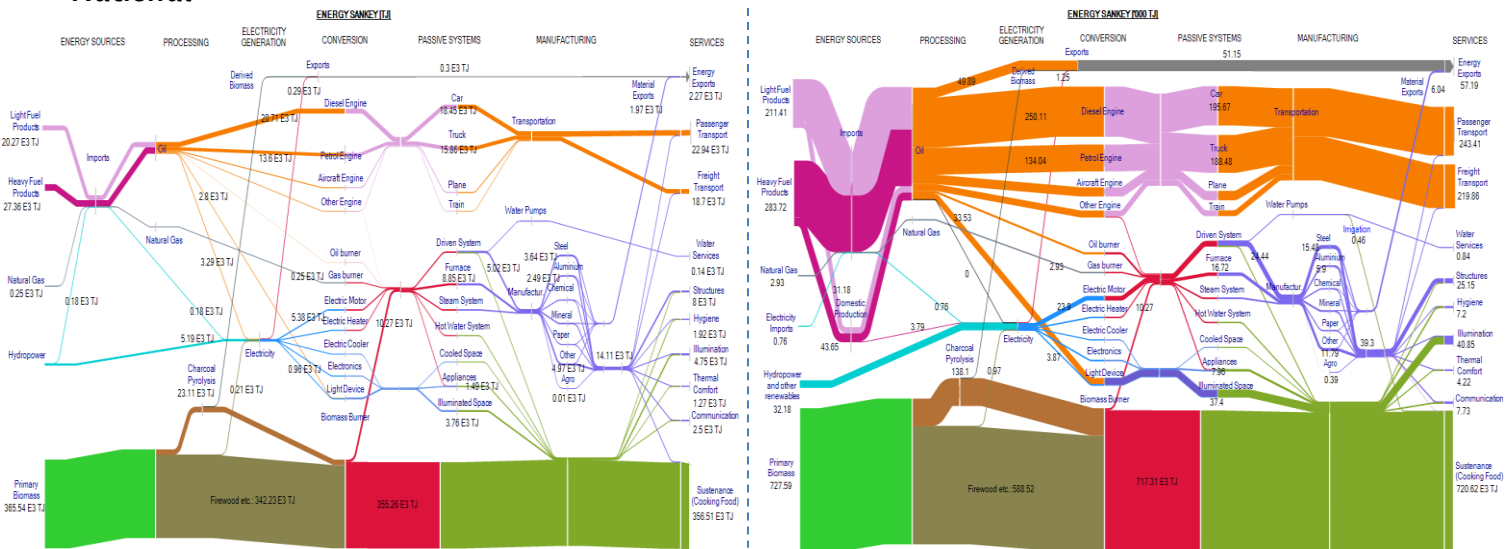
Figure 8: 2012 to 2050 (left to right) Energy resources Source-to-Service fluxes, from national to local scale (top to bottom)

ENERGY FLUXES

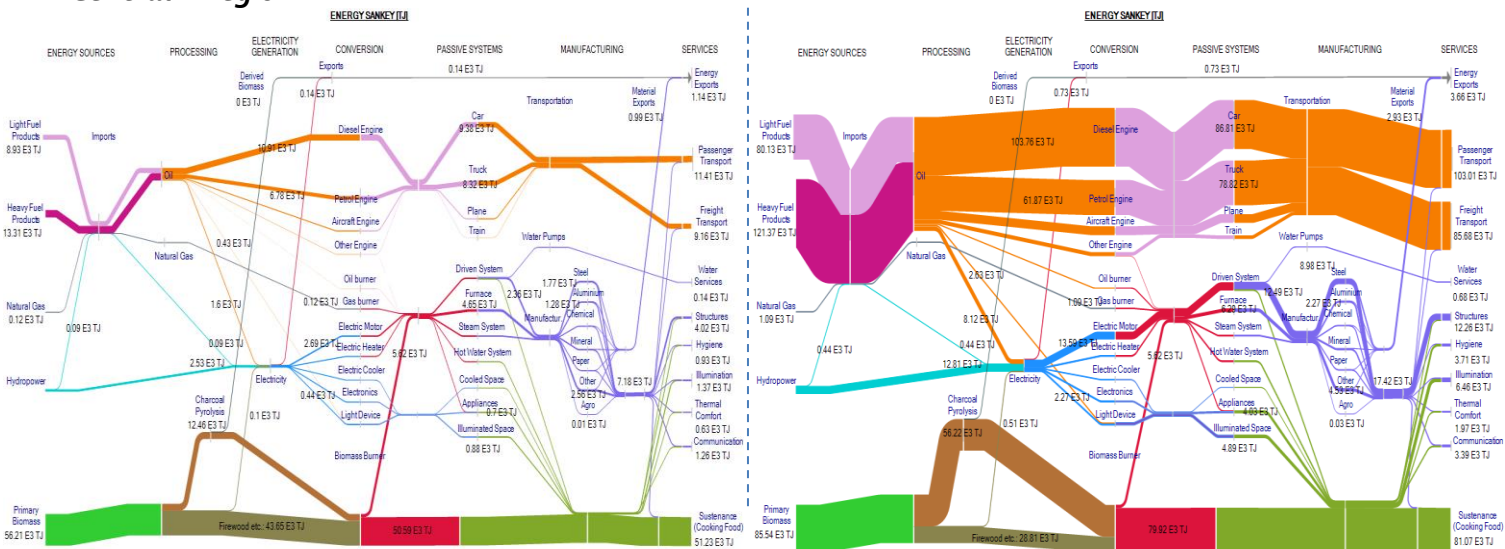
2012

2050

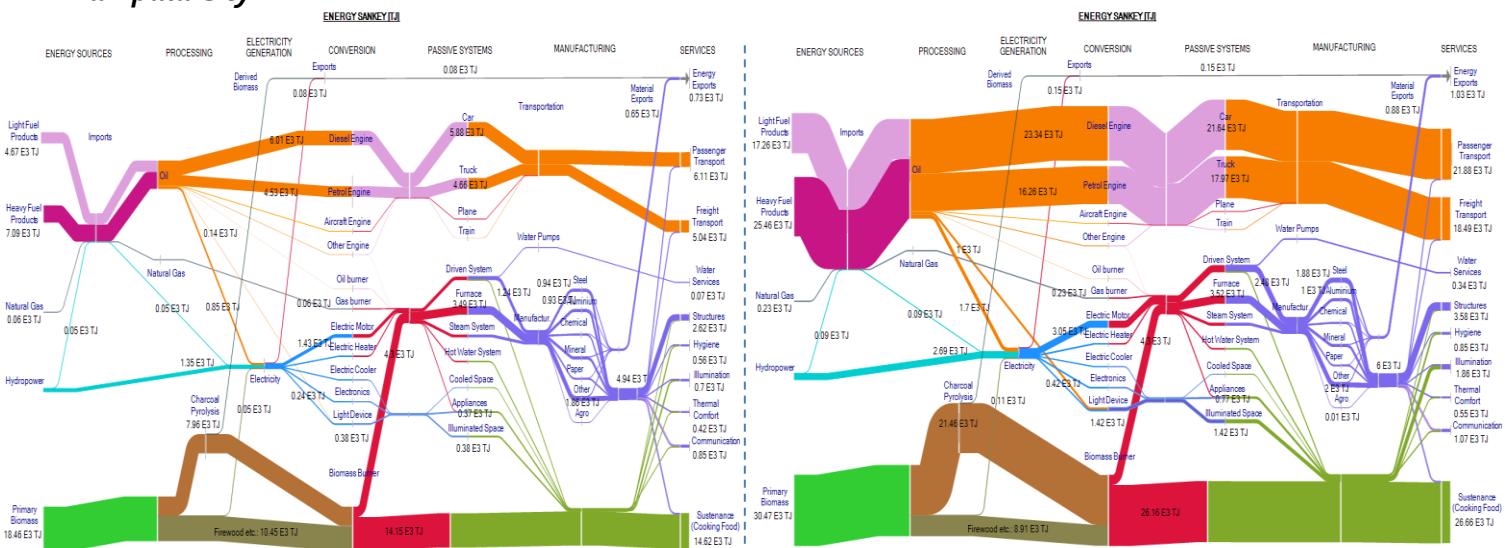
National



Central 1 Region



Kampala City



4.1 Managed Water Resource Flows 2012–2050

At the country scale as of 2012, managed water flows to agriculture were less than 1% of the total IRWR at only 0.6 km³ (*Figure 6 top left*) (MWE, 2011). Most of Uganda's water flows are channelled for hydropower production (see *Figure 6 top left*), accounting for 39 km³ of Surface water flows (AQUASTAT, 2013) used to power the Nalubaale and Bujagali Large Hydropower Schemes along the Nile, and small hydropower projects spread out around the country, such as Buseruka, Bugoye, and Nyagak (MWE, 2012). This water may not be readily available for subsequent irrigation given that these dams are optimised primarily for energy production. The potable water flux is estimated at a comparatively miniscule 0.08 km³ which includes treated water used for domestic, industrial, commercial and industrial consumption, produced mainly by the National Water and Sewerage Corporation (NWSC, 2012). Water used for sustenance and industry is mostly obtained directly from the IRWR without conventional treatment.

The regional scale 2012 water resource transformation Sankey for the Central 1 region (*Figure 6 middle left*) is dominated by Eco-system services flows (4.2 km³). The Central 1 regional level analysis shows a likely food resource tension with preserving environmental flows, given that the region currently accounts for only about 8% of current agricultural water withdrawals (0.049 km³ of 0.6 km³ national). In contrast, municipal water flows to the Central 1 region make up most (79%) of the national treated water flows (0.062 km³) pointing to significant competition from urbanisation in the region, particularly the capital – Kampala city. The main managed water flow in the Kampala city water Sankey (*Figure 6 bottom left*) is actually food water imports or '*Avoided Water*' (that is, the water resources that would have otherwise been used to produce the imported food locally). This suggests that the food resource interventions at the city scale should potentially focus on securing strategic import routes and links to production centres.

Figure 6 (top right) gives the projected 2050 managed water Sankey for Uganda showing the bulk of the water flows still going to hydropower production. The analysis however, also shows a major rise of over in avoided water imports to 13 km³ driven by rapid urbanisation and increased demand due to population growth. There is also an almost five-fold increase

in treated water consumption from 0.082 km³ to 0.38 km³ in line with the projected rapid urbanisation and population growth. Significantly, the anticipated completion of all the planned irrigation schemes by 2050 would result in over a 380% increase in managed water flows to agriculture from 0.6 km³ in 2012 to over 2.9 km³ (1.3 km³ for irrigation) which would be 26% of the projected 2050 country IRWR. The regional and district scale 2050 water resource flux analysis shows the dominant effect of the impact of rapid urbanisation on renewable water flows (*Figure 6* middle & bottom right). Central 1 region is projected to consume over 7.1 km³ of food water imports (Avoided Water) which is more than 3 times the region's projected internal renewable water flows (2.2 km³). The analysis for Kampala shows a significant increase in municipal treated water withdrawals from 0.08 km³ in 2012 to 0.19 km³ by 2050, as well as an extensive increase in avoided water from 0.62 km³ to over 4.5 km³ (over 600%) (*Figure 6* bottom right). The contrasting flux significance between the three scales for 2012 is shown in the pie charts in *Figure 9*.

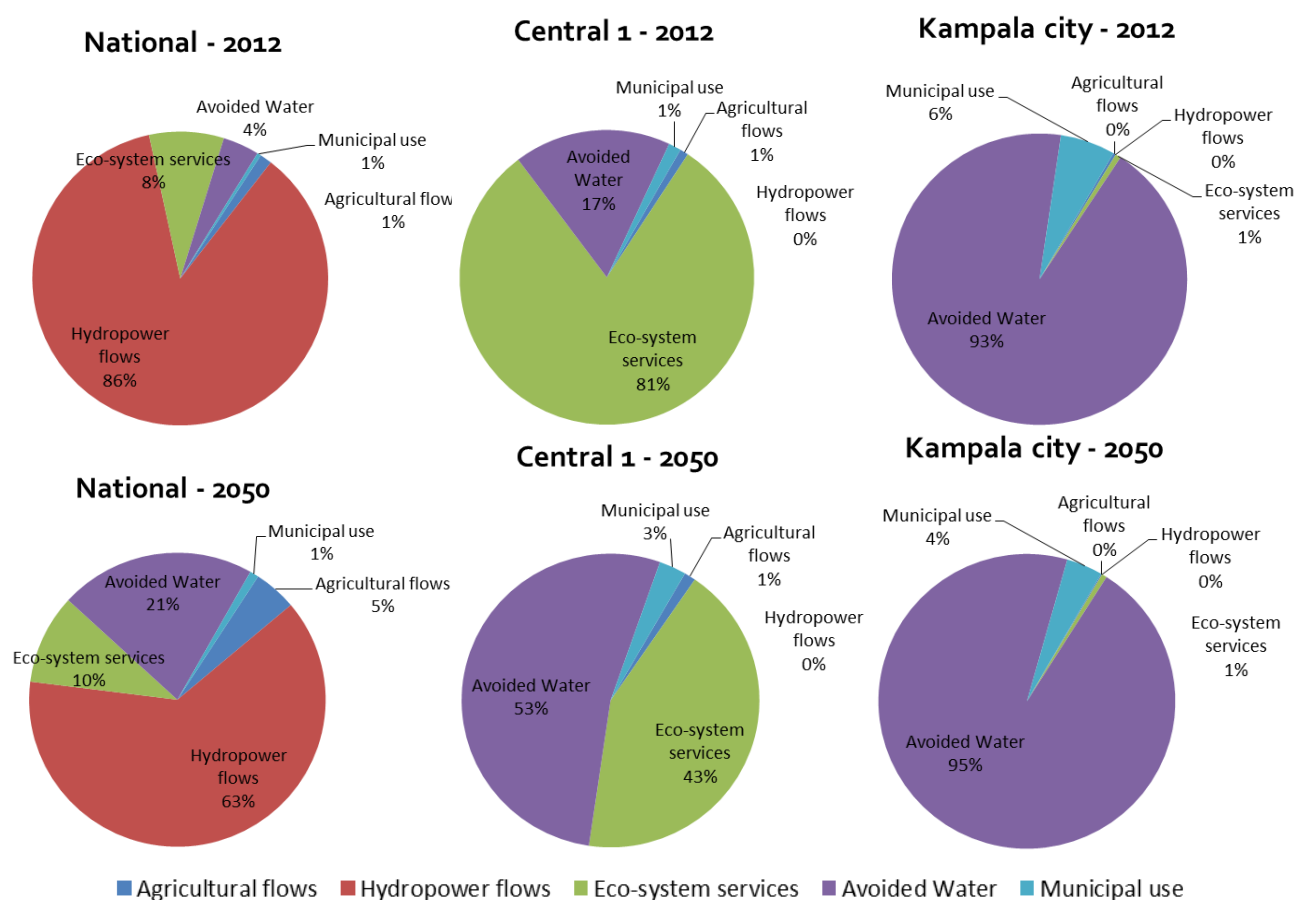


Figure 9: 2012 & 2050 competing food system water resource demands for Uganda at different scales

4.2 Land Resource Flux Analysis 2012–2050

The 2012 country-scale land resource analysis shows an extensive depletion of tropical forest PNV for agricultural land use as of 2012 (see Figure 7 top left) with over 71% of Uganda's forest PNV converted into small-scale farmland as a result of long-term rapid deforestation (almost 2% p.a.) [UBOS, 2013]. The analysis also shows over 45% percent depletion of Grassland PNV with only about 49,000 km² of high-ecological value grasslands left (Figure 7 top left). Regarding Net Primary Productivity (NPP), the cultivable land produces a total available food supply estimate of about 4 TgC which is part of a total equivalent of about 187 million tonnes of carbon biomass equivalent (TgC) inclusive of soil biomass. Post-harvest food losses are calculated as 0.4 TgC (10% of food produced). 0.3 TgC of food biomass is exported, 0.21 TgC (5%) is lost during consumption and the rest is consumed. Significantly, over 52% of cooking fuelwood biomass is sourced from eco-sensitive forests and woodlands (Figure 7 top left).

The regional level 2012 Sankey (Figure 7 middle left) shows different land transformations in comparison to the national analysis, with a lower relative level of deforestation in Central 1 region of 41% of forest PNV (2,290 km² of 5,526 km²). In addition, the contribution of Grassland PNV at the regional level to Central 1 agricultural land is marginal, in contrast to the dominant Grassland PNV contribution to agricultural land at the national level. Most of the Central 1 farmland is from the lower NPP Bushlands, that is, 3,816 km² which is about 52%. Being the capital, the Kampala city land resource mix primarily consists of built space (172 km²) which is taken mostly from Tropical Rainforest PNV (118 km²). The absence of cultivable land in the city and the high food demand results in an NPP deficit of -0.13 TgC (Figure 7 bottom left).

The 2050 country-scale land resource projection shows further heavy depletion of tropical forest PNV for agricultural land use by 2050 (see Figure 7 top right) with over 95% of Uganda's forest PNV converted into agricultural land. These land conversions would result in a potential drop in NPP of almost 45% from 1370 TgC in 2012 to about 760 TgC by 2050. The projected 42% reduction in fuelwood biomass use to 8 TgC would however provide some NPP gains.

The regional level 2050 land analysis (*Figure 7* middle right) shows a similar trend to the national analysis, with the depletion of Grassland, Bushland, and Wetland PNV, but with a more prominent proportion going to urban land-use in Central 1 region. Built area is projected to grow almost four-fold from 420 km² in 2012 to over 2,000 km² taking up over 20% of the region's Tropical Rainforest PNV (*Figure 7* middle right). Notably, NPP in Central 1 region would experience a drop of almost 52% from 92 TgC in 2012 to about 42 TgC by 2050, which is greater than the national eco-system service NPP reduction highlighting the greater adverse effect of urbanisation on productivity. In addition, a resulting NPP deficit of -9 TgC would accrue in the Central 1 region due to increased livestock feed and urban population food demand. The Kampala city land resource analysis shown in *Figure 7* (bottom right) shows no major PNV conversions but as expected, reflects a large increase in urban food demand rising from 0.12 TgC in 2012 to about 0.5 TgC in 2050.

4.3 Energy Resource Transformations 2012–2050

The 2012 energy flux transformation analysis at the country scale shown in *Figure 8* top left illustrates the prevalent use of unsustainable cooking fuelwood biomass, which accounts for over 80% of Uganda's 2012 total energy consumption of 420,000 TJ (UNSD, 2012). Most of the fuelwood is used in rural areas for cooking food using methods with very low burner efficiency (less than 10%) [Okello *et al.*, 2013, p.55]. 24,000 TJ is converted charcoal fuel. A miniscule percentage of fuelwood energy (3%–10,000 TJ) is used in industry (Buchholz & Da Silva, 2010, p.57). The Sankey diagram also shows the 2012 electricity generation mix which consists of renewable hydropower (4200 TJ) generated by large hydropower schemes along the Nile (Kiira, Nalubaale, Bujagali) and other small hydropower schemes, supplemented by oil powered thermal plants (2,500 TJ) at Aggreko I, III and Namanve (UBOS, 2013). Imported petroleum products account for 42,000 TJ used for passenger and freight transport (WB, 2014; Kebede *et al.*, 2010, p.533), including the distribution of food from rural production centres to urban consumption and export points particularly Kampala city. A nearly negligible 10 TJ is used for tillage and irrigation energy use plantation (UBOS, 2013; UNSD, 2012).

The regional and district scale energy distributions (*Figure 8* middle & bottom left) show a similar pattern to the national scale with cooking fuel wood also accounting for most of the energy use at these scales, albeit with lower proportions of 69% for Central 1 region and 58% for Kampala city. Charcoal use (processed fuelwood) and petroleum products for transportation are major energy flows in Kampala city making up 24% and 37% of the capital's total energy use.

Uganda's 2050 energy use is projected to be more than double to more than 1,280,000 TJ (*Figure 8* top right) from 420,000 TJ in 2012, in line with the country's current long-term economic growth and energy efficiency growth rates. The national transportation energy use is projected to increase to over 460,000 TJ up from 42,000 TJ in 2012, of which between 8% – 21% would be increased food transportation (Kamuhanda & Schmidt, 2009). Transportation energy would thereby increase from 10% of total national energy consumption in 2012 to 36% by 2050. About 15% (~72,000 TJ) of this transportation energy would be supplied by domestic petroleum production, which in total would provide ~124,000 TJ or 9.6% of total energy availability by 2050 (*Figure 8* top right). The agricultural energy use projection under current trends remains relatively low at only ~1,200 TJ consisting of 460 TJ of irrigation energy and only ~390 TJ for mechanised tillage, agro-processing, and fertilizer/input manufacture, retaining considerable pre-harvest and post-harvest losses. Moreover, despite increased biomass burner efficiency and domestic petroleum production, the unsustainable biomass energy footprint would still more than double in the BAU scenario from ~357,000 TJ in 2012 to over ~720,000 TJ in 2050 due to rapid population growth. However, in relative terms biomass energy-use would drop to 54% of national energy use by 2050 down from ~90% in 2012. Even so, achieving 2050 food security for Uganda with a totally-renewable energy mix under the BAU scenario appears unattainable. The development of all the planned renewable energy stations would only supply about 22,000 TJ (only 2% of projected 2050 energy use) meaning the use of unsustainable energy sources such as cooking fuelwood and fossil fuels is likely to remain prevalent unless different energy sources are pursued.

The 2050 energy flux analysis at regional and district scales shows cooking fuelwood use remaining prominent, similar to the national level trend. However, biomass energy use for cooking is projected to be highly prevalent in Kampala city by 2050, forming over 31% of the capital's 2050 energy use due to urban migration (*Figure 8* bottom right). This would be higher than the cooking fuelwood proportion in the Central 1 region where it is projected to form about 27% of 2050 regional energy consumption (*Figure 8* middle right). The difference is the result of growth in regional transport networks on the one hand and the increased use of charcoal fuel in the city on the other due to projected rural urban migration.

5. Discussion

Overall, the analysis reveals declining food water and land resources in contrast to increasing agricultural energy availability by 2050. Exceptions occur in two districts, namely Abim district in Karamoja and Amuru district in Acholi region which are projected to have surpluses of all three resources based on projected agricultural, economic, climate change, and population growth trends (*Figure 5a, b, c*). Abim district's 2050 WLE resource surpluses are projected to arise from having the lowest projected population density in the country (~30 people per km² compared to a national average of ~490) and a projected growth rate of only 0.72% (UBOS, 2013). It also has a low computed livestock water demand density of ~340 m³/m² per year (17%) compared to a national average of ~1,960 m³/m² per year. The overall result is surplus WLE resource availability up to 2050. Amuru district's WLE surpluses arise from having one of the lowest computed livestock water demands at less than 10% of the national average (190 m³/m²), and the second lowest projected population density (~64 people per km²) after Abim with a modest projected growth rate of 2.7% which is below the national average. Consequently, the projected WLE surpluses in these locations make them key locations with additional capacity that could be utilised for future food policy planning at the national level.

WLE Resource Interactions and Constraints

The critical resource constraint to Uganda's food system by 2050 appears to be agricultural water resource stress. Exceptions of 2050 food water surpluses are projected to occur around the lake areas in the South of the country where there is access to high renewable water inflows (IRWR) due to projected increases in precipitation (Figure 5a). In contrast however, land resource surpluses are projected to occur in the Central, North and North East of the country which would result in the need for agricultural water transfers (Figure 5b). Projected increases in energy availability from increased hydropower and fossil-fuel reserves would help resolve this challenge to power water transfers over substantial distances. However, this is based on the assumption of steady economic growth and increasing oil production; trajectories that come with considerable uncertainty.

The multi-scale coupled WLE analysis shows variations in apparent significance of resource stress in Uganda's food system at the different analytical resolutions. Whereas national level food resource policy is likely to contend with competing water demand for hydropower production, the Central 1 regional level analysis shows a likely tension between potential irrigation water demand and preserving flows to the environment (Figure 6 top & middle). The national scale Sankey diagrams however best illustrate these tensions, highlighting the need for further investigation of the planned hydropower projects in relation to potential agricultural water withdrawals and competing water demands from municipal use, industrial demand, as well as the other WLE nexus resource dependencies. Particular emphasis is required on the need to maintain flows to all the planned irrigation schemes as well as critical environmental flows. According to low and high flow analysis and hydrological modelling by Smakhtin *et al.*, (2004), environmental flow in the Nile basin ranges from about ~ 20% to 25% of long-term Total Accumulated Runoff (TAR) (Smakhtin *et al.*, 2004, p.12). However Richter *et al.*, (2012), found that this level of flow results in severe damage to ecosystem services and therefore propose a sustainable 'presumptive standard' of between 89% - 100% of long-term TAR for 'moderate' to 'high' ecosystems preservation (Richter *et al.*, 2012, p.1318).

At the *district/local* scale in Kampala city, *avoided water/food* import appears to be most significant water flux (*Figure 6* bottom right). Avoided water flows are projected to play an increasingly significant role at all scales from 2012 to 2050, albeit most significantly at the Central 1 regional and Kampala city level. This is in line with the high projected urbanisation rates, with the urban population projected to exceed 30% of the national population by 2050 – the majority living in Kampala (UN-HABITAT, 2014, p.148). Crush *et al.* (2012, p.272) in their paper discussing the findings of a broad household survey on urban food -insecurity carried out in 11 SSA cities in 2008–2009, indicate that a large proportion of the urban populations in the region will be the urban-poor without the financial capacity to afford adequate nutrition imported from the global market. Given the adverse effects of urbanisation on land resource availability for food production; also shown to be more significant at the regional and district/local scales (*Figure 7 middle & bottom right*), there is likely to be a growing need for significant urban food -welfare mechanisms to mitigate the projected deficits, which needs to be at the forefront of policy consideration (Crush *et al.*, 2012, p.287).

Elsewhere, the energy flux transformation analysis shows that projected increases in irrigation water use at national level (over 1200% gain from 0.1 to 1.3 km³) (*Figure 6 top right*) would be met by increased availability of commercial energy to enable water transfers to meet irrigation requirements. However, this would be through increased reliance on non-renewable petroleum energy production as already mentioned, which would contribute to adverse climate change and come with considerable uncertainty. In addition, the projected increase in irrigation demand would also be coupled with increased land conversion for agriculture (*Figure 7 top and middle right*). The increased demand would also result in further deforestation to meet cooking fuelwood energy-use – specifically processed charcoal biomass in Kampala city and other urban centres (*Figure 8 bottom right*). This is in line with the projected inadequate renewable energy availability (meeting only ~2% of projected energy demand), and the BAU economic and burner efficiency enhancement projections. The adverse side-effect of this would be considerable loss of ecologically sensitive tropical forests and grassland, leading to major adverse impacts on eco-system services. Accordingly, a more aggressive renewable energy policy appears to be

necessary. In addition, concerted efforts by the Uganda government with support of German Agency for International Cooperation (GIZ) (Okello *et al.*, 2013, p.59), to disseminate improved biomass stoves throughout the country should be enhanced, with particular focus on rapidly growing urban centres.

6. Conclusion

This study has provided a comprehensive analysis of Uganda's food system resource constraints at multiple scales (national, regional and district/local), as a test case for similar analysis across Sub-Saharan Africa. The multi-scale WLE analysis particularly highlights the scale variability of the different resource constraints and the associated dependencies on the food system. The major benefit of this approach is the ability to evaluate resource policy impacts at multiple scales. This helps to avoid unforeseen or unintended adverse outcomes at the local scale of policies developed at the national level, as was the case in Uganda in 1999 where more than half of the 1,081 micro-catchment valley dams and tanks developed were not operational due in part to insufficient runoff and overwhelming demand (UN-WWAP, 2006, p.121). The results also draw attention to the potential adverse impacts of the projected enhanced agricultural productivity on eco-system services. The analysis shows that the critical water resource flow varies from hydropower flows at the national scale to environmental and avoided water flows at the Central regional and Kampala district levels. With regard to land-use, agriculture and fuelwood driven deforestation and land degradation are key food policy concerns at the national scale. In contrast the adverse effects of urbanisation on land productivity appear to be more significant at the regional and district/local scales. The coupled energy resource flux analysis emphasizes the reliance on environmentally-costly unsustainable cooking fuelwood and fossil fuels, which is projected to result in further deforestation in varying degrees at the different scales. The co-dependent nature and scale variability of these stresses identified in the analysis point to the need for holistic policy evaluation to enhance efficient resource use and ensure resource co-optimisation for the achievement of food security. Overall, these inferences emphasize the need for a multi-scale integrated approach to resource policy interventions aimed at achieving food security in Uganda.

Word Count (11,143)

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