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Water Productivity and Water Requirements in Food Production
– Examples from Ethiopia, Tanzania and Burkina Faso

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Water Productivity and Water Requirements in Food Production
– Examples from Ethiopia, Tanzania and Burkina Faso

Vattenproduktivitet och vattenbehov i livsmedelsproduktion
– Exempel från Etiopien, Tanzania och Burkina Faso

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Errata för/for
Water Productivity and Water Requirements in Food Production

- Examples from Ethiopia, Tanzania and Burkina Faso

Av/By Louise Malmquist

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Find the text: First section from equation 7

Existing text:

Water requirement per food category [m^3] [7]

$$WR_{Food\ category} = \frac{Median\ WP_{food\ category}}{Dietary\ weight_{crop\ category}}$$

Dietary weight per food category was calculated from the median value of energy [kcal kg^{-1}] of ingoing crops per food category and divided by energy consumption [kcal] per food category and diet (equation [8]). Energy content of ingoing crops and animal products were obtained from nutrition data from references in Table 10, section 3.6..

$$Dietary\ weight_{food\ category} = \frac{Median\ energy\ content_{food\ category}}{Energy\ intake_{food\ category}} \quad [8]$$

Should be:

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Page 56: Table 14

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Table 1. Calculated annual water requirements as a share of total annual precipitation and as shares of total renewable water resources (IRR). The values are summarized for the total populations per respective diet per socio-economic category: low-income- (LD), lower middle-income (LMD), upper middle-income- (UMD), and high-income (HD) population in Ethiopia, Tanzania, and Burkina Faso.

			Dietary and total water requirement of total annual precipitation calculated with inefficient WP and efficient WP										**Dietary and total water requirement of total renewable water resources (IRR) calculated with inefficient WP and efficient WP**									
Country	**Total precipitation**	**Total renewable water resources**	[%]										[%]									
			Inefficient WP					**Efficient WP[1]**					**Inefficient WP**					**Efficient WP[1]**				
	[G m^3 y^{-1}]		LID	LMD	UMD	HID	Total	LID	LMD	UMD	HID	Total	LID	LMD	UMD	HID	Total	LID	LMD	UMD	HID	Total
Ethiopia	936.4	122	1.3	16.3		23.6	41.2	0.3	1.9		1.7	3.9	10.3	124.8		181.0	316.0	2.3	14.5		12.9	29.7
Tanzania	1015	96.27	0.7	9.9	4	6.3	21.3	0.2	0.9	0..4	0.4	1.9	7.6	104.3	46.3	66.8	225.0	1.8	9.4	4	3.6	19.6
Burkina Faso	205.1	13.5	1.3	16.9		10.2	28.5	0.2	1.4		0.8	2.4	19.7	257.3		155.6	432.5	3.7	21.2		12.1	37.0

[1] 2014 FAO: AQUASTAT Available: http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en [2018-05-10]

Should be:

Table 14. Calculated annual water requirements as a share of total annual precipitation and as shares of total renewable water resources (IRR). The values are summarized for the total populations per respective diet per socio-economic category: low-income- (LD), lower middle-income (LMD), upper middle-income- (UMD), and high-income (HD) population in Ethiopia, Tanzania, and Burkina Faso.

Country	Total precipitation	Total renewable water resources	Dietary and total water requirement of total annual precipitation calculated with inefficient WP and efficient WP [%]										Dietary and total water requirement of total renewable water resources (IRR) calculated with inefficient WP and efficient WP [%]									
			Inefficient WP					Efficient WP[1]					Inefficient WP					Efficient WP[1]				
	[G m^3 y^{-1}]		LID	LMD	UMD	HID	Total	LID	LMD	UMD	HID	Total	LID	LMD	UMD	HID	Total	LID	LMD	UMD	HID	Total
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[1] 2014 FAO: AQUASTAT Available: http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en [2018-05-10]

Abstract

The majority of agricultural croplands globally is rainfed. This calls for agricultural practices which promote as productive use of precipitation water as possible, to maintain sufficient crop growth for food production. Global population is estimated to increase to 9.3 billion by 2050 leading to a projected increase in food demand of 60 % from today. This, together with climate change which is projected to entail uneven precipitation patterns, will put further pressure on water resources and demands more thoughtful water management to maintain and improve yields.

Additionally, another global issue is malnutrition, a consequence of uneven food distribution, food availability and food accessibility. Nutritive deficiencies together with global population increase and changes in dietary patterns call for increased food production both in biomass yield and crop qualities considering nutrition. To meet these demands with limited water resources, food production requires systems with high water productivity (WP) to gain most quality output as possible in terms of yield, to water input. In this case the input is seen as evapotranspiration.

The aim with this study was to elucidate the concept Dietary Water Productivity (WP_{diet}) in Sub-Saharan Africa (SSA) for diets differentiated by income levels in Ethiopia, Tanzania, and Burkina Faso. The study included a review of WP and calculations of energy and nutritive output related to evapotranspiration in crop production and diet composition. This was put in relation to national available water resources in respective country.

This study shows:

1. A data gap of values of WP in SSA for main crops included in diets.
2. Country specific differences in water productivity of energy and nutrition outcome depending on food composition and total food consumption.
3. Insecurities in estimated supplies of national precipitation and liquid water resources to sustain future national food production in Ethiopia, Tanzania, and Burkina Faso.

Keywords: Evapotranspiration, Nutrition, Water management, Water Scarcity, Yield gap, Water use efficiency, Sub-Saharan Africa

Sammanfattning

Den största delen av växtproduktionen i världen får sitt vatten via nederbörd. För att upprätthålla så hög produktion som möjligt krävs det effektiva jordbruksmetoder för att ta tillvara på nederbörden i jordbrukslandskapet så den kommer till nytta i produktionen. Världens befolkning har uppskattats att öka till 9,3 miljarder till år 2050, vilket kommer att medföra en ökad efterfrågan på livsmedel, uppskattad till 60%. En ökad efterfrågan på livsmedel tillsammans med klimatförändringar, som är prognostiserade att medföra oregelbunden nederbörd, kommer att öka trycket på tillgängliga vattenresurser. Detta kräver matproduktion som hushållar med det vatten som finns tillgängligt.

Ytterligare ett globalt problem är undernäring till följd av ojämn matförsörjning och livsmedelstillgångar. Undernäring tillsammans med den globala befolkningsförhöjningen och förändringar i dietkomposition kräver ökad livsmedelsproduktion både som kvantitativ och kvalitativ skörd, vilket inkluderar nutritivt innehåll för humankonsumtion i odlade grödor. För att uppfylla dessa produktionskrav med begränsade vattenkällor krävs effektiv livsmedelsproduktion med effektivt nyttjande av vatten för att erhålla hög vattenproduktivitet.

Studiens syfte var att koppla växtproduktion med nutrition och vattentillförsel genom att belysa vattenproduktivitet (WP) kopplat till dietkomposition i Afrika söder om Sahara (SSA) för dieter i Etiopien, Tanzania och Burkina Faso differentierade av inkomstnivåer. Studien har omfattat en referensgenomgång av WP och beräkningar av energi [kcal] och nutrition som utgående faktor, relaterad till evapotranspiration i växtproduktion. Dessa beräkningar har utvärderats i relation till nationella vattentillgångar för jordbruksproduktion.

Denna studie visar:

1. Att det finns en avsaknad av värden för WP i SSA för huvudsakliga grödor som ingår i dieter i Etiopien, Tanzania och Burkina Faso.
2. Landspecifika skillnader i vattenproduktivitet med avseende på nutrition beroende på dietkomposition och totalt intag av livsmedel.
3. Osäkerheter i uppskattade tillgångar av nationell nederbörd och fria vattenresurser för att upprätthålla framtida nationell livsmedelsproduktion i Etiopien, Tanzania och Burkina Faso.

Nyckelord: Evapotranspiration, Nutrition, Vattenbrist, Vattenhantering, Skördeförlust, vatteneffektivitet, Afrika söder om Sahara

Popular scientific summary-
How to link water and nutrition in Sub-Saharan Africa

This study addresses diets in Ethiopia, Tanzania, and Burkina Faso and how the diets' accumulated nutritive content is related to water requirements in the production of food products included in the diets. Water is essential for sustaining crop growth. It is a component for plant uptake of essential crop nutrients from the soil, as building block in plant tissue, for transport of molecules and for keeping vital processes within the plant. Increasing water scarcity is a global problem which is further constrained by climate change, an increasing global population, and changes in diets due to variations in water requirements in production of different crops and food products. There is also an uneven distribution of available food at the global market. Food inaccessibility and unbalanced diets lead to problems as undernourishment with insufficient intake of macronutrients (carbohydrates, protein, fat, and fibre), overweight and obesity due to excessive energy intake, and deficient intake of essential micronutrients (vitamins and minerals). Uneven food distribution and a global population increase calls for increased food production. However, with water resources being more limited with national variations, agricultural production needs to use water resources wisely to produce as high output of yield, energy, and as nutritious crops as possible to the applied water in the cropping areas.

This study shows that different amounts of nutritive output is possible to receive for the same water input depending on diet composition. They also indicate that national available water resources theoretically might be sufficient as input in cropping systems to support production of national food requirements with present food compositions in Ethiopia, Tanzania, and Burkina Faso. However, there is an insecurity in whether it is possible to maintain sufficient food production within the countries with future population increase and changes in food intake patterns. This study was based on previous studies done on water input in crop production in connection to crop yield. However, such studies are few and to do proper estimations of nutritive outputs, there are requirements of further studies of nutritive content and water requirement for crops included in diet composition.

Preface

The content of this thesis is related to a project performed by Stockholm International Water Institute (SIWI) in collaboration with Food and Agricultural Organization (FAO). The aim of the project was to develop a methodology for linking nutrition to production at farm level concerning choice of crop, farm and water management and how the inputs can be reduced to the highest possible output in terms of nutrition, income, and farmers livelihood.

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Abbreviations

BF	Burkina Faso
ET_a	Actual evapotranspiration
ET_c	Crop evapotranspiration
ETH	Ethiopia
ET_o	Reference evapotranspiration
HID	High-income diet
LID	Low-income diet
LMD	Lower middle-income diet
MID	Middle-income diet
NWP	Nutritional water productivity
NWP_{diet}	Dietary nutritional water productivity
SDG	Sustainable development goals
SSA	Sub-Saharan Africa
TZ	Tanzania
UMD	Upper middle-income diet
WF	Water footprint
WP	Water productivity
WP_{diet}	Dietary water productivity
WR	Water requirements
WUE	Water use efficiency
Y_a	Average actual yield
Y_g	Yield gap
Y_p	Potential yield
Y_w	Water limited yield

1 Introduction

Water is essential for sustaining life and a main input factor in crop production which determines yield potential (see van Ittersum & Rabbinge, 1997). Irrigated agriculture is responsible for 70 % of global surface and groundwater withdrawals (The World bank, 2017 a) which support 40 % of global food production while posing 20% of global cropland (The World Bank, 2017 a). The remaining cropland is thus rainfed. To meet a forecasted global population increase to 9.3 billion by year 2050, it is estimated that an increased agricultural production by 60 % is required to meet an overall raised food demand (FAO, 2014). An increasing global population will lead to less water per capita and consequently higher risk of water scarcity, especially where rainfall is low (Rijsberman, 2006). Thus, it will put more pressure on available water sources as higher agricultural production will require more water.

Food production is already today under constrains of land and water scarcity (with local variations) which is worsened by climate change (Sadras *et al*., 2010). Changed precipitation patterns, flooding, droughts, and higher temperatures are some consequences of climate change on agriculture (European Environment Agency, 2015). This affect potential accumulation in national water storages and thus potential water availability for crop water supply and evapotranspiration (European Environment Agency, 2015). Increased temperatures might also change cropping patterns and cropping seasons (European Environment Agency, 2015).

An additional problem to present and future food safety is uneven food availability which results in malnutrition (WHO, 2017 a). This is a term including inadequate, excessive and unbalanced food intake (WHO, 2017a). These three pillars of malnutrition are not isolated from each other but can occur within the same region (Keding, 2016). Of the global human population, 11 % suffer from chronic hunger and additionally 13 % are undernourished (The World Bank, 2017 b). Alarming is the disrupted trend of previous decreasing numbers of undernourished, which has increased since the year of 2014 (FAO *et al*., 2017). Simultaneously to undernourishment, are overeating and food losses two problems along the food chain. Of the global adult population were 13 % suffering from obesity in year 2016 (WHO, 2017 b). Additionally, a substantial amount of produced food is lost or wasted throughout the value chain (Gustavsson *et al.,* 2011). With losses, uneven distribution, and an increasing global population, one issue is to receive proper quantity of daily energy intake adapted to a global population increase, to improve distribution and reduce food waste.

There is a complexity to malnutrition as it is a global issue with sufficient food quantity regarding energy but inequality in food quantities- and especially energy distribution. However, undernourishment and micronutrient deficiencies are yet an additional issue and will still be so with increased agricultural production, unless nutrition quality is linked to agricultural food production (FAO, n.d) as energy rich food might still be poor in nutrition (Chibarabada *et al*., 2017).

Challenges of climate change effects, food accessibility, input availability in crop production and productivity of water input are comprised in the 2030 Agenda for Sustainable Development (SDG) (General Assembly, 2015). Of these 17 development goals do number 2, 6 and 12 include food security and water availability, nutrient availability and sustainable agriculture, water management, -productivity and -consumption (General Assembly, 2015). These goals address sustainable use of water resources and requirements of increased food production (General Assembly, 2015).Another requirement included in the SDGs is nutritive food content (General Assembly, 2015). Uneven distribution and infrastructure result in unequal food availability and food intake despite enough global food production today to supply the world's population with sufficient energy per day (FAO, 2017).

Nutrition connected to food production has, and will become, more important to include throughout the food production chain from producer to consumer, due to increased food requirements but with more limited resources. In the context of food quality does crop differentiation and diet composition become an important factor. Plants have varying composition of chemical compounds which fulfil different purposes in human diets (Gerbens-Leenes & Nonhebel, 2004). Essential nutrition for humans includes the macronutrients proteins, fatty acids, carbohydrates and fibre and the micronutrient consisting of 13 vitamins (Livsmedelsverket, 2017 a) and 14 minerals (Livsmedelsverket, 2017 b). Total nutrition intake and water use is a function of total dietary composition. This differ between location and income level with different clustered water requirements (WR) for production of primary crops (van Wart *et al.*, 2013).

With an increased production where inputs as water are limited, considering quality of products produced with limited resources address the issue of sufficient nutritive intake and a nutrition balanced diet to overcome undernourishment and unbalanced food intake. The importance of nutritive content in crops has been addressed for more than two decennium (e.g.(Welch & Graham, 1999). Yet, to elucidate nutritive content of crops in the context of available water resources is still something which is required (Mabhaudhi *et al*., 2016).

In the context of an increasing global population, limited agricultural inputs needs to be exploited cautiously to receive the highest achievable amount of output. Where water already is a limiting resource, changed water conditions demand crop species and/or -varieties which are more drought tolerant (European Environment Agency, 2015) to achieve successful crop growth. Limiting water resources which affect stability in food production in both irrigated and rainfed systems, require food production which uses water productively and adaptions of cropping systems to the new climate conditions (Turral *et al*., 2011; Bastiaanssen & Steduto, 2017) to assure sufficient water access to support yields. The value of nutrition and water as production inputs is important to be able to rationalize crop production considering water resources and nutrition content. This to deliver crops which are as nutrition dense as possible and to use site specific resources within agriculture effective, thus reduce global malnutrition and increase water productivity and nutrition content. In the end the request is to produce 'more nutrition per drop', that is producing more nutrition per unit water.

Water productivity (WP) is one measure for obtained crop biomass per water volume used in crop production (Molden *et al*., 2007). This measure can include several dimensions of water use in agriculture but is overall a measure of water input versus beneficial output (Molden *et al.*, 2007) . In the context of crop production and water scarcity, the aim is to receive as productive system as possible, with most output attributed to the water input. This is possible in agriculture where physical water scarcity is yet not too severe (Molden *et al.,* 2007).The implementations are to increase yields by sufficient agricultural inputs and reduce water requirements (WR) by increasing preservation of soil water, use supplemental irrigation in rainfed agriculture,or by using efficient water application techniques in irrigated cropping systems (Molden *et al.*, 2007).WP can additionally to yield [kg] or energy [kcal] be put in relation to other outputs from crop production, resulting in the measure Nutritional Water Productivity (NWP), to include the obtained nutritional portion from crop yield in relation to WR (Renault & Wallender, 2000). Accomplished studies of the concept of NWP are in its initial stage (e.g. Renault & Wallender, 2000; Nyathi *et al*, 2016; Chibarabada *et al*., 2017;) and these studies are mainly focused in one location or on one specific diet. This demands more studies of NWP to distinguish crops and diets which are nutrition dense and water resource effective.

SDGs in Agenda 2030 address food security and nutritious food with sustainable use of water resources, thus combining quantity and quality demands to fulfil nutritious needs, with WR in crop production (General Assembly, 2015). There are several studies performed on average country diets. However, national differences are addressed to a minor extent and thus are national WR so far overlooked. This knowledge-gap calls for a further step by including national dietary differentiation due to differences in nutrition food sources, WR and WP.

1.1 Objective and research questions

This thesis explored specified examples of Dietary Water Productivity (WP_{diet}) and Dietary Nutritional Water Productivity (NWP_{diet}) for income differentiated diets in three Sub-Saharan Africa (SSA) countries, Ethiopia, Tanzania and Burkina Faso. The values of WP were compared with national water resources as limiting factor for crop production. The purpose was to bring up a discussion of how diet composition relates to WR in agriculture in present and future cropping conditions.

The aim of this thesis was to pilot a methodology where crops emanated from income-dependent diets are compared to WR in the cropping systems and to compare with the crops nutritive content. In other words, nutrition per unit water. Questions which have been explored follow below:

1. Which is the water productivity for the specified diets and the respective crops considering economic yield [kg m^{-3}], energy [kcal m^{-3}], and nutrition [g m^{-3}]?
2. How do values of WP_{diet} and NWP_{diet} differ from each other for the specified crops and diet compositions?
3. How do water requirements for the crops in the diets relate to present and estimated future water access at the example countries in SSA?

Question 1 is explored in result section 4.1 *Synthesis of Water Productivity data from empirical studies in SSA*, question 2 in section 4.2 *Estimates of water requirements for diets per income level in Ethiopia, Tanzania, and Burkina* Faso and question 3 in section 4.3 *Comparison of water appropriation for diets with national water resources*

2 Background

2.1 Water resources for crop production

A nation is considered water scarce when water access is below 1000 m^3 cap^{-1} y^{-1} and with a nearly constant volume of national available water (Rijsberman, 2006). As the main part of agriculture is rainfed (Falkenmark & Rockström, 2014), this brings in the importance of differentiating between rained and irrigated agriculture.

Two main water resources are available for crop production. Either precipitation which is stored directly in the soil profile at the cropping site and available for transpiration (Stroosnijder, 2009) or open water resources as streams and lakes (Rijsberman, 2006), available for crop irrigation (Rockström *et al.*, 2009). Precipitation which ends in soil profiles is according to Rijsberman (2006) 60 % of the total precipitation volume, while the remaining 40 % on a global annual long-time basis ends in open water resources.

Water in plants after harvest indirectly becomes a factor in import and export of food product as water is required elsewhere than where the food is consumed (Renault, 2002; Allan, 2003). This is especially important for water scarce nations not able to support sufficient food production for national requirements (Renault, 2002). This also makes improvements of WP within crop production in these water scarce countries more critical (Renault, 2002).

2.2 Evapotranspiration and yield yap

Water is essential for crop production where transpiration enables turgor (Campbell *et al.*, 2015, p 847), gas exchange; nutrient uptake and as transport medium of dissolved compounds within the plant (Campbell *et al.*, 2015, pp 851–851). Water is further essential for chemical reactions within the plant, in photosynthesis as electron donor and as a main building block in plant biomass as carbohydrates (Campbell *et al.*, 2015, p 265). Water consumption in cropping systems consist of two main components (Jägermeyr *et al.*, 2015). Transpiration which contributes to crop growth, and evaporation which is depleted water which does not contribute to production (Jägermeyr *et al*., 2015). Water possible to include more productively in crop production can be seen as the difference of precipitation and the volume used in transpiration (Rockström *et al*., 2009).

Crop water uptake is a function of water movement towards lower water potential in the atmosphere (Grip & Rodhe, 1994). As transpiration is controlled by opening of stomata, transpiration reduction, and thus water saving for the crop, is a competitive trait towards uptake of carbon dioxide for photosynthesis and thus crop growth - with increased transpiration follows increased photosynthesis (Grip & Rodhe, 1994). Transpiration rate is determined by available energy from sun radiation and wind velocity, for transferring water from liquid to gas phase, as well as temperature which determine air humidity and thus is a factor for the water gradient between crop and atmosphere (Grip & Rodhe, 1994). The link between abiotic factors and evapotranspiration is further explained in section 3.2.

The abiotic factors sun radiation (R), temperature (T), carbon dioxide levels (CO_2) and additionally crop species and-crop variety are factors determining potential maximum yield (Y_p) (equation [1]) (van Ittersum & Rabbinge, 1997). As these abiotic factors are location specific, Y_p will consequently differ between cropping sites.

Potential yield $$Y_p = R + T + CO_2 + genetic\ properties \quad [1]$$

(van Ittersum & Rabbinge, 1997)

Y_p is the maximum yield level to strive towards by reducing limiting and reducing factors defining actual yield (Y_a) (equation [2]) and thus reducing the yield gap (Y_g) which is the difference between Y_p and Y_a.

Average actual yield $$Y_a = Y_p - (Y_p * (limiting\ factors + reducing\ factors) \quad [2]$$

(van Ittersum & Rabbinge, 1997)

Limiting factors are access to water and plant nutrients while elements of competition for water and nutrients are reducing factors (van Ittersum & Rabbinge, 1997). The reducing factors were excluded in the context of this thesis as the focus is on the yield limiting factors and especially water availability for crop production.

Water application in rainfed systems can only partially be manipulated through farming practices which means that there might not be sufficient water to sustain the maximum potential yield (van Ittersum & Rabbinge, 1997). This affect Y_p as water becomes a limiting factor for crop growth, resulting in water limited yield (Y_w) (van Ittersum & Rabbinge, 1997).

2.3 Limitations of water availability in crop production

Three types of droughts affecting crop production and contribute to Y_g can be recognized in cropping systems according to Stroosnijder (2009). Limited precipitation patterns, limitations in the soil profile hindering crop access to soil water, and lastly the scenario when plant nutrient availability in the soil is the limiting factor (Stroosnijder, 2009). These sorts of drought contribute to an additional dimension of the perspective of Y_w, giving two reasons for water limitation as water might be available at the location but limited by cultivation practices or spot soil properties (Figure 1)

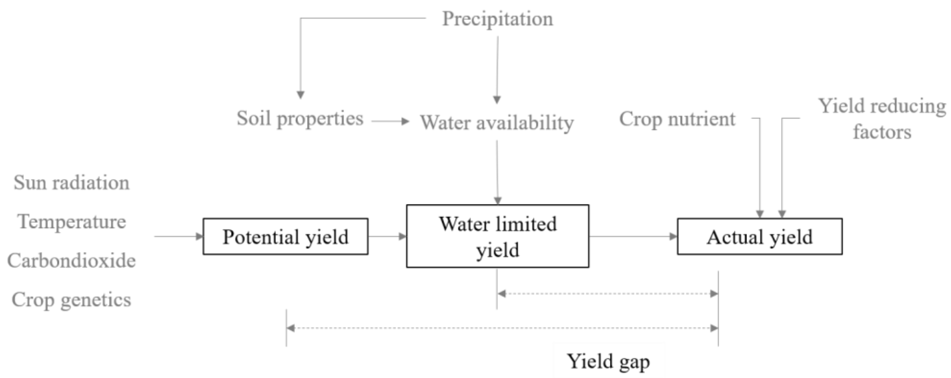

Figure 1. Factors determining levels of possible crop yield. Potential yield is the highest achievable yield without limitations and reducing factors and actual yield the yield obtained at field due to limiting factors. Aggregated concept from van Ittersum & Rabbinge (1997) and Stroosnijder (2009).

This thesis has concentrated on the link between national water resources available for water application to sustain crop production for dietary food intake and limitation in field. Crops will not benefit from applied water unless soil conditions enable water transport from soil to plant, enhancing evapotranspiration, crop growth and consequently crop yield.

Several reasons affect plant accessibility of soil water, for example both by changes of land cover and by physical properties in the soil profile (Stroosnijder, 2009). Initially, soil texture and structure affect soil porosity and thus soil water holding capacity (Eriksson *et al.*, 2011, p 172). Porosity determines the volume available soil water and water holding capacity is a function of pore size (Eriksson *et al.*, 2011, p 172) which in turn affects the shares of drainable water and available water for transpiration (Eriksson *et al.*, 2011, p 181). Factors affecting soil structure and porosity and therefore the possibility for the soil to hold water are for example decreasing organic matter content and soil compaction from above-ground pressure or compacted layers in the soil profile (Stroosnijder, 2009).

Improving productivity of precipitation is of concern in all dryland agriculture and where majority of agricultural production is rainfed with little support by irrigation practises (Kristjanson *et al*., 2012). Several measures can improve WP of precipitation by increasing soil moisture content, for example mulching and to improve actions from soil fauna which increase soil porosity, water infiltration and water holding capacity. Further examples are adding barriers in the cropping area either as terraces or crops which hinder soil erosion, and implement water-saving actions as rainwater harvesting techniques, with the most common in SSA being pitting, contouring, terracing and micro-basins (Biazin *et al.*, 2012). Lastly, WP can be improved by ensuring crop nutrient availability to receive synergetic effect of water application (Biazin *et al.*, 2012) as water is essential for crops to take up nutrients (Campbell *et al.*, 2015, p 864), but nutrients is also a driving force for transpiration and water use in plants. Examples are potassium which is required for stomata functions, manganese for splitting water and acquire energy in photosynthesis, chlorine which is required in small amounts for water splitting and regulation of osmosis and thus water balance within plants (Chen *et al.*, 2010; Campbell *et al.*, 2015, p 869).

Over all, increasing WP is to highest extent possible in areas with scarce or depleting water resources and high $Y_{g,}$; where WP is low with existing poverty, or where additional small extra water application will result in higher crop production (Molden *et al.*, 2010).

3 Study locations and methods

This study is built on a review of values of water productivity (WP) for crops grown in- and included in diets in Sub-Saharan Africa (SSA). Values of WP were used to calculate dietary water requirements (WR) for income-based diets in Ethiopia (ETH), Tanzania (TZ) and Burkina Faso (BF). These values were compared to national available water resources to estimate possibilities to nationally sustain production of the diets. Emanated from WR, the dietary water productivity (WP_{diet}) was calculated which enabled comparison with agricultural production systems between the locations as well as comparisons between qualitative production of energy per water volume [kcal m^{-3}]. WP_{diet} was also put in relation to nutritive contents of the ingoing crops (nutritional water productivity, NWP_{diet}) in the diets according to formulas in Molden (1997) and Renault & Wallender (2000) (elaborated in section 3.3). To receive indications of nutritional output in relation to WR, ETH, TZ and BF were used as countries to specify diets in relation to national water availability, crop production systems and income levels (Figure 2).

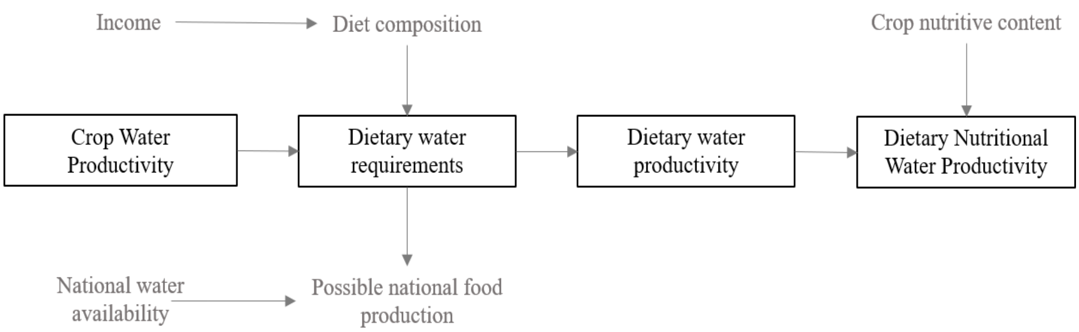

Figure 2. Flow chart over the methodology for comparing how differences in diet composition affect water requirement in national crop production, water productivity regarding energy and nutrient content and how dietary water requirement relate to national available water resources. The calculated measures in these studies are framed and required data for calculations is the text in grey.

Crop water productivity is related to results in section 4.1, dietary water productivity and dietary nutritional water productivity to section 4.2 and dietary water requirements to section 4.3.

3.1 Measures of water appropriation in agriculture

Several measures exist for efficiency and productivity of water use in agriculture. The *water footprint* (WF) approach considers the whole life cycle of a product. Following the European standard, ISO 14046:2016, WF is a measure of water-related environmental impacts from a product and can include the whole- or parts of the life cycle of the product depending on the set limits. WF does also include water quantity and quality and additionally geographical differences and variations in water regimes from a time perspective (Swedish Standard Institute, 2016). Focus in this study was on water use in agriculture. Factors as water quality were excluded as well as a true environmental perspective, thus missing the main criteria for a WF assessment (Swedish Standard Institute, 2016).

Another measure besides WP is Water Use Efficiency (WUE). Both WP and WUE have ratios between agricultural output and the water input which can be defined differently depending on the objectives with the measurements (Molden *et al.*, 2007). For example yield divided by precipitation (rainwater use efficiency), irrigation (irrigation water use efficiency), total volume applied water, evapotranspiration or as a share between transpired- and applied water (Duivenbooden *et al.*, 2000; Stroosnijder, 2009).

In this study, WP was characterized as the ratio between actual economic yield (Y_a) and actual evapotranspiration (ET_a), which is adopted as crop water use in agriculture, though it essentially is the water output in crop production (Renault & Wallender, 2000). Productivity is usually a measure including applied water as precipitation or irrigation (Renault & Wallender, 2000). However, water not evaporated or transpired is recycled through runoff or percolation through the soil profile. Thus, ET_a is used as denominator as this is the water which is depleted from the local landscape during the cropping season from a field-perspective, neither recycled to other geographical locals in a short-term perspective (Renault & Wallender, 2000) nor through the crops as food- or fodder intake after harvest.

3.2 Equations to determine Water Productivity

Initial calculations of evapotranspiration (ET) are often based on the FAO Penman-Monteith equation (equation [3]). This equation is one of the most common methods to determine reference evapotranspiration (ET_o). The equation is set to a reference crop with fixed height and surroundings with fixed albedo and surface resistance (Allen *et al*., 1998). ET_o is determined by the factors net sun radiation (R_n), soil heat flux (G), daily temperature (T) and wind speed (u_2) at the height of 2 m and the air's vapor pressure deficit (e_s-e_a) (Allen *et al.*, 1998).

FAO Penman-Monteith equation [mm] $$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad [3]$$

The FAO Penman-Monteith equation is a development of the original Penman-Monteith equation, that include the factors mean air density (ρ_a), the air's specific heat (c_p), bulk surface (r_s) and aerodynamic (r_a) resistances and the slope for the curve of saturation vapour pressure (Δ) for a specific air temperature (Allen *et al.*, 1998). Further, the calculation also include the psychrometric constant (γ) and the energy required for changing the water's state of aggregation (λ) (Allen *et al.*, 1998) (equation [4]).

Penman-Monteith equation [mm] $$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \qquad [4]$$

(Allen *et al.*, 1998)

Bulk surface resistance (r_s) and bulk aerodynamic resistance (r_a) vary with crop species, crop variety and maturity (Allen *et al*, 1998). This makes the Penman-Monteith equation applicable to determine ET for any crop, compared to the FAO-Penman-Monteith equation where r_a and r_s are set to the reference crop (Allen *et al.*, 1998). The adoption of a reference evapotranspiration (ET_o) eliminated the need of local calibration of calculations for specific crops and their growth stages (Allen *et al.*, 1998).

The specific evapotranspiration of a certain crop stage (ET_c) (equation [5]) is instead estimated by including a crop coefficient (K_c) which depends on crop maturity stage, crop height, wind velocity and air humidity (Allen *et al*., 1998).

Crop evapotranspiration [mm] $$ET_c = K_c * ET_o \qquad [5]$$

(Doorenbos *et al.*, 1977)

Initially, evapotranspiration will be dominated by evaporation from the soil surface, while as the crop develops, transpiration will dominate (Allen *et al*., 1998).

From these formulas it is stated that ET_c is the potential evapotranspiration affected by crop characteristics, climatic factors and time factors. The actual evapotranspiration (ET_a) in field however is also affected by soil water availability and can include values of evapotranspiration when water is insufficient to meet the crops needs. This compared to calculated values of ET_c where soil water content is considered to be sufficient.

Water productivity (WP) [kg m^{-3}] for specific crops of interest in this study is determined by the actual economic yield (Y_a) [kg m^{-2}] and actual evapotranspiration (ET_a) [m] (equation [6]). The value of WP thus varies with seasonal fluctuations in climate, variations in crop characteristics as well as with soil water availability.

Crop water productivity [kg m^{-3}] $$WP = \frac{Y_a}{ET_a} \quad [6]$$
(Molden, 1997; Molden *et al.*, 2007)

3.3 Calculations to determine Dietary Water Productivity

The calculations in this study are based on values of field data and some modelled data of WP, from reviewed studies previously performed in Sub-Saharan Africa (SSA). The reviewed values of WP were included with the criteria of being calculated as in equation [6]. All reviewed references and values of WP included in the calculations below, are presented in Appendix D, Table 22. The limitations and search queries for the review are further described in section 3.6 *Databases and search queries* and *Selection of references.* The reviewed values of WP are from different parts of SSA due to limited findings of references with WP from solely Ethiopia, Tanzania or Burkina Faso.

Values of WP were clustered in main food categories within diets in ETH, TZ and BF. WP for crops within food categories were calculated to quartiles (Q0 to Q5), where the median value (Q2) and quartiles Q1 (inefficient WP) and Q3 (efficient WP) represented the interval of the reviewed WP for the food categories. The median was used as guideline value as this value is less sensitive to outliers in a dataset compared to average values (Olsson *et al.*, 2005). By including these three quartiles (Q1, Q2 and Q3), calculations resulted in a range of water requirements. This indicated the sensitivity of the methodology (this is further described in Section 4). Values of WR were used to calculate required water volume for the share of food categories in the different diets (equation [7]).

Water requirement per food category [m^3] [7]

$$WR_{Food\ category} = \frac{Median\ WP_{food\ category}}{Dietary\ weight_{crop\ category}}$$

Dietary weight per food category was calculated from the median value of energy [kcal kg^{-1}] of ingoing crops per food category and divided by energy consumption [kcal] per food category and diet (equation [8]). Energy content of ingoing crops and animal products were obtained from nutrition data from references in Table 10, section 3.6.

$$Dietary\ weight_{food\ category} = \frac{Median\ energy\ content_{food\ category}}{Energy\ intake_{food\ category}} \quad [8]$$

The main measure for this study, Dietary Water Productivity (WP_{diet}) is a further step from calculations of WP in equation [6]. To calculate WP_{diet} for the country specific diets under headline 3.4, values of $WR_{food\ category}$ were summarized for each diet and used as denominator in equation [9] with the numerator being the summarized energy consumption per food category.

Dietary water productivity [kcal m^{-3}] [9]

$$WP_{diet} = \frac{\sum Energy\ intake_{food\ category}}{\sum WR_{food\ category}}$$

Moreover, WP_{diet} was put in relation to nutritive content of the crops and animal products within the diets, calculating the measure Dietary Nutritional Water Productivity (NWP_{diet}). This measure was calculated with the same equations as for WP_{diet} [kcal m^{-3}] (equation [9]) but the numerator was varied with median values of macro- and micronutrients for the food categories.

The concept of NWP is adopted from Renault & Wallender (2000) which calculates NWP for individual crop species by multiplying nutritive content with WP (equation [10]).

Nutritional water productivity [weight unit m^{-3}] [10]

$$NWP = \frac{Y_a * crop\ nutrient\ content}{ET_a}$$

(Renault & Wallender, 2000)

Weight unit is the weight of ingoing nutrition [g], [mg] or [µg]. Individual NWP could not be calculated in this study due to missing data of individual WP values for

all ingoing crops or animal products in the diets. Instead, NWP was calculated for the food categories which included crop or food product belongs to.
For a discussion of uncertainties in the calculation method, se section 5.3 in *Discussion.*

3.4 Diets in Ethiopia, Tanzania, and Burkina Faso

In a global context are specific examples of diet compositions important to increase food production and food quality per unit water input due to food demands, malnutrition, and water scarcity issues. This is especially a concern in Africa where stunting have shown an increasing trend the past years compared to globally where stunting is decreasing overall (The World Bank, 2017 b). Furthermore, Africa is the continent with highest proportion of individuals under the international poverty line of $ 1.90 per day (SEK 17.20) (Economic Commission for Africa, 2017) and with least energy supply per capita per day according from numbers from 2013 years Food Balance Sheets (FAO). The analysis of van Ittersum *et al.* (2016) shows there is a production gap throughout Sub-Saharan Africa (SSA) with high needs on closing Y_g. This to increase the self-sufficiency without expanding land under agriculture, or to increase food import to compensate for the gap in national food production (van Ittersum *et al.*, 2016).

Agricultural production in SSA is mainly rainfed with low mechanization rate (Sheahan & Barrett, 2017). However, inputs in other areas as fertilizer and pesticides are used to higher extent throughout SSA than what might usually be brought forward (Sheahan & Barret, 2017). In their work did Sheahan & Barret, (2017) for example find that the use of inorganic fertilizers tended to decrease with increasing farm size. Though there is a variation of inputs between regions at national level and absence of differentiation at farm level, as well as practices missing of farmers using several inputs together and thus missing the positive synergetic effect (Sheahan & Barrett, 2017). This requires changes in the cropping and input use to increase the cropping productivity over all in SSA.

Locations

Ethiopia (ETH), Tanzania (TZ) and Burkina Faso (BF) were chosen as specified countries as they lie in different regions of SSA and are vulnerable due to undernourishment. However, these countries also have different water regimes giving different agro-hydrological options for their national security of food and nutrition which accounts for both rainfed and irrigated agriculture (Rockström *et al.*, 2009)

(Table 1). BF and ETH are predicted to the same water regime but have different agricultural conditions due to lying on different longitudes Furthermore, the diet composition of different food categories varies between the countries.

Table 1. Undernourishment and predicted agricultural water management options in Ethiopia, Tanzania, and Burkina Faso

Country	**No. of undernourished people [10^6] (% of total population)[1]**	**Predicted water regime[2]**
Ethiopia	28.6 (28.8)	Rainfed agriculture, scarcity of free water resources
Tanzania	17.3 (32.3)	Available soil water- and free water resources
Burkina Faso	3.7 (20.2)	Rainfed agriculture, scarcity of free water resources

References:
[1] FAO, IFAD, UNICEF, WFP & WHO (2017). *The state of food security and nutrition in the world 2017: building resilience for peace and food security*. Rome: FAO. ISBN 978-92-5-109888-2.
[2] Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S. & Gerten, D. (2009). Future water availability for global food production: The potential of green water for increasing resilience to global change. Water Resources Research vol. 45(7). DOI: 10.1029/2007WR006767

Precipitation volumes are highest in TZ and lowest in BF. The volume of total renewable water resources is highest in ETH and lowest in BF, of which Ethiopia uses the highest share and BF the lowest (Table 2). Regard that the numbers are long time averages, not representing specific years. Total renewable water resources include surface water recharged trough run-off, groundwater recharged trough infiltration from precipitation, and transboundary water available through inflow via rivers and canals (FAO, AQUASTAT).

Table 2. Annual precipitation, total renewable water resources and water use in agriculture in Ethiopia, Tanzania, and Burkina Faso

Country	**Annual Precipitation [$Gm^3\ y^{-1}$]**	**Annual Precipitation [$mm\ y^{-1}$]**	**Total renewable water resources [$Gm^3\ y^{-1}$]**	**Part of total renewable water resources used in agriculture [%]**
Ethiopia[I]	936.4	848	122	7.94 [II]
Tanzania[I]	1015	1071	96.27	4.8[III]
Burkina Faso[I]	205.1	748	13.5	3.12[IV]

[I] year 2014, [II] year 2016, [III] year 2002, [IV] year 2005
Adopted from AQUASTAT, FAO Available: http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

Site specific diets

The diets were based on product categories in FAOs food balance sheets (FAO FBS). Ingoing categories in FBS constitute of *cereals, root and tubers, oil crops, vegetables, pulses, tree nuts, fruits, animal products* (these are divided into further categories but these subcategories were clustered as crops are the main focus in this thesis), *sugar crops, sugar & sweeteners, stimulants, spices* and *alcoholic beverages* (Grünberger, 2014). The categories *sugar crops, sugar & sweeteners stimulants, spices,* and *alcoholic beverages* were not included in the diets due to their non-nutritional contribution. *Tree nuts* and *oil crops* and *vegetable oils* were clustered to the category *oil crops* as done in the Global Dietary Database (GDD)

Income level and rural or urban households vary consumption patterns and the share of income put on food consumption decreases with increased income level (Kearney, 2010; Berhane *et al.*, 2013) as well as dietary diversity and food security increases with higher income (Savy *et al.*, 2008; Goshu *et al.*, 2013; Workicho *et al.*, 2016; Wilkinson *et al.*, 2017) thus leading to differences in WR for the diets. Three socio-economic levels were included in the calculations: Low-income diet (LID), middle-income diet (MID) and high-income diet (HID) (Table 3, Table 4 and Table 5). For TZ the MID were further divided in lower middle-income diet (LMD) and upper middle-income diet (UMD). The additional diet category in TZ was due to different numbers of average food consumption in the country indicating differences in energy consumption. However, there was an absence of gathered numbers for differentiated diet compositions, thus was an assumption made that the composition might be similar but total energy consumption increases to start with, with an income increase (Cochrane & D'Souza, 2015). Diet composition does also vary between locations within the countries (e.g. Cochrane & D'Souza, 2015). However, this was not included as a differentiating factor in this study due to that no such numbers were found during the review for this study.

No complete diet composition was found of dietary consumption for different income levels in neither ETH, TZ nor BF during the review. Reviewed studies included some of the food categories, but some categories were clustered differently, and most diet compositions were for average food consumption in the countries. To be able to perform calculations of WP_{diet} and NWP_{diet} the numbers of diet composition in reviewed references where used as total dietary values of dietary consumption when they were available for specific diets. For food consumption of categories separated differently in reviewed references than the categories in this study, incomplete numbers in references were summed to match the content of the food categories for this study. For example, milk was often separated from meat in reviewed

studies, but has been clustered in the category *animal products* in this work. Where numbers were insufficient for this approach, values were estimated from references containing information of overall dietary patterns (e.g. Worku *et al*., 2015) saying that with a higher income, a higher share of income is put on *animal products* than on *cereals* and *roots and tubers*). Therefore, some values from rural food consumption were interpreted to low-income diets.
The shares of energy consumption for the food categories do not cover total daily consumption given in the tables as references also have included more food categories which are not considered in this study. Food composition within the food categories differs between the countries to some extent. The most common food products within the food categories for the countries are presented in Table 6, Table 7 and Table 8.

Most of the references have divided food consumption after income quintiles, thus these are the shares of populations used for the diets for ETH and BF (low-income diet, LID, middle-income diet (MID) and high-income diet, HD (see Kazianga & Udry, 2006; Berhane *et al.*, 2013) . The share of individuals for the TZ diets are considered from the population within the intervals of daily income under the national poverty line (low-income diet, LID), between national poverty line and lower middle-income class (lower middle-income diet, LMD), between lower middle-income class poverty line and upper middle-income class poverty line (upper middle-income diet, UMD) and the number of people above the upper middle-income class poverty line (High-income diet, HID) (see The World Bank, 2017 b).

Diet numbers from the references are insecure whether they address consumption or intake, as the terms are used inconsequently in the references. Consumption can be synonymous with actual food intake and thereby addressing the food goods which are beneficial from a nutritive perspective (Cambridge University Press, n.d.). However, consumption can also include the total quantity of food which is brought to the household (Cambridge University Press, n.d.). The diet compositions might therefore be overestimated from a nutritive perspective, as there might occur food waste before the food is served. Due to these insecurities the term *consumption* is used throughout this thesis. Preferably though, numbers of the actual food *intake* are what is important from a nutritive perspective.

Table 3. Income-dependent diets in Ethiopia. The diets are estimated for different socio-economic levels based on income quintiles and poverty data

	Low income diet	**Middle income diet**	**High income diet**
Percentage of population[1]	20	60	20
Total energy consumption [kcal][1]	1948	3001[2]	3716
Food category: % of total food consumption			
Cereals	65[3]	63.5[I]	60[I]
Roots and tubers	20[3]	13.7[2]	6.2[1]
Pulses & legumes	8.0[II]	7.1[2]	5.0[1]
Oil crops	2.2[1]	4.3[2]	7.4[1]
Vegetables and fruit	1.5[IV]	2.1[2]	3.1[1]
Animal products	0[III]	2.0[III]	10[IV]
Food categories shares of daily consumption [%]	96.7	92.7	91.7

References:

[1] Berhane, G., McBride, L., Hirfrfot, K. T. & Tamiru Seneshaw (2013). Patterns in food grain consumption and calorie intake. In: Dorosh, P. & Rashid, S. (Eds) *Food and agriculture in Ethiopia: Progress and policy challenges*. pp 190–216. Philadelphia: University of Pennsylvania Press. ISBN; 9780812245295

[2] Worku, I. H., Dereje, M., Minten, B. & Hirvonen, K. (2015). Diet transformation in Africa: the case of Ethiopia. *Agricultural Economics*, vol. 48(S1), pp 73–86. DOI: 10.1111/agec.12387;

[3] Ethiopian Central Statistical Agency & World Food Programme (2014*). Comprehensive Food Security and Vulnerability Analysis* (CFSVA) – Ethiopia: ECSA/WFP. Available: https://documents.wfp.org/stellent/groups/public/documents/ena/wfp265490.pdf?_ga=2.233501726.1231214005.1526372317-523263838.1522766284 [Accessed 2018-05-15]

[I] Estimated from average numbers of consumed cereals in Hirvonen, K., Taffese, A. S. & Worku, I. H. (2015). *Seasonality and household diets in Ethiopia*. Addis Ababa: EDRI, IFRI. (Working paper 74)

[II] Average value of daily dietary consumption of pulses and legumes from Hirvonen, K., Taffese, A. S. & Worku, I. H. (2015). *Seasonality and household diets in Ethiopia*. Addis Ababa: EDRI, IFRI. (Working paper 74).

[III] Calculated from the average rural and urban energy consumption per capita of animal products in Berhane, G., Paulos, Z., Tafere, K. & Tamru, S. (2011). *Foodgrain Consumption and Calorie Intake Patterns in Ethiopia*. Addis Ababa: IFPRI, EDRI. (ESSP II Woking Paper 23).

[IV] Estimation from an average meat consumption 2.1 times per week in richer households and a low consumption of vegetables and fruits according to reference [3].

Table 4. Income-dependent diets in Tanzania. The diets are estimated for different socio-economic levels based on income quintiles and poverty data

	Low-income diet	**Lower middle-income diet**	**Upper middle-income**	**High- income diet**
Percentage of population[1]	28.2	50.7	14.2	6.9
Total energy consumption[kcal] [2]	1414	2137[3]	2270	3040
Food category: % of total food consumption				
Cereals	65.2 [I]	63.7 [2]	57.8 [I]	51.0 [4]
Roots and tubers	18.0 [4]	13.4 [4]	11.4 [4]	2.0 [II]
Pulses and legumes	7.3 [III]	6.0 [IV]	6.0[IV]	5.5 [4]
Oil crops	1.2 [III]	4.3 [IV]	5.1 [IV]	8.5 [III]
Vegetables	4.5 [4]	5.9 [4]	5.9 [4]	4.9 [2]
Fruits	0.6 [I]	0.9 [3]	0.9 [3]	1.2 [II]
Animal products	0.0[V]	5.1 [VI]	8.3 [VI]	20.0 [VII]
Food categories shares of daily consumption [%]	96.6	99.3	95.4	93.1

References:
[1] The World bank (2017). *Country Poverty Brief, Sub-Saharan Africa - Tanzania*. HBS/SSAPOV/GMD (Fact sheet). Available: http://databank.worldbank.org/data/download/poverty/33EF03BB-9722-4AE2-ABC7-AA2972D68AFE/Global_POV_SP_CPB_TZA.pdf [2018-04-12].
[2]Abdulai, A. & Aubert, D. (2004). Nonparametric and parametric analysis of calorie consumption in Tanzania. *Food Policy*. Vol. 29. pp. 113-129. DOI: 10.1016/j.foodpol.2004.02.002
[3]Cochrane, N. & D'Souza, A. (2015). Measuring Access to Food in Tanzania: A Food Basket Approach. Economic Information Bulletin. No. 135. 27pp.
[4] Pauw, K. & Thurlow, J. (2011). Agricultural growth, poverty and nutrition in Tanzania. *Food Policy.* vol. 36. pp. 795-804. DOI: 10.1016/j.foodpol.2011.09.002

[I] Estimated from references [2] and [4] by subtracting calculated intake of *roots & tubers* for poor and non-poor in ref.[4] from the total intake of *cereals, roots and pulses* in ref. [2].

[II] Calculated from reference [3] assuming a higher share of high-income population in Dar es Salaam, thus summed consumption values from this city.

[III] Calculated from numbers in reference [3] and [4] by dividing numbers of consumed pulses & oilseeds in ref. [4] with total intake of the respective diet, then subtract from intake of beans from diets in the different regions in ref. [3].

[IV] Calculated from reference [4] from average intake of pulses and oilseeds compared to average total energy intake, then subtracted from average intake of beans.

[V] Estimated from reference [3] and Ethiopian Central Statistical Agency & World Food Programme (2013). *Comprehensive Food Security and Vulnerability Analysis Tanzania 2012*. Rome: WFP, WHO, mentioning low intake calories from animal products

[VI] Estimate from reference [2] and Ethiopian Central Statistical Agency & World Food Programme (2013), from average intake of animal products in different regions attributed to higher or lower income levels.

[VII] Calculated from reference [2] and Ethiopian Central Statistical Agency & World Food Programme (2013). with a high intake of animal products compared to total estimated energy intake for HID and sum of intake of animal products, milk, and milk products in top 10% income takers in reference [2.]

Table 5. Income-dependent diets in Burkina Faso. The diets are estimated for different socio-economic levels based on income quintiles and poverty data

	Low income diet	**Middle-income diet**	**High-income diet**
Percentage of population[1]	20	60	20
Total energy consumption [kcal][1]	1659 [1]	2017 [1]	2647 [2]
Food category: % of total food consumption			
Cereals	80.0 [I]	75.6 [3]	57.6 [II]
Roots and tubers	0.2 [III]	0.7 [3]	0.7 [3]
Pulses and legumes	2.0 [I]	3.0 [3]	9.8 [IV]
Oilseeds	10.0 [I]	11.0 [3]	2.1 [IV]
Vegetables	6.0 [I]	0.6 [3]	2.5 [IV]
Fruit	0.0[3]	0.3 [3]	3.6 [IV]
Animal products	0.3 [I]	4.7 [3]	7.0 [IV]
Food categories shares of daily consumption [%]	98.5	95.9	83.3

References:

[1] Kazianga, H. & Udry, C. (2006). Consumption smoothing? Livestock, insurance and drought in rural Burkina Faso. *Journal of Development Economics*. Vol. 79(2). pp. 413-446. DOI: 10.1016/j.jdeveco.2006.01.011

[2] FAO (2014). *Burkina Faso - Socio-economic context and role of agriculture. Rome: FAO. (Country Fact Sheet on Food and Agriculture Policy Trends).* Available: http://www.fao.org/docrep/field/009/i3760e/i3760e.pdf [2018-05-02]

[3] Permanent Interstate Committee for Drought Control in the Sahel (2004). *Normes de consommation des principaux produits alimentaires dans les pays du CILLS*. Burkina Faso: CILLS. Available: http://www.hubrural.org/IMG/pdf/cilss_rapport_normes_conso_alimentaires.pdf [Accessed 2018-05-22]
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[I] Average numbers taken from diets in Central West Africa from reference [3] due to no other accurate number of dietary consumption for low-income diet was found.

[II.] Calculated from Reference [3] by estimating the same consumption of cereals in kcal for middle-income diet, thus resulting in a lower share of the total energy consumption for HID.

[III] Calculated from Savadogo, K. & Kazianga, H. (1999). Substitution between domestic and imported food in urban consumption in Burkina Faso: assessing the impact of devaluation. *Food Policy*. Vol. 24(5). pp. 535-551. and median values for energy consumption for the consumed food categories by multiplying average consumption weight for respective food category and multiplied by median energy content [kcal[1] kg-1] and divided with the total daily energy consumption for the diet

[IV] Calculated from Global Dietary Database (n.d.) *Dietary Intake of Foods and Nutrients by Country.* Available: http://www.globaldietarydatabase.org/dietary-data-by-country.html [2018-04-29], by multiplying average consumed weight for respective food category and multiplied by median energy content [kcal kg^{-1}] and divided with the total daily energy consumption for the diet

Table 6 Food crops and animal products commonly consumed in Ethiopia within main food categories

Food category	Cereals	Root and tubers	Pulses	Oil crops	Vegetables	Fruits	Animal products
Product	Maize	Enset	Chickpeas	Linseed	Cabbage	Apple	Bovine
	Millet	Potato	Haricot verts	Niger seed	Carrots	Avocado	Mutton & sheep
	Rice	Sweet potato	Horse bean	Oil palm	Leek	Banana	Pig
	Sorghum		Lentils	Safflower	Onion	Grapes	Poultry
	Teff		Peas	Sesame seed	Peppers	Mango	Milk
	Wheat				Shallot	Orange	
					Squash/pumpkin	Papaya	
					Spinach	Pear	
					Tomato	Pineapple	
						Plantain	

Data of food products are collected from:

- FAO Food Balance Sheet. http://www.fao.org/faostat/en/#data/FBS Available: [2018-02-10],
- FAO (n.d.) *Ethiopia at a glance*. Available: http://www.fao.org/ethiopia/fao-in-ethiopia/ethiopia-at-a-glance/en/ [2018-02-06],
- Taffese, A.S., Dorosh, P. & Gemessa, S.A. (2012). Crop production in Ethiopia, Regional patterns and trends. In: Dorosh, P. & Rashid, S. (Eds) *Food and agriculture in Ethiopia: Progress and policy challenges*. pp 53–83. Philadelphia: University of Pennsylvania Press. ISBN; 9780812245295
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- Demissie, T. & Zerfu, D. (2009). Availability and consumption of fruits and vegetables in nine regions of Ethiopia with special emphasis to vitamin A deficiency. *Ethiopian Journal of Health Development.* vol. 23(3). pp. 216-222. DOI: http://dx.doi.org/10.4314/ejhd.v23i3.53242

Table 7. Food products commonly consumed in Tanzania within main food categories

Food category	Cereals	Root and tubers	Pulses	Oil crops	Vegetables	Fruits	Animal products
Product	Maize	Cassava	Chickpeas	Almond	African eggplant	Banana	Bovine
	Millet	Potato	Cowpeas	Bambara ground-nut	Amaranth (leaves & grain)	Guava	Fish
	Rice	Sweet potato	Haricot verts	Cashew	Avocado	Jackfruit	Egg
	Sorghum	Yams	Kidney beans	Coconut	Cabbage	Lemon	Mutton & sheep
	Wheat		Lentils	Cotton seed	Carrots	Mango	Pig
			Mung bean	Groundnuts	Okra	Orange	Poultry
			Peas	Oil palm	Pumpkin/pumpkin leaves	Pawpaw	Milk
			Pigeon pea	Soybean	Peppers	Pear	
				Sunflower seed	Mushroom	Pineapple	
					Jute mallow	Plantain	
					Spinach	Watermelon	
					Squash		
					Swiss chard		
					Sweet potato leaves		
					Tomato		

Data of products are collected from:

- FAO Food Balance Sheet. Available: http://www.fao.org/faostat/en/#data/FBS.
- Keding, G.B., Msuya, J.M., Maass, B.L. & Krawinkle, M.B. (2011). Dietary patterns and nutritional health of women: The nutrition transition in rural Tanzania. Food and Nutrition Bulletin. vol. 32(3). pp. 218-226. DOI: http://dx.doi.org/10.18697/ajfand.76.16045
- Kinabo, J., Mamiro, P., Dawkins, N., Bundala, N., Mwanri, A., Majili, Z., Jumbe, T., Kulwa, K., Mamiro, D., Amuri, N., Ngowi, M. & Msuya, J. (2016). Food Intake and Dietary Diversity of Farming Households in Morogoro Region, Tanzania. *African journal of food, agriculture, nutrition and development*. vol. 16(4). pp. 11295 - 11309. ISSN: 1684-5358
- Lukmanji, Z. & Hertzmark, E. (2008). *Tanzania Food Composition Tables.* 1st ed. Dar es Salaam: MUHAS, TFNC & HSPH. ISBN: 978 - 9987- 9071-1-3

Table 8. Food products commonly consumed in Burkina Faso within main food categories.

Food category	Cereals	Root and tubers	Pulses	Oil crops	Vegetables	Fruits	Animal products
Product	Maize	Potato	Beans	Bambara groundnuts	Amaranth	Bananas	Bovine
	Millet	Sweet potato	Cowpeas		Baobab fruit	Mango	Eggs
	Rice	Yams		Peanuts	Cabbage	Papaya	Fish
	Sorghum				Chillies		Goat
	Wheat				Jute leaves		Milk
					Okra		Poultry
					Onion		Sheep
					Tomato		

Data of food products are collected from:

- FAO, Food Balance Sheet. Available: http://www.fao.org/faostat/en/#data/FBS.
- Becquey, E. & Marton-Prevel, Y. (2010). Micronutrient Adequacy of Women's Diet in Urban Burkina Faso Is Low. *The Journal of Nutrition.* Vol. 140(11). pp. 2079-2085. DOI: 10.3945/jn.110.123356
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- Savy, M., Marint-Prével, Y., Traissac, P., Eymard-Duvernay, S. & Delpeuch, F. (2006). Dietary Diversity Scores and Nutritional Status of Women Change during the Seasonal Food Shortage in Rural Burkina Faso. *The Journal of Nutrition.* Vol. 136(10). pp.2625-2632. DOI: 10.1093/jn/136.10.2625
- Lykke, A. M., Mertz, O.& Ganaba, S. (2002). Food consumption in rural Burkina Faso. *Ecology of Food and Nutrition.* Vol. 41.pp. 119-153. DOI: 10.1080/03670240214492
- SOS Children (n.d.) Food and Daily Life. Available: http://www.our-africa.org/burkina-faso/food-daily-life [2018-04-29]

3.5 Nutritional composition of main food categories

The calculations of WPdiet and NWPdiet presented under Section 3.3 were performed with the median numbers of nutritive contents for each food category: cereals 3453 kcal kg^{-1}, roots and tubers 1155 kcal kg^{-1}, pulses and legumes 3530 kcal kg^{-1}, oil crops 5850 kcal kg^{-1}, vegetables 550 kcal kg^{-1}, fruits 1500 kcal kg^{-1} and animal products 1390 kcal kg^{-1} (Figure 3). Median values were used as they are more stable against extreme values in a dataset (Olsson *et al*., 2005).The values for the quartiles in Figure 3 are presented in Table 19 and the ingoing crops in Table 21 in Appendix C.

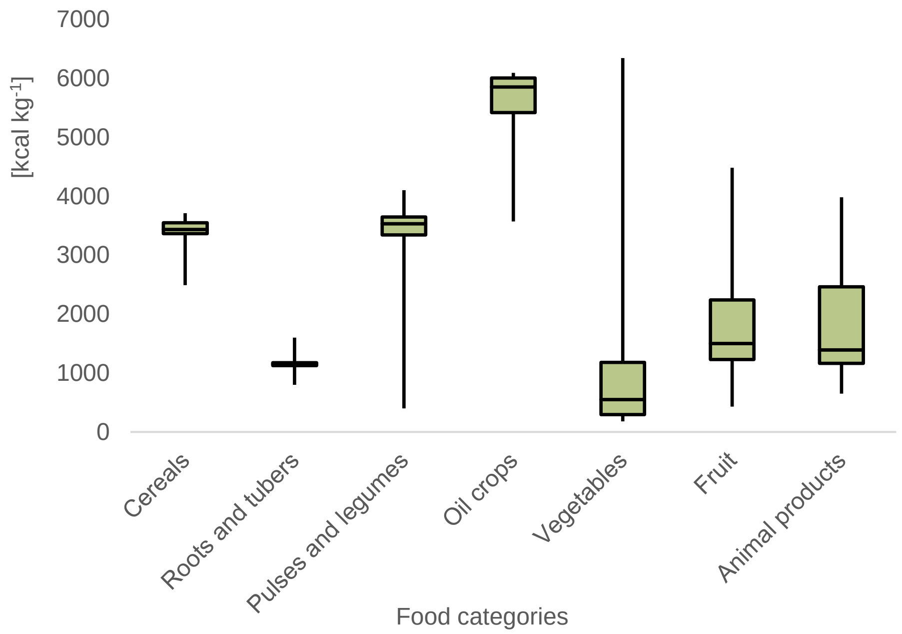

Figure 3. Distribution of energy content per kg crop of main food crops and animal products consumed in Ethiopia, Tanzania, and Burkina Faso, divided in main food categories.
References:

- *Swedish National Food Administration – Food database*
- *FAO/INFOODS Food Composition Database:*
    - *Global food composition database for pulses*
    - *West African food composition table*
- *United States Department of Agriculture – USDA Food Composition Databases*
- *Montagnac, J., Davis, C.R. & Tanumihardjo, S.A. (2009). Nutritional Value of Cassava for Use as a Staple Food and Recent Advances for Improvement. Comprehensive Reviews in Food Science and Food Safety. Vol. 8(3). pp. 181-194. DOI: 10.1111/j.1541-4337.2009.00077.*

Included products in the food categories were limited to crops and food products most commonly consumed and eaten according to information obtained from references of food intake and food consumption in ETH, TZ and BF (*Table 3*Table 6, Table 7, and Table 8 in section 3.4). The category *vegetables* had the highest number of included crops (7) and *root and tubers* the lowest number (4) (Table 9).

Table 9. Number of crops and animal products included for calculating median values of nutrition content for food categories in diets in Ethiopia, Tanzania, and Burkina Faso

Cereals	**Roots and tubers**	**Pulses and legumes**	**Oil crops**	**Vegetables**	**Fruits**	**Animal products**
8	4	7	7	16	16	8

In calculations of NWP_{diet} the macronutrients carbohydrates, protein, fat, and fibre were included, as well as the micronutrient calcium, magnesium, iron, zinc, vitamin C, vitamin A and folate. Especially deficiencies of vitamin A, zinc and iron are of concern in SSA ((WHO *et al.*, 2017 b). The additional nutrients are adopted from Charrodière (2017) in connection to food and nutrition in SSA. Further, they are also addressed in Renault & Wallender, (2000); DeFries *et al.*, (2015); and Herrero *et al.*, (2017), which studied different measures of nutrition and productivity. This study thus becomes a complement to these other studies, even though in the end all essential micronutrients should be of interest to put in relation to productivity. The values for individual nutrients used in calculation of NWP_{diet} are summarized in Table 18 in Appendix C.

3.6 Data

Data were collected from the databases and main references in Table 10. This table summarises the variables of which data have been used in the calculations of $WP_{diet,}$ and which references that were used to find required information.

Table 10. Databases and references used for collecting data for calculations of Dietary Water Productivity in Ethiopia, Tanzania, and Burkina Faso.

Variables	**Reference**
Yield, consumption, production, export and import	FAO FAOSTAT (FBS)
Water resources and access	FAO AQUASTAT
Nutritive content and -composition of crops and food products	Swedish National Food Administration – Food database FAO/INFOODS Food Composition Database: • Global food composition database for pulses • West African food composition table United States Department of Agriculture – USDA Food Composition Databases Montagnac, J., Davis, C.R. & Tanumihardjo, S.A. (2009). Nutritional Value of Cassava for Use as a Staple Food and Recent Advances for Improvement. *Comprehensive Reviews in Food Science and Food Safety*. Vol. 8(3). pp. 181-194. DOI: 10.1111/j.1541-4337.2009.00077.x
Population and poverty data	The World Bank - Open Data.

Databases and search queries

Information was searched for in the databases Food Science and Technology Abstracts (FSTA), Google, Google Scholar, Primo, Scopus and Web of Science. Table 11 contains main search queries used for different aimed information search. Information of diets and consumed food products where required to gain knowledge of diet composition for different income levels within ETH, TZ and BF. WP as category was necessary for gaining values of WP for specific crops within the countries. Information of water availability was required to draw conclusions from calculated data of WP_{diet} and NWP_{diet}. The words in the queries were used in different combinations and encapsulations for maximizing finding of relevant references (Table 11).

Table 11. Search queries used in databases for information of diet composition, water productivity and water availability in Ethiopia, Tanzania, and Burkina Faso

Search category	**Words included in search queries**
Diets and consumed food products	Dietary diversity, food intake, food consumption, food composition, eating habits, diet, Dietary Diversity Scores, food balance sheets, consumption *in combination with the specified food categories*, Food composition tables, Calorie intake, calorie consumption, income *and* Ethiopia, Tanzania, Burkina Faso
Water productivity	Water productivity, water use efficiency, Crop water requirement, *In combination with:* SSA, Sub Saharan Africa, Sub-Saharan Africa, West Africa, East Africa, Africa, Ethiopia, Tanzania, Burkina Faso
Water availability	Water access, water availability, green water, agriculture, crop production, farming *In combination with Ethiopia OR Burkina Faso OR Tanzania*

*The ending *, encapsulations () "…", and the conjunctions AND and OR, have been used in different combinations with the search queries to widen the number of potential references.*

Selection of references

Data was limited to rainfed agriculture in SSA with ET as denominator for water use and not older than from year 2000. References included in the calculations of WP_{diet} and NWP_{diet} where selected with the criteria of being calculated as $Y_a\ ET_a^{-1}$ (see other variations under Section 3.1 and equation [6]). In the references this equation was ascribed both WP and WUE, still calculating the same values and thus being comparable.

The review of studies of WP in SSA gave less results than expected. Using the search query in Table 11 (("Water productivity" OR "Water use efficiency") AND Ethiopia; as topics, only gave 173 results in Web of Science. Using "Tanzania" as search topic gave 60 search results and Burkina Faso gave 41 results.

To put together values for the average WP, a total of 650 reports in Web of Science were considered with the search query (“Water productivity” OR “Water use efficiency”) AND (Africa OR SSA OR sub-Saharan Africa OR "sub Saharan Africa" OR "west Africa" OR "east Africa").

The query was refined to the years 2000-2018 and set to sort the search results by “relevance”. This resulted in 1,712 reports. By report number 600, the results became irrelevant for the scope of this study, thus the remaining reports were rejected. Ingoing crops from the diets were used as additional initial search criteria but resulted in too few search results. Therefore, the wider query only including WP and WUE were used, not selecting for ETH, TZ or BF.

4 Results

Water productivity (WP) shows large variation in agricultural production in SSA. Though, few references of WP are available in the area done in rainfed agriculture with evapotranspiration as denominator. Calculations of dietary water requirements (WR) resulted in an overall trend of highest WR for producing high-income diets (HID) and lowest for LID. Dietary water productivity (WP_{diet}) and Dietary nutritional water productivity (NWP_{diet}) were overall highest for low-income diets (LID) and lowest for HID with exception from Burkina Faso (BF), where values of NWP_{diet} were higher for vitamin C and vitamin A for HID than middle income-diet (MID). Of total annual WR for the total share of population per diet, did Ethiopia (ETH) have the highest requirements for HID calculated with inefficient WP and for MID calculated with efficient WP. Tanzania (TZ) had highest requirement for population with lower middle-income diet (LMD) and BF for MID. All three countries had lowest requirements for LID population. Of the total share of available national water resources did Ethiopia (ETH) require the highest share of precipitation. BF required the highest share of total renewable water resources. TZ required the least share for both water resources. Precipitation water seem to be able to support the annual dietary WR. Only using IRR-water resources, the water resources would only support dietary requirements when calculated with efficient WP for ETH, TZ and BF. However, there are several factors in the food production which necessitate additional water input in than the total WR calculated for the diets.

4.1 Synthesis of Water Productivity data from empirical studies in SSA

There is a large variation in WP within food categories affected by crops, cropping system and location. Distribution of values for WP identified in the review (section 4.1) are varied, with a range for *cereals* between 0.3–2.3 kg m^{-3} , *roots and tubers* 2.2-3.7 kg m^{-3}, *pulses and legumes* 0.2-0.5 kg m^{-3}, *oil crops* 0.4-0.5 kg m^{-3}, *vegetables* 0.9-1.8 kg m^{-3}, *fruits* 0.9-1.6 kg m^{-3} and *animal products* 0.01-0.2 kg m^{-3}, thus *oil crops* having the least, and *cereals* the largest variation in WP (Figure 4. Distribution of Water Productivity (= Ya ET_a^{-1}) from rainfed production within food categories in diets in Ethiopia, Tanzania, and Burkina Faso.). Though, findings of studies of WP in SSA from rainfed agricultural systems calculated as the ratio between actual yield (Y_a) and actual evapotranspiration (ET_a) were few (See Table 12 in next paragraph) and not possible to find for all food categories in neither ETH (see Appendix A, Figure 14 for WP values specific from ETH) nor TZ or BF. The reviewed studies in Figure 4. Distribution of Water Productivity (= Y_a ET_a^{-1}) from rainfed production within food categories in diets in Ethiopia, Tanzania, and Burkina Faso. are from West Africa (Burkina Faso, Togo, Niger and Nigeria, Volta delta, Niger delta, around the Niger River basin), East Africa (Ethiopia, Kenya, Tanzania, Uganda, and the Nile Basin) and Southern Africa (Botswana, Malawi, Zimbabwe, and South Africa) thus representing different parts of SSA except central Africa.

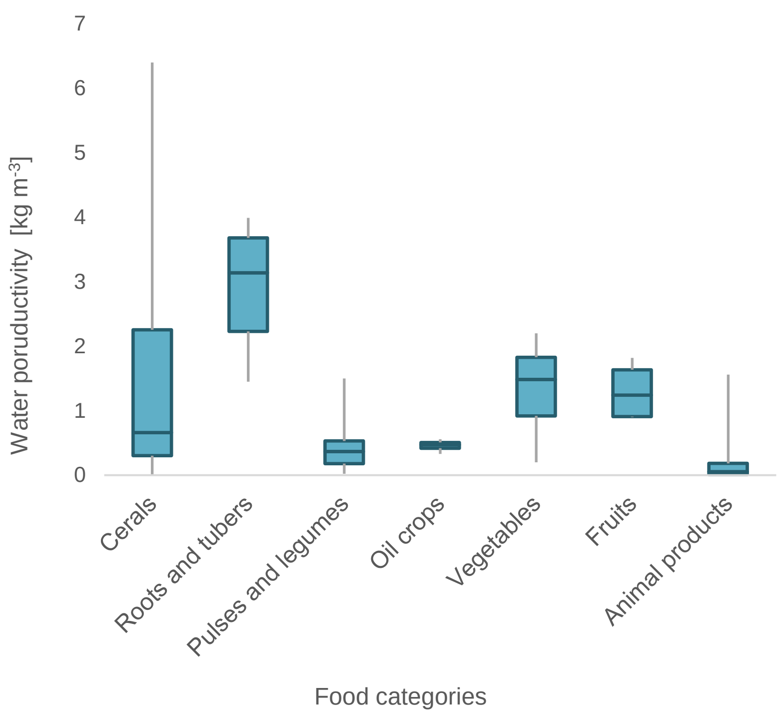

Figure 4. Distribution of Water Productivity (= Y_a ET_a^{-1}) from rainfed production within food categories in diets in Ethiopia, Tanzania, and Burkina Faso.

Most references where found for the category *cereals* (25) and the least amount for *fruits* (one (1) reference from SSA). For the category *fruits*, two global values of rainfed WP where included from Siebert & Döll (2010). In total 47 references for

WP calculated as $Y_a\ ET_a^{-1}$ where found and included in the food categories in Figure 4 (Appendix D, Table 22). The total number of values for WP within the categories varied with most included for *cereals* (172) and least numbers or *fruits* (4) (Table 12).

Table 12. Number of references and values of Water Productivity (WP) included in the review of WP in Sub-Saharan Africa.

	Cereals	Roots and tubers	Pulses and legumes	Oil crops	Vegetables	Fruits	Animal products
Number of references within food categories	25	4	13	4	6	2	5
Number of values of WP within food categories	172	23	33	8	8	4	80

Calculations of WP_{diet} and for WR were done with the lower quartiles (inefficient WP), median and upper quartiles (efficient WP) from Figure 4. Distribution of Water Productivity (= $Y_a\ ET_a^{-1}$) from rainfed production within food categories in diets in Ethiopia, Tanzania, and Burkina Faso. The variation in WP within food categories indicate the importance of having representative values of WP in calculations of WP_{diet} in general. Values of WP were also relatively high, especially for water consuming food categories compared to other measures from SSA (see section 5.2 for further elaboration).

4.2 Estimates of water requirements for diets per income level in Ethiopia, Tanzania, and Burkina Faso

The WP_{diet} and NWP_{diet} for the socio-economic diets are changing due to varying total energy content and differences in composition between the food categories over all for ETH, TZ and BF. HID had an overall higher consumption of *animal products* and *oil crops* with lower WP-values, resulting in a larger WR for the total diet. The LID had overall high values for WP_{diet} and NWP_{diet} due to a lower consumption of total energy, and a higher share of *cereals, pulses and legumes* and *vegetables*. The share of these products and the total amount [kg] of each food category affect the overall WR for the diets. The food categories have different nutritional composition, affecting the total consumption for the diets and amount of nutrition obtained per unit of water.

Ethiopia

Total required dietary water volume per capita was calculated to be the highest for HID (2.1-29.5 $m^3\ cap^{-1}\ d^{-1}$) and lowest for the LID (0.4-1.7 $m^3\ cap^{-1}\ d^{-1}$) despite the value of WP used per food category (inefficient, median or efficient WP, see section 4.1) (Figure 5. Water requirement (WR) for producing three diets for the socio-economic levels low-income, middle-income, and high-income population in Ethiopia. The lower WR is calculated with efficient WP-values and the higher water output is calculated with inefficient WP-values for ingoing food groups (cereals, roots and tubers, pulses and legumes, oil crops, vegetables, fruits, and animal products) in the diets. The point in the middle is calculated with a median value of WP.). Differences in WR where highest between diets calculated with the least efficient WP. This refers to the higher share of animal products (10 % of the diet's total energy content) in the HID which had the most inefficient WP range (0.01-0.2 kg m^{-3}) of all ingoing food categories (Figure 4, section 4.1). The second largest contributor to the WR were the category *cereals*, contributing to the highest share of energy consumption for the three diets (Table 3, section 3.4). The high difference within HID shows the large uncertainty in WP-values for the food groups and the requirement to have accurate input data in the calculations. The differences between food groups are due

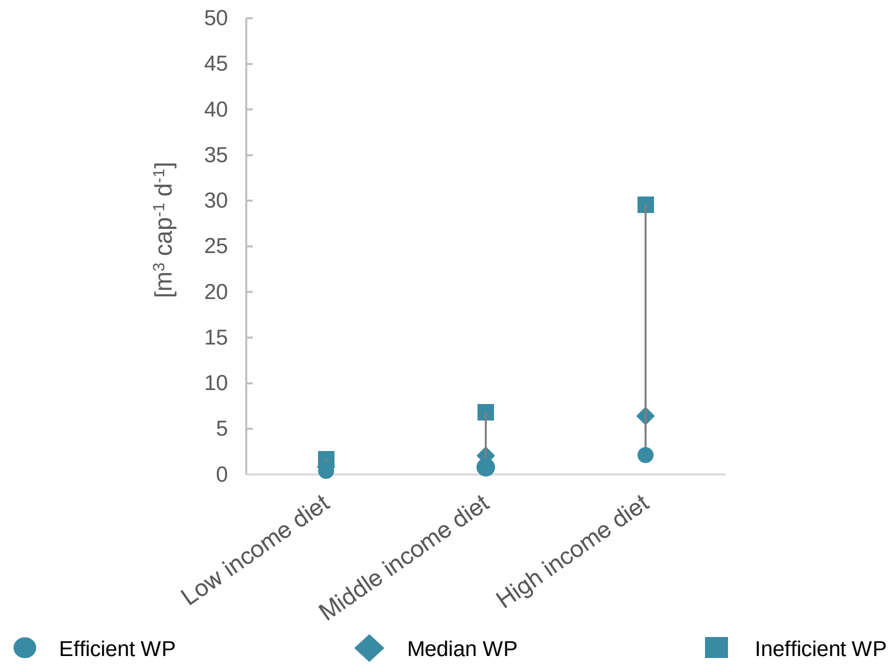

Figure 5. Water requirement (WR) for producing three diets for the socio-economic levels low-income, middle-income, and high-income population in Ethiopia. The lower WR is calculated with efficient WP-values and the higher water output is calculated with inefficient WP-values for ingoing food groups (cereals, roots and tubers, pulses and legumes, oil crops, vegetables, fruits, and animal products) in the diets. The point in the middle is calculated with a median value of WP.

to the differences in total energy consumption and shares of energy from different food categories (Table 3, section 3.4) These numbers are further compared to other studies in section 5.2.

For WP_{diet} the LID showed higher values for energy (1126-5027 kcal m^{-3}) compared to MID (410-3532 kcal m^{-3}) and HID (115-1617 kcal m^{-3}) (*Figure 6*). WP_{diet} was higher than the total daily dietary energy consumption for LID when calculated with median WP and higher than total dietary energy consumption for LID and MID when calculated with efficient values of WP. Compared to recommended daily energy intake (1550-4500 kcal cap^{-1} d^{-1}) (grey area in Figure 6) calculations with efficient WP resulted in values of WP_{diet} within the range of recommended daily energy intake according to (FAO *et al*, 2001) (grey area in Figure 6) for all three diets. All diets calculated with inefficient WP required more than 1 m^3 for producing energy according to the recommended energy intake range, and only the LID reached above the lower value of recommended daily energy intake when calculated with the median WP

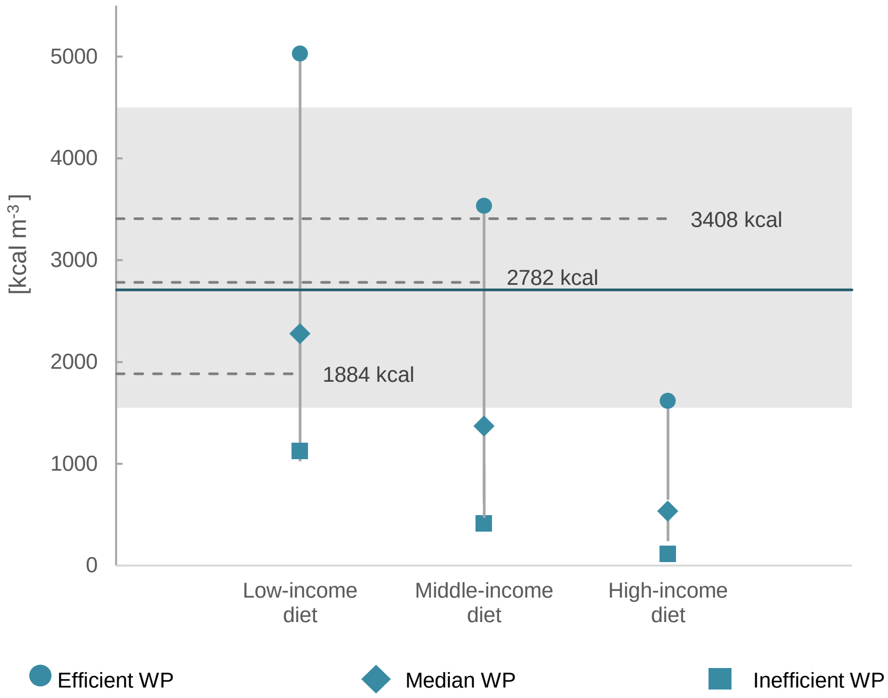

Figure 6. Dietary Water Productivity (WP$_{diet}$) for socio-economic diets in Ethiopia. Values represents lower-, median- and upper values of WP$_{diet}$ calculated with different efficient values of Water Productivity (WP) for ingoing food categories in the three diets. The lowest value for each diet is calculated with inefficient WP per food category. The dashed lines show total energy intake of the diets. Shaded area is the range of recommended daily energy intake [kcal cap $^{-1}$d^{-1}] for adults. The continuous line indicates the average recommended dietary energy intake for adults (2708 kcal cap^{-1} d^{-1}), calculated from Table 5.4 – 5.9 in FAO, WHO, UNU (2001). Human energy requirements. Rome: FAO. (Food and nutrition technical report series 1). ISSN 1813-3932

LID showed higher productivity values for all included nutrients except from fat in NWP$_{diet}$ macronutrients: carbohydrates (205.8-918.5 g m^{-3}), protein (36.2-161.6 g m^{-3}), fibre (27.5-122.7 g m^{-3}), fat (9.5-42.5 g m^{-3}) (Figure 7) and the micronutrients (Table B17, Appendix B. See calculations in section 3.3). NWP$_{diet}$ for fat was equal for LID and MID calculated with efficient WP, but lower for MID calculated with inefficient WP. The more efficient NWP$_{diet}$ for the LID is explained by an overall lower consumption of all food categories with exception from roots and tubers, where the HID had a lower consumption (0.3 kg cap^{-1} d^{-1} for the LID compared to 0.2 kg cap^{-1} d^{-1} for HID).

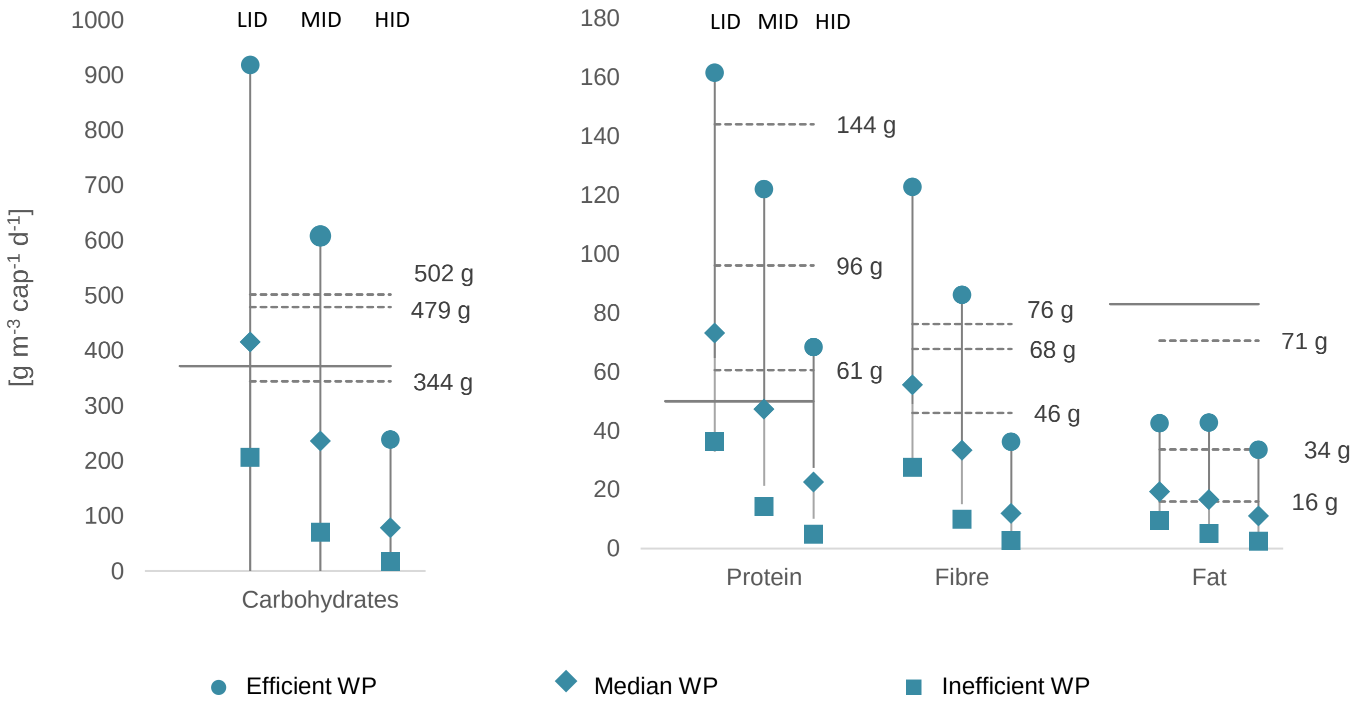

Figure 7. Dietary Nutritional Water Productivity (NWP_{diet}) for diets attributed to low-income-, middle-income and high-income population in Ethiopia. The productivity is presented for the macronutrients carbohydrates, proteins, fibre, and fat with the low-income diet having the highest values of NWP_{diet} for all the nutrients and the high-income diet having the lowest NWP_{diet} -values. The dashed lines indicate the sum of respective diet's dietary consumption of respective macro nutrient as the sum of consumption from the food groups cereals, roots and tubers, oil crops, vegetables, fruits, and animal products. The lower dashed line is the consumption of the low-income diet, the middle line shows consumption of the middle-income diet and the upper line for high-income diet. The continuous lines are the average recommended dietary energy intake for adults for respective macronutrient: carbohydrates: 372 g cap^{-1} d^{-1} (FAO, WHO., 1998), protein: 50g cap^{-1} d^{-1} (WHO, FAO, UNU, 2007), fats: 83 cap^{-1} d^{-1} (FAO, WHO, 2009). These values are calculated from the average recommended intake of energy and the recommended energy percent of respective nutrient.

Note that the axis for carbohydrates has higher values compared to the axis for protein, fibre, and fat.

Of total nutritional consumption, HID showed the highest consumption for all nutrients except from vitamin C. The highest consumption of vitamin C was seen in the MID (95 mg day^{-1}) followed by LID (82 mg day^{-1}) compared to the HID (73 mg^{1} day^{-1}). This is explained by a higher share of roots and tubers included in the LID (20 %, 0,3 kg d^{-1}) and MID (13.7 %, 0.4 kg d^{-1}) than in the HID (6,2 %, 0.2 kg d^{-1}). Roots and tubers is the food category which contains a higher share of vitamin C compared to the other food categories except from fruits (complete median values of nutritive content for the main food categories are presented in Table 18, Appendix

C). However, due to the low consumption of *fruits* in the diets, this food category does not have a high contribution to the overall consumption of vitamin C.

Tanzania

WR [m^3 cap^{-1} d^{-1}] was calculated to be highest for the HID (3.0-45.9 m^3 cap^{-1} d^{-1}) with decreasing WR with lower income (UMD 1.2-15.5 m^3 cap^{-1} d^{-1}, LMD 0.9-9.8 m^3 cap^{-1} d^{-1} and LID 0.3-1.3 m^3 cap^{-1} d^{-1}) Figure 8). This is due to the higher share of animal products (20 % HID, 8.3 % UMD, 5.1. % LMD and 0 %f for LID) for the diets attributed to higher income levels (see Table 4 and Table 5 under Section 3.4).

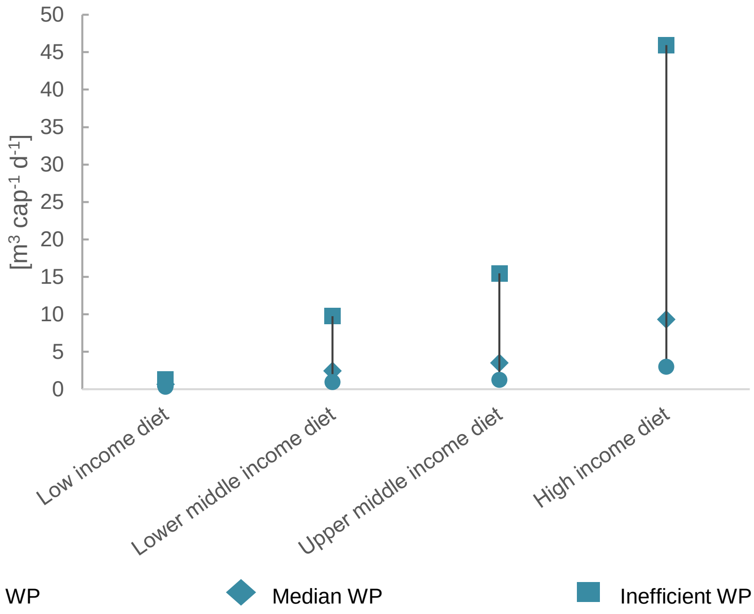

Figure 8. Water requirement for producing four diets for the socio-economic levels low-income, lower middle-income, upper middle-income and high-income population in Tanzania. The intervals show water output calculated with a range of values for Water Productivity (WP) (low-income diet 0.3-1.3 m^3 cap^{-1} d^{-1}; lower middle-income diet 0.9-9.8 m^3 cap^{-1} d^{-1}; upper middle-income diet 1.2 -15.5 m^3 cap^{-1} d^{-1} and high-income diet 3.0-45.9 m^3 cap^{-1} d^{-1}) The lower water output is calculated with efficient WP-values and the higher water output is calculated with inefficient WP-values for ingoing food groups

The high difference within HID shows the large uncertainty in WP-values for the food groups differences between diets are due to the differences in total energy consumption and shares of energy from different food categories (Table 4, section 3.4). These numbers are further compared to other studies in section 5.2.

Values of WP_{diet} were highest for the LID (1064-4467 kcal m^{-3}) and decreased with diet and increased economic level for calories, being lowest for the HID (62-950 kcal m^{-3}) (Figure 9). Total daily energy consumption was calculated to only be met with less than one square meter (1 m^3) for LID and LMD diet calculated with high WP and only met with less than 1 m^3 for the LID when calculated with the median WP. LID, LMD, and UMD values of WP_{diet} fulfilled the recommended daily energy intake (1550-4500 kcal $cap^{-1}d^{-1}$) (grey area in Figure 9) with less than 1 m^3 calculated with efficient WP. Only LID fulfilled the lower range of recommended dietary daily intake with less than one square meter calculated with the median value of WP. However, one notation is that average daily energy consumption is not sufficient to be within the range of recommended daily energy intake.

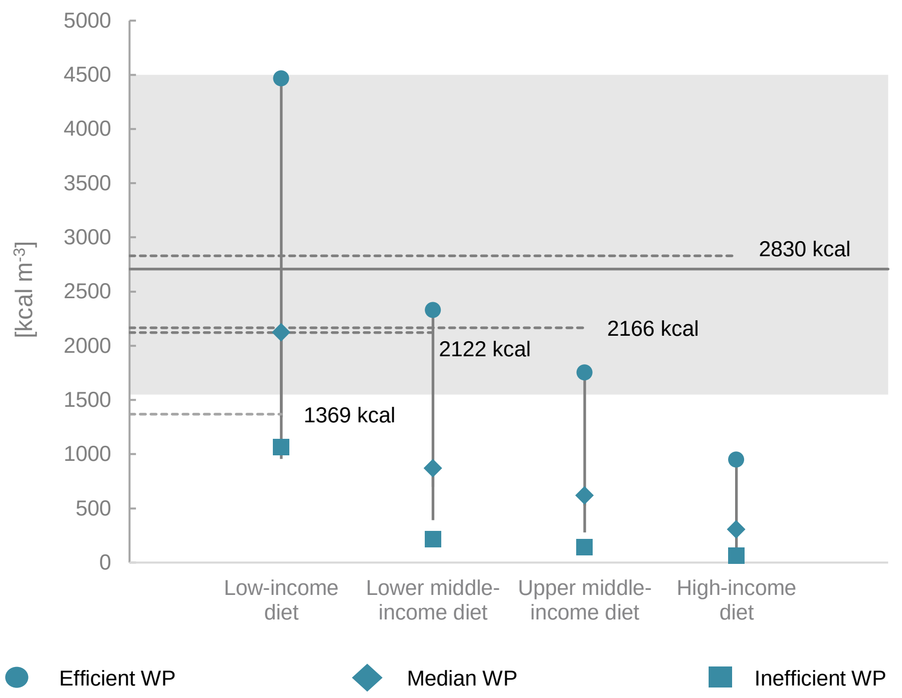

Figure 9. Dietary Water Productivity (WP_{diet}) for socio-economic diets in Tanzania. Marked values for each diet represent lower-, median- and upper values of WP_{diet} calculated with different values of Water Productivity (WP) for ingoing food groups. The lowest value for each diet is calculated with the lower value for WP per food group and vice versa. The dashed lines show total energy intake of the diets including the food groups cereals, roots and tubers, oil crops, vegetables, fruits, and animal products. The shaded area represents the range of recommended daily energy intake (2708 kcal cap^{-1} d^{-1}) for adults calculated from Table 5.4 – 5.9 in FAO, WHO, UNU (2001). Human energy requirements. Rome: FAO. (Food and nutrition technical report series 1). ISSN 1813-3932

NWP_{diet} were highest for the LID for all macronutrients and decreased with increased economic levelled diet with the same tendency for values of micronutrients (Figure 10 and Table B17 in Appendix B).

Of total nutritive consumption had LMD a marginally higher consumption of vitamin C (92 mg cap^{-1} d^{-1}) compared to UMD (89 mg cap^{-1} d^{-1}), LID (67 mg cap^{-1} d^{-1}) with the least consumption for the HID (60 mg cap^{-1} d^{-1}). These values depend on the consumption of *roots and tubers*, *vegetables* and *fruits* in the diets which have the highest C-vitamin content of the food categories. (Table B17 Appendix C).

There was also a difference in total carbohydrate consumption with the being marginal difference for LMD (346 g cap^{-1} d^{-1}), HID (341 g cap^{-1}d^{-1}) and UMD (332 g cap^{-1}d^{-1}) with the lowest value for LID (247 g cap^{-1} d) (and Table B17, Appendix C)

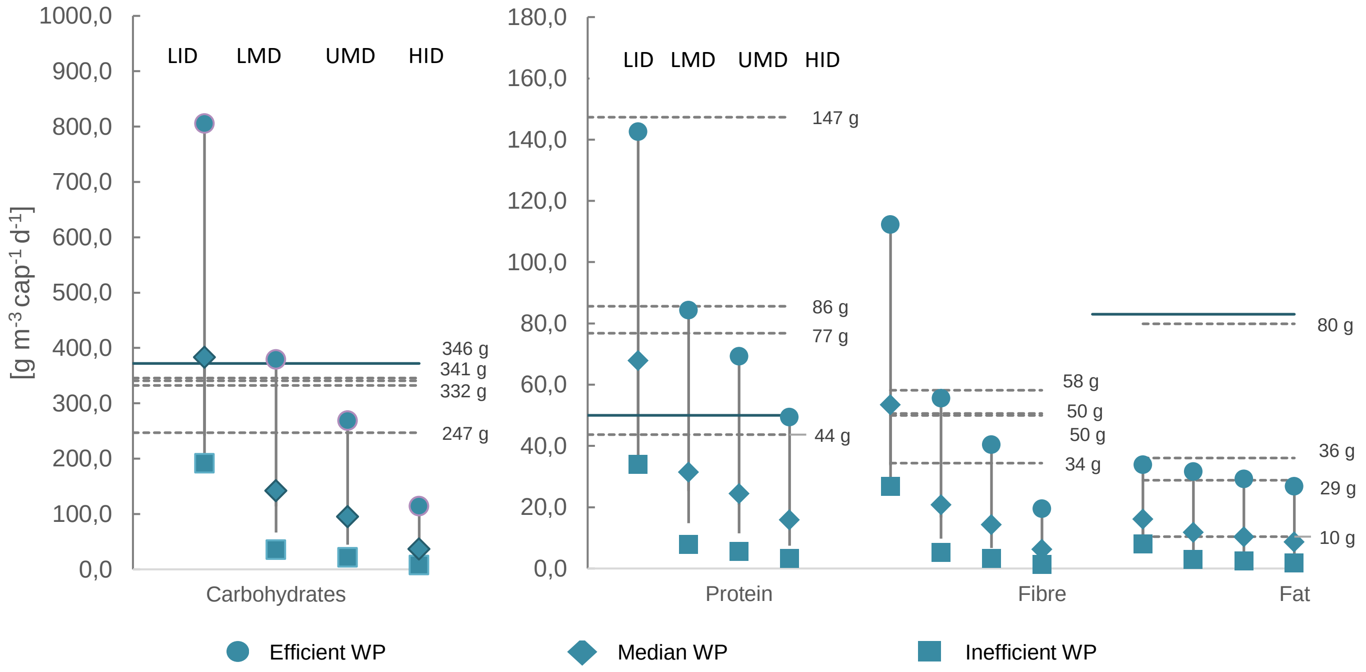

Figure 10. Dietary Nutritional Water Productivity (NWP_{diet}) for diets attributed to low-income-, lower middle-income, upper middle-income and high-income population in Tanzania. The productivity is presented for the macronutrients carbohydrates, proteins, fibre, and fat with the low-income diet having the highest values of NWP_{diet} for all the nutrients and high-income diet having the lowest NWP_{diet} -values. The dashed lines indicate the sum of respective diet's dietary consumption of respective macro nutrient and the lower dashed line is the consumption of the low-income diet, the middle line shows the consumption of the middle-income diet and the upper line is the consumption of the high-income diet with exception for carbohydrates where middle-income diet had the highest carbohydrate consumption (346 g cap^{-1} d^{-1}), followed by high-income diet (341 g cap^{-1} d^{-1}), upper middle-income diet (332 g cap^{-1} d^{-1}) and low-income diet (247 g cap^{-1}d^{-1}). The continuous lines are the average recommended dietary energy intake for adults for respective macronutrient: carbohydrates: 372 g cap^{-1} d^{-1} (FAO, WHO., 1998), protein: 50g cap^{-1} d^{-1} (WHO, FAO, UNU., (2007), fats: 83 cap^{-1} d^{-1} (FAO, WHO (2009). These values are calculated from the average recommended intake of energy and the recommended energy percent of respective nutrient. Note that the axis for carbohydrates has higher values compared to the graph for protein, fibre, and fat.

Burkina Faso

Highest WR were calculated for the HID (1.2-15.4 m^3 cap^{-1} d^{-1}) and the lowest for the LID (0.4-2.6 m^3 cap^{-1} d^{-1}) with the range for MID being 0.7-8.5 m^3 cap^{-1} d^{-1} (Figure 11). The higher WR for the HID is due to higher consumption of the groups *pulses and legumes* (10%, 0.4 kg cap^{-1} d^{-1}) and *animal products* (7 %, 13 kg cap^{-1} d^{-1}).

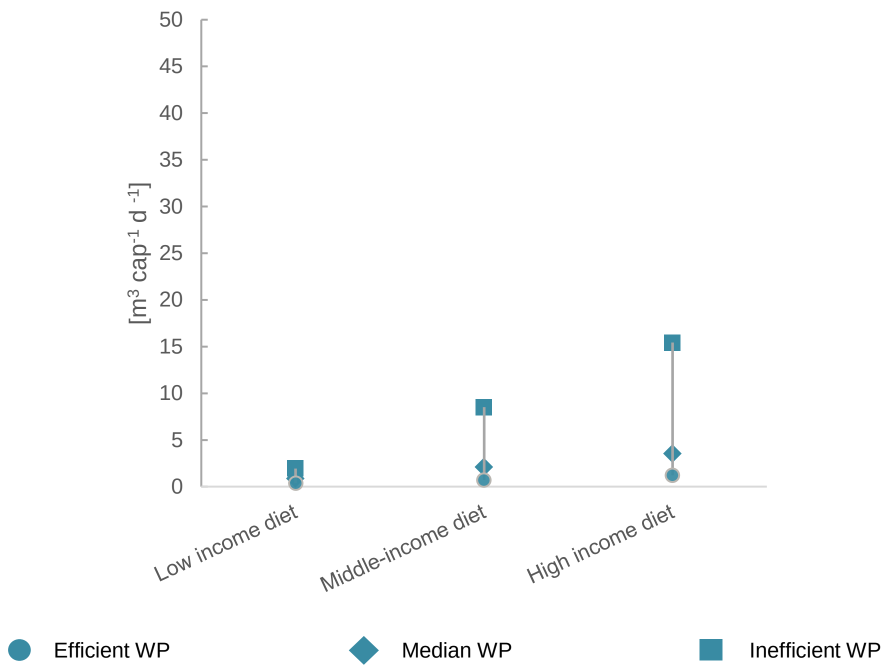

Figure 11. Water requirement for producing three diets for the socio-economic levels low-income, middle-income, and high-income population in Burkina Faso. Intervals show water output calculated with a range of values for Water Productivity (WP). The lower water output is calculated with efficient WP-values and the higher water output with inefficient WP-values for ingoing food categories.

The values for WP_{diet} where highest for the LID (4486-838 kcal m^{-3}) and lowest for the HID (143-1832 kcal m^{-3}) with all values of WP_{diet} calculated with efficient WP being in the range of recommended daily energy intake (grey area in Figure 12). Values of WP_{diet} calculated with inefficient WP were out of the range indicating that even to support the lowest range value of recommended daily energy intake it would require more than 1 m^3 of water (Figure 12).

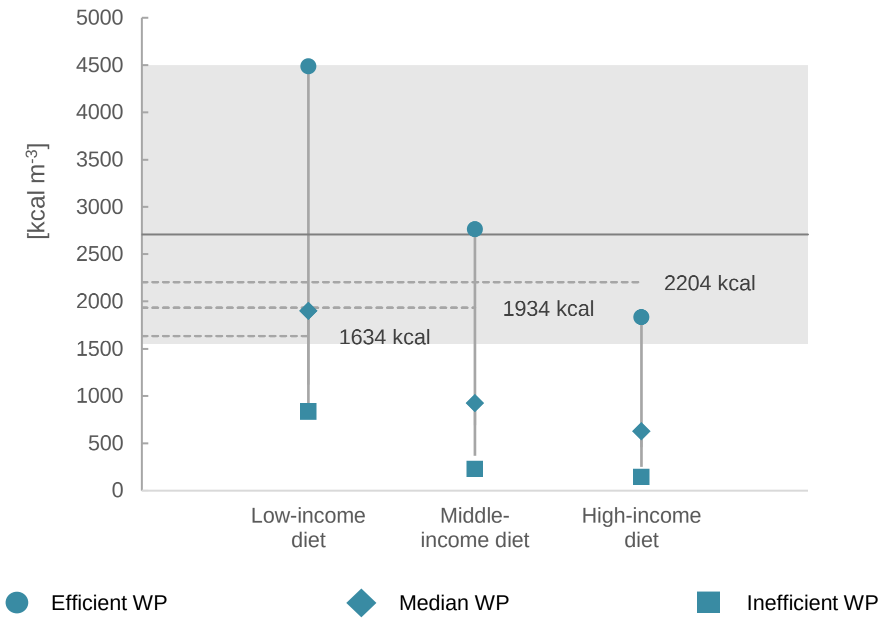

Figure 12. Dietary Water Productivity (WP$_{diet}$) for socio-economic diets in Burkina Faso. The marked values within each range for the different diets represents lower-, median- and upper values of WP$_{diet}$ calculated with different values of Water Productivity (WP) for ingoing food groups in the three diets. The lowest value for each diet is calculated with the lower value for WP per food group. The dashed lines show the total energy intake of the diets. The shaded area represents the range of recommended daily energy intake (2708 kcal cap^{-1} d^{-1}) for adults calculated from Table 5.4 – 5.9 in FAO, WHO, UNU (2001). Human energy requirements. Rome: FAO. (Food and nutrition technical report series 1). ISSN 1813-3932

The values of NWP$_{diet}$ for macro- and micronutrients were over all highest for the LID and lowest for the HID (Figure 13 and Table B17, Appendix B) except from vitamin C and vitamin A with all values highest for LID (Vitamin C: 14-73 mg m^{-3} and vitamin A: 38-201 µg m^{-3}), the NWP$_{diet}$ values were higher for HID (Vitamin C: 3-37 mg m^{-3} and vitamin A: 5-60 µg m^{-3}) than for the MID (Vitamin C: 1-12 mg m^{-3} and vitamin A 2-25 µg m^{-3}) (see Appendix B Table B17 for full values of the NWP$_{diet}$). These differences are due to higher food consumption for HID of *pulses and legumes*, *vegetables*, and *animal products* than for MID and in relation to the total WR in production of the diets (see Table 8, section 3.4).

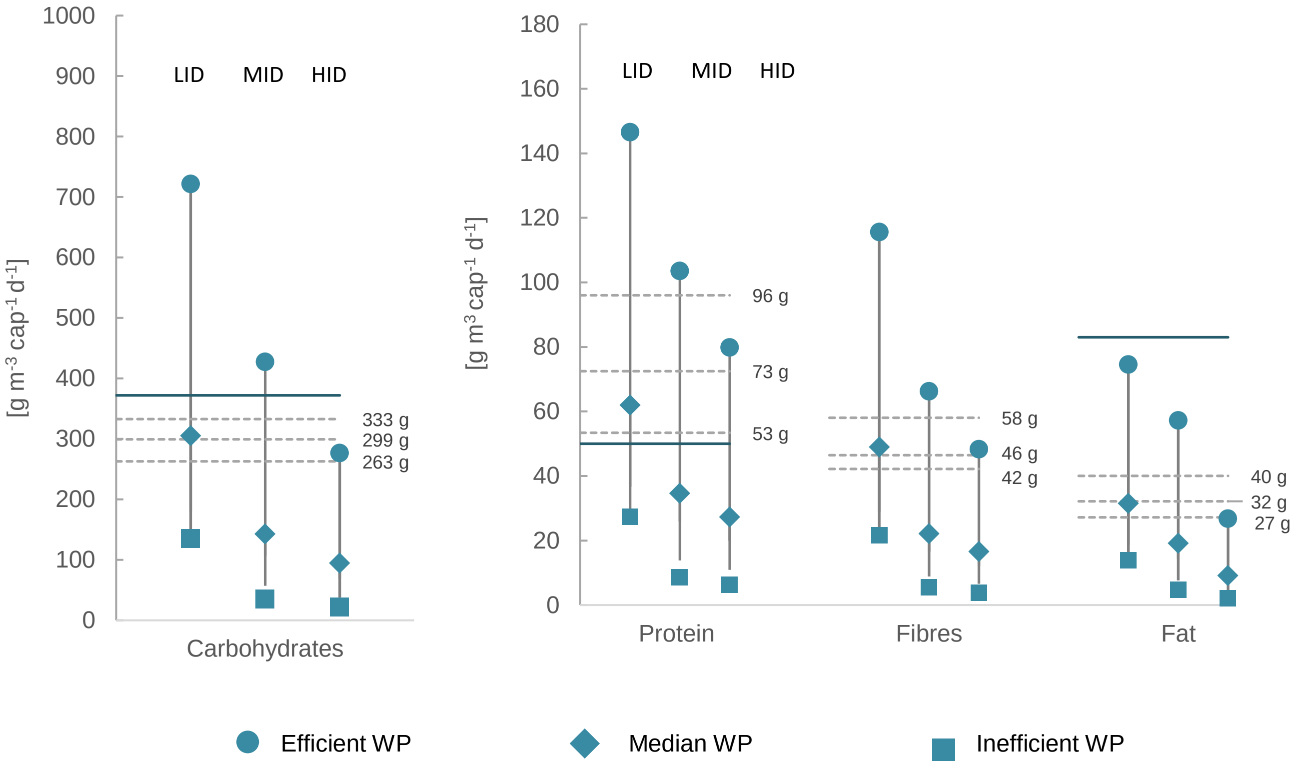

Figure 13. Dietary Nutritional Water Productivity (NWP_{diet}) for diets attributed to low-income-, middle-income and high-income population in Burkina Faso. The productivity is presented for the macronutrients carbohydrates, proteins, fibre, and fat with the low-income diet having the highest values of NWP_{diet} for all the nutrients and the high-income diet having the lowest NWP_{diet} -values. The dashed lines indicate the sum of respective diet's dietary consumption of respective macro nutrient. The lower dashed line is the consumption of the low-income diet, the middle line shows for middle-income diet and the upper line for high-income diet. The continuous lines are the average recommended dietary energy intake for adults for respective macronutrient: carbohydrates: 372 g cap^{-1} d^{-1} (FAO, WHO., 1998), protein: 50g cap^{-1} d^{-1} (WHO, FAO, UNU., (2007), fats: 83 cap^{-1} d^{-1} (FAO, WHO (2009). These values are calculated from the average recommended intake of energy and the recommended energy percent of respective nutrient. Note that the axis for carbohydrates has higher values compared to the axis for protein, fibre, and fat

Of the total nutritive consumption vitamin C, and vitamin A were higher for the LID (vitamin C: 27 mg cap^{-1} d^{-1}; vitamin A: 73 µg cap^{-1} d^{-1}) than for the MID (vitamin C: 8 mg cap^{-1} d^{-1}; vitamin A: 18 µg cap^{-1} d^{-1}) with the highest consumption for HID (Vitamin C: 44 mg cap^{-1} d^{-1}; vitamin A: 71 µg cap^{-1} d^{-1}).

4.3 Comparison of water appropriation for diets with national water resources

The LID population was calculated to require the lowest volume ((2.8-12.5 Gm^3 y^{-1}) of the annual WR in ETH. The highest volume was different depending on calculated with efficient or inefficient values of WP. With inefficient WP the highest WR were calculated for the high-income population (15.7-220.8 m^3 y^{-1}). Calculated with an efficient WP, WR was higher for the middle-income population (17.7 -152.3 Gm^3 y^{-1}). This is due to the difference in WR per capita where the ratio between HID and MID depends on if it is calculated with efficient WP (ratio 2.7) or inefficient WP (ratio 4.4). The higher WR with inefficient WP for HID overcomes the higher share of population attributed to the MID, thus resulting in a larger total WR.

For Tanzania (TZ) the low-income population was attributed with the lowest WR (1.8-7.4 m^3 y^{-1}) and the LMD population the highest (9.4-100.4 m^3 y^{-1}). The UMD population had the second lowest WR (4.2-44.5 m^3 y^{-1}) after the low-income population.

The WR followed the same pattern in BF (population with LID (0.5-3.5 m^3 y^{-1} and MID 2.8-34.7 m^3 y^{-1}). This is due to the high number of population attributed to the middle-income diets compared to the share of population with HID (Table 13, note that in in the table MID is put to the abbreviation LMD to compare with the diets for TZ).

Table 13. Calculated total annual water requirements for food production to meet the estimated total amount of food required for diets for low-income- (LID), lower middle-income (LMD), upper middle-income- (UMD), and high-income (HID) population in Ethiopia, Tanzania, and Burkina Faso

Country	**Population**[I]	**Annual required water volume to fulfil estimated need of the total population per socio-economic diet and WP effectiveness** [Gm^3 y^{-1}]									
		Inefficient WP					**Efficient WP**[1]				
		LID	LMD	UMD	HID	Total	LID	LMD	UMD	HID	Total
Ethiopia	102,403,196	12.5	152.3		220.8	385.6	2.3	17.7		15.7	36.2
Tanzania	55,572,201	7.4	100.4	44.5	64.3	216.6	1.8	9.4	3.6	4.2	18.9
Burkina Faso	18,646,433	2.7	34.7		21.0	59.2	0.5	2.9		1.6	5.0

[I] 2016 WHO: World Bank Open Data. Available: https://data.worldbank.org/ [2018-05-10]

With these diets, the total population in ETH requires the highest share of annual precipitation (4 - 41 %) and TZ the least share (2 - 21 %). BF has the lowest annual precipitation but due to the lower population and diets requiring the least volume of water compared to ETH and TZ, the overall use of the precipitation becomes lower.

Total annual required water volume for the diets in relation to the national total renewable resources (IRR) show that BF would require the highest share and TZ the lowest share (BF: 37-433 %; TZ: 20-225 %; ETH: 30-316 %) (Table 14). These numbers show that with inefficient WP the renewable water resources are not sufficient to support production to supply the requirement for the national food intake with these diets. If precipitation is considered, the total WR for supporting production of food in the diets would still be sufficient even with inefficient values of WP for the food categories. Note that this is a theoretical comparison which shows proportions of water availability from the two water resources, for food production. Realistically none of ET, TZ of BF will likely not develop their agriculture to be dependent on irrigation to largest extent, thus precipitation will play the largest role in supporting the agriculture.

Table 14. Calculated annual water requirements as a share of total annual precipitation and as shares of total renewable water resources (IRR). The values are summarized for the total populations per respective diet per socio-economic category: low-income- (LD), lower middle-income (LMD), upper middle-income- (UMD), and high-income (HD) population in Ethiopia, Tanzania, and Burkina Faso.

Country	Total precipitation	Total renewable water resources	Dietary and total water requirement of total annual precipitation calculated with inefficient WP and efficient WP [%]										Dietary and total water requirement of total renewable water resources (IRR) calculated with inefficient WP and efficient WP [%]									
			Inefficient WP					Efficient WP[1]					Inefficient WP					Efficient WP[1]				
	[G m^3 y^{-1}]		LID	LMD	UMD	HID	Total	LID	LMD	UMD	HID	Total	LID	LMD	UMD	HID	Total	LID	LMD	UMD	HID	Total
Ethiopia	936.4	122	1.3	16.3		23.6	41.2	0.3	1.9		1.7	3.9	10.3	124.8		181.0	316.0	2.3	14.5		12.9	29.7
Tanzania	1015	96.27	0.7	9.9	4	6.3	21.3	0.2	0.9	0..4	0.4	1.9	7.6	104.3	46.3	66.8	225.0	1.8	9.4	4	3.6	19.6
Burkina Faso	205.1	13.5	1.3	16.9		10.2	28.5	0.2	1.4		0.8	2.4	19.7	257.3		155.6	432.5	3.7	21.2		12.1	37.0

[1] 2014 FAO: AQUASTAT Available: http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en [2018-05-10]

5 Discussion

5.1 Water Productivity and dietary water requirements

It is not possible to draw conclusions for specific cropping systems and inputs in the countries. This is due to the data gap of water productivity (WP) for individual crops species within the food categories. However, it is possible to conclude a requirement to increase inputs in the cropping systems which increase WP overall in SSA. Examples are soil management practices to sustain soil moisture, nutrient availability to reduce limiting factors as well as inputs as pesticides to decrease yield reducing factors in accordance with Biazin *et al.* (2012). This can improve yields and beneficial water use consistent with Jägermeyr *et al.* (2015). Connecting the crops in food categories to nutritional values indicate higher overall nutritive content for *oil crops* and *pulses and legumes*. The highest content of carbohydrates for *cereals*; vitamin A for *vegetables* and vitamin C for *fruits.* With the goal to achieve more “nutrition per drop” it is suggested to implement further studies of WP on crops in other food categories which have higher general nutritive values than *cereals*.

Overall higher WR and lower water productivity (WP_{diet}) were modelled for high-income diets (HID) and vice versa for the low-income diets (LID) in Ethiopia (ETH), Tanzania (TZ) and Burkina Faso (BF). These results were expected due to higher energy consumption and consumption of more water demanding food categories in high-income diets (HID) compared to low-income diets (LID). However, due to insecurities in food intake in the diets and few WP values, the calculated numbers should only be considered in the terms of magnitude and not as absolute numbers.

Higher dietary nutritional water productivity (NWP_{diet}) for LID than middle-income diets (MID) and HID could be interpreted as that WR might be less to support the same nutritive content for the three diets. However, this conclusion should be taken cautiously, as this highly depends on ingoing crops and animal products in the diets and food categories, due to a large variation of WP_{crop} and crop nutritive content (section 3.5 and section 4.1). This strongly affect total required water volumes, values of WP_{diet} and how accurate they are to the specific site for the evaluated agricultural system.

Water is calculated to be sufficient to meet dietary WR in ETH, TZ and BF in rainfed agriculture in theory. This, even when WP_{diet} was calculated with inefficient WP. Renewable water resources (IRR) also seemed sufficient to sustain dietary WR if efficient WP was considered. This partly agrees with Rockström *et al.* (2009) who modelled sufficient resources of clustered soil water and internal renewable water resources (IRR) to meet food demand in Ethiopia and Tanzania, while Burkina Faso was modelled to reach water scarcity and rely more on land expansion and/or food import. The importance of precipitation as water resource in ETH, TZ and BF is confirmed when comparing calculated dietary WR with numbers from FAO AQUASTAT (Table 2 in section 3.4) where calculated requirements of total renewable water resources clearly exceed the annual use of IRR in agriculture in the three countries.

In practice, several factors influence national WR:

- Yield gaps (Y_g) are a result of farmers not producing highest possible yield with system inputs. Closing Y_g require additional inputs than sufficient water supply, as nutrients and plant protectants, thus seeing to which factor which is limiting production as water supply might me sufficient, thus other factors being limiting (see section 2.2).
- Food import and -export move water requirements outside nation borders. Of the most common crops in diets in ETH, TZ and BF, there is net-import of *roots* and *tubers*, *vegetables* and *animal products* in BF, *oil crops* in ETH and TZ and *cereals* and *fruits* in all three countries according to FAO FBS. Only clustered products in the category *pulses and legumes* are net-exported from all three countries (Table 20, Appendix C). Food import is one way to bypass national water unproductivity and water limitations as energy and nutrition becomes available without national water depletion. However, this should only be a long-term solution for countries where neither IRR nor precipitation are sufficient to meet future production demands and for the food requirement which cannot be supplied by reduction of Y_g through increasing crop productivity. van (van Ittersum *et al.*, 2016) showed that to meet future cereal demands in ETH and BF the yield gaps (Y_g) needs to be

reduced to 80 % of water limited yield (Y_w). This call for improvements in WP which in accordance to above numbers of WP, are established to be low to a global standard. In contrast to ETH and BF was TZ estimated not being able to reach self-sufficiency by just closing Y_g but would require additional cropping land (van Ittersum *et al.*, 2016).

- Counting on all precipitation being available for agriculture is an overestimate. Other ecological functions also require water, as supporting habitats and total crop biomass as not all water contributes to economic yield. Further, irregular precipitation patterns contribute to variety in water availability for crops – not being continuously sufficient to sustain crop growth as these precipitation patterns affect recharge of soil water by e.g. droughts of flooding.
- In a shorter perspective, available water for total application needs to be considered. This study has only included depleted water through evapotranspiration (ET). However, the true WR per season to sustain crop growth is higher as more water is required for the production than just the volumes transpired and evaporated. The importance is that ET is depleted water, while additional applied water is recycled to the system in a long-term perspective.

Projected precipitation patterns for the period 2040 to 2059 from the Climate Change Knowledge Portal (The World Bank c, d, e) compared to average precipitation for the period 1991 to 201,5 indicate a precipitation increase by 30 % in TZ and a decrease in ETH (-1 %) and BF (-3 %). This signal that available water resources might still be sufficient to cover dietary requirements with forthcoming precipitation if the diets stay the same. However – these numbers should also consider the dietary change connected to changed income levels (see section 3.4) and population increase (e.g. the population increase between 2015 and 2016 were in ETH + 2.5 %, TZ + 6.4 % and BF + 3 % (calculated from population data from The World Bank – Open data). van Ittersum *et al.* (2016) conclude though that increased WR are mainly due to population increase rather than diet changes. Despite driving force, there is a need for further inclusion of estimated dietary changes and population increase in predicted water availability, to foresee probable scenarios of food intake which will affect water availability and thus possible national food production.

5.2 Comparison of the results to other studies

National WR were calculated to 36-386 $Gm^3\ y^{-1}$ for ETH, 19-217 $Gm^3\ y^{-1}$ for TZ and 5-58 $Gm^3\ y^{-1}$ for BF. These ranges show the uncertainty if not accurate values of WP are used in the calculations. Calculations with median dietary WP (ETH: 100

$Gm^3\ y^{-1}$; TZ: 52 $Gm^3\ y^{-1}$ and BF: 15 $Gm^3\ y^{-1}$) were more like earlier estimates of present WR. Rockström *et al.* (2009) presented that somewhat over 50 % of available water was used for rainfed agriculture in ETH, compared to the range of 4-41 % in this study. The numbers differ due to differentiations in calculation. Noteworthy is that values from this study exclude total dietary consumption, as more food products are included in the total diets than the main food products (see dietary tables in section 3.4). The difference in use of available soil water of 9-46% compared to Rockström's results (2009) implies that actual WR for the total diets are higher.

A comparison with Chapagain & Hoekstra (2004) indicates a higher similarity to the calculated values with efficient WP for ETH and median WP for TZ and BF. Total national water footprint (WF) in Chapagain & Hoekstra (2004) were 42.88 $Gm^3\ y^{-1}$ for ETH, TZ 37.51 $Gm^3\ y^{-1}$ and BF 17.03 $Gm^3\ y^{-1}$. These numbers include - except from agricultural water use – also domestic and industrial water withdrawals. Total dietary WR in this study seems to be overestimated compared to Chapagain & Hoekstra (2004) as they also included the agricultural water use being equal to Ya ET_a^{-1}, indicating that dietary WR should be lower than calculated here.

This study shows a wide range of WP-values for specified diets. from inefficient (HID) to values higher than the other studies of diets in SSA (see Figure 6, Figure 9 and Figure 12 for values of WP_{diet}). The lower range of WP_{diet} were of the same magnitude, while median values for at least MID and LID where high compared to other studies done in SSA This indicates similar productivity as European or North American agro-systems, which Jägermeyr *et al.* (2015) presented as 4000-5000 kcal m^{-3}. The difference from previous studies (Table 15) is that this study includes variations in diet composition, indicating a range in productivity between diets not shown with national average diets.

Table 15. Values of Water Productivity from Sub-Saharan Africa and North America

Country/Location	**Reference**	**Measure**	**Unit**	**Value**
SSA North America	Jägermeyr *et al.*, 2015	$\mathbf{WP_{diet}}$	*kcal* m^{-3}	< 2000 4000-5000
Ethiopia	Molden *et al.*, 2007	$\mathbf{WP_{diet}}$	*kcal* m^{-3}	585
Ethiopia Tanzania Burkina Faso	Gerten *et al.*, 2011	$\mathbf{WP_{diet}}$	*kcal* m^{-3}	500-1000 588-1000

WP for individual crops determine the wide range of water demanding values for WP_{diet}. Adaption of values of WP from SSA over all to ETH, TZ and BF can though be questioned. Some values of WP per food category (see section 4.1 and Table 19 in Appendix C) were in the same magnitude (*cereals, roots & tubers, pulses & legumes* and *fruits*), as global averages. (*oil crops, vegetables* and *animal products* were lower). Mekonnen & Hoekstra (2010), presents global WP values of *cereals* to 0.8 kg m^{-3}; *starchy roots* 3.1 kg m^{-3}; *pulses* 0.3 kg m^{-3}; *oil crops* 0.6 kg m^{-3}; *vegetables* 5.2 kg m^{-3}; *fruits* 1.4 kg m^{-3} and *animal products* 0.4 kg m^{-3}. The cause for these similarities is probably that many studies from SSA are not performed at locations representative for overall low WP. The wide ranges of values of WP per category are also doubtless a matter of differences in agricultural properties between cropping areas of where the reviewed studies have been accomplished as shown in formulas for Y_p and ET (see section 2.2). The lower values of *oil crops* and *vegetables* might be due to the low number of values reviewed of WP. *Animal products* showed lower values probably due to overall more extensive production system.

5.3 Strengths and weaknesses in data and method

Large variation of WP_{crop} in the food categories (Figure 4, section 4.1) gave large effect on WP_{diet} and thus WR for the diets. The issue was a low number of values for WP for individual crops. Thus, the robustness of using median values of WP per food category was exposed to being affected by potential outliers, therefore resulting in a higher or lower value than what might have been the true value. This was the concern for all food categories except *cereals* and *roots and tubers* (see Figure 4 under headline 4.1). The low number of WP-values and numbers of crops were partly covered by calculations with the range of inefficient and efficient WP. Thus, variation of WP_{diet} and thus in total WR were considered. To improve accuracy of WP_{diet} the best would of course be if values were available for the total food intake and WP of all ingoing crops in the diets, as there are large variations in WP within the food categories (Figure 3, section 3.5). However, this would require a large effort of gathering dietary data from a large pool of household dietary intake on an annual basis which is rather unrealistic.

The review of WP further showed an insufficient number of studies in other food categories than cereals. The low number of values reduces the reliability of how representative the WP values for food categories were for the diets. A higher number of values is also of extra relevance to be able to connect WP to nutrition intake, as especially much of the micronutrients is gained from the food categories *pulses and legumes, vegetables,* and *fruits.* The same approach is valid for the use of median values of nutrient content for the food categories (Figure 3). To refine the NWP_{diet}

calculations, nutrition values of several crop varieties could be included, as the nutrition values varies within the same crop species (e.g. Sarker & Oba, 2018).
The calculations were performed with continental values from SSA instead of specific values form ETH, TZ and BF due to the absence of studies done on WP_{crop} in rainfed systems in SSA with WP calculated as $Y_a\ Et_a^{-1}$not giving numbers which are specific for the countries. However, this continental approach was more reliable than calculations done with global values as discussed in section 5.2 above.

Calculated values of daily protein consumption were higher than average recommended intake for HID, upper middle-income (UMD) and lower middle-income (LMD) in ETH, TZ and BF. LID also had a calculated higher consumption of protein in ETH and BF. Carbohydrate consumption was calculated to be higher than the daily recommendation in ETH for HID and MID (Figure 7, Figure 10 and Figure 13 in section 4.2). These values indicate possible overestimations of protein consumption as protein intake from animal products in SSA is overall low (Fanzo, 2012) in addition to problems with deficient protein intake in SSA (Fanzo, 2012; Schonfeldt & Hall, 2012). However, pulses are a staple food in ETH, TZ and BF a main source of protein (e.g. Becquey *et al.*, 2010; Ngassapa *et al.*, 2010; Cochrane & D'Souza, 2015). With a higher protein content in pulses than animal products used in the calculations for the macronutrient contents (Table B17, Appendix B) together with total daily food intake including protein from other food categories, e.g. *cereals* and *oil crops*, this have contributed to an overall higher value of protein consumption than what is recommended and what might be the realistic picture of food intake in SSA. However, important in this context is not just protein quantity but also protein quality (amino acid composition) and bioavailability (Fanzo, 2012; Schonfeldt & Hall, 2012), though this is not included in the scope of this study.

As stated, consumption of animal products in low-income households is low in ETH, TZ and BF (e.g. Ethiopian Central Statistical Agency & World Food Programme, 2014; Cochrane & D'Souza, 2015). A diet with zero intake of animal products as in LID for ETH and TZ (Table 3, Table 4 and Table 5, section 3.4) might be realistic from a daily perspective. However, on an annual basis, some animal products should be included also in LID. The same approach was used for estimation fruit consumption for BF. The overall consumption of fruit is low within the country (Permanent Interstate Committee for Drought Control in the Sahel, 2004). However, on annual basis the intake will contribute to energy and nutritive intake.

Several assumptions were done for the calculations of WP_{diet} and NWP_{diet}. The assumption likely to mostly affect the results is the diet composition for the income levels. As these numbers were put together from different references from different years of publication, there is a large uncertainty in reliability of how well the diets correspond to actual food intake in the countries and for the income levels. Probably more diet compositions should be considered, for example due to location and season (e.g. Ethiopian Central Statistical Agency & World Food Programme, 2014, Cochrane & D'Souza, 2015; Worku *et al.*, 2015; Keding, 2016; Ntwenya *et al.*, 2017) which affect the countries total WR.

Preferably, numbers of dietary compositions from the same reference should have been used. However, absence of aggregated dietary data made including data from several references for the different socio-economic levels to the best option. Despite these uncertainties, the strength of this study is that diets in this study represents a pattern of dietary food consumption for income levels, compared to other studies which mostly are done on WP_{diet} for average diets for total nations. Thus, they miss national differences in WR. Despite the insecurity in these clustered values, there is an overall data gap of dietary composition and food intake. For example, FAO FBS supply information of average per capita food supply. However there is a difference between the food supply and actual dietary food intake which is indicated in (Del Gobbo *et al.*, 2015) which compares FAO FBS with Global dietary Database (GDD), showing an overestimation between supply and food intake and a gap of data for actual national food intake.

To supplement numbers of total WR to sustain the diets, values of total agricultural production in the ETH, TZ and BF and export and import numbers of food products can be included. The actual WR in agriculture are affected by production of food crops in other food categories, other crops as cash crops as well as crops for export and imported products. Additionally, the calculations do not consider non-edible parts or food losses along the food processing chain which will require additional production and thus WR to produce the amount of food included in the diets.

5.4 Future next steps

The diets determine the total energy and nutritive food intake. The methodology in this study is a first attempt to link human nutritive intake to water appropriation in the crop systems. However, there are many factors missing:

- To perform accurate calculations of WP_{diet} and NWP_{diet}, more studies are required of WP for specific crops and their nutritive content from the site of interest and from representative production systems. Preferably nutritive content of varieties should be included in further studies as this also varies within species (Chibarabada *et al.* 2017).

- To draw conclusions of recommendable food products from a productivity perspective, there is a call for mapping trade-offs in the production system between water requirements, energy output, nutritive output, fertilizer inputs, plant protectant inputs, as well as extern factors as labour requirements and farmer's income. This mapping can open a discussion between the three pillars of sustainability and connect to the sustainable development goals.

- Separating water availability from precipitation and water accessibility in the field, further initiatives are necessary to initiate measures of improving soil physical properties for maintaining soil water. This can be a way to improve water limited yields and the usefulness of other inputs in the system, in accordance with Sheahan & Barrett (2017) who take up that inputs in cropping systems in SSA are often not used synergistically. In the end these measures together are the way to reduce Y_g and thus also improve WP.

6 Conclusions

1. To state values of water productivity (WP) for individual crops or for food categories was not possible due to data gaps of WP in rainfed agriculture in Sub-Saharan Africa (SSA).
2. Dietary Water productivity (WP_{diet}) and Dietary Nutritional Water productivity (WP_{diet}) was overall higher for low-income diets. However, this pattern needs further inquiries connected to improved data of WP, diet composition and nutrient content of the actual crops included in type diets.
3. Dietary water requirements indicate that national water resources with precipitation included might be sufficient to meet dietary requirements with increased WP in the cropping systems in theory. Practically, these numbers are insecure due to missing water requirements in the diets as well as due to estimated changes in precipitation patterns and population increase. This leads to changes in diet composition and thus national food production requirements.

Further, this study has confirmed that:

- There are large variations of water productivity within food categories and between ingoing crops/products which affect the overall water requirement to produce diets with different composition
- There is a data gap of studies of water productivity of main crops in Sub-Saharan Africa. Especially for crops which might be more valuable from a "nutrition per drop" perspective, to be able to lift the numbers of undernourishment in the continent whilst contributing to reach SDG 6 on water efficiencies.
- Improving rainfed crop production in SSA is of large importance to economize with the national water resources in order to sustain crop production and meet demand from increased population and diet change.

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Appendix A: Data from review of Water Productivity in Ethiopia

Few studies were found of Water Productivity (WP) in rainfed cropping systems from SSA calculated as actual yield divided by evapotranspiration over all. Thus, only a limited number were found from Ethiopia, Tanzania, and Burkina Faso. These references were too few to use on their own when calculating Dietary Water Productivity in respective country. Ethiopia was the country of these three with most found references (Figure 14).

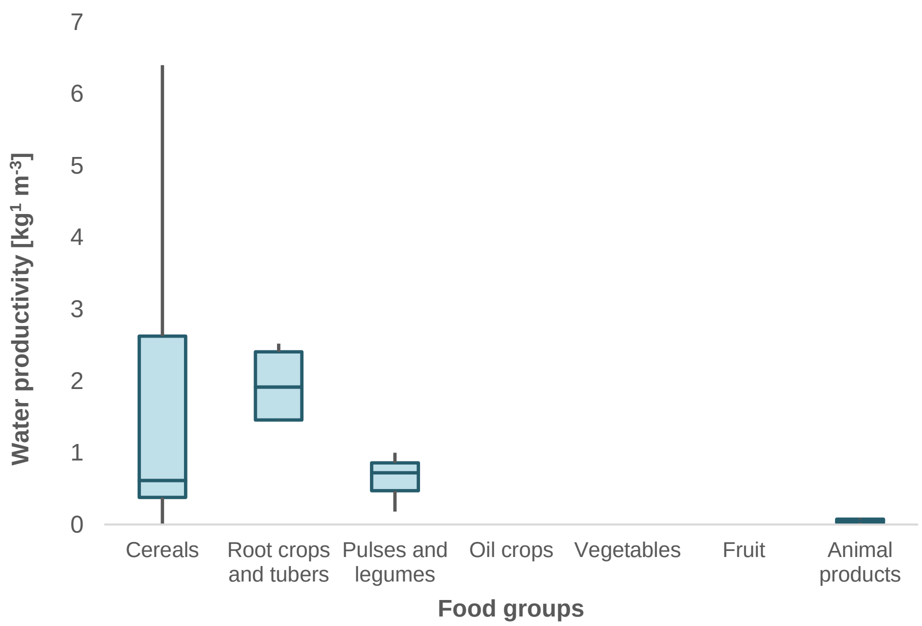

Figure 14. Distribution of water productivity (WP) [kg m^{-3}] within main food categories. The distribution is made of numbers of WP found in previous studies performed in Ethiopia of rainfed cropping systems. No studies of WP for rainfed crops were found for oil crops or fruits and only a limited number within the groups" vegetables" (1 reference, 1 value for WP) and "animal products" (2 references, 6 values of WP). The included numbers of WP do only contain numbers calculated as the ratio of actual yield and evapotranspiration.

The highest number of references for Ethiopia were found for cereals, none for oil crops or fruits and only a limited number for vegetables (1 reference, 1 value) and animal products (2 references, 6 values) (Table 16).

Table 16. References used to calculate Water Productivity for food categories in Ethiopia under rainfed conditions

Food category	References
Cereals	Adgo, E., Teshome, A. & Mati, B. (2013). Impacts of long-term soil and water conservation on agricultural productivity: The case of Anjeie watershed, Ethiopia. *Agricultural Water Management.* Vol. 117. pp. 55-61. DOI: 10.1016/j.agwat.2012.10.026
	Araya, A., Keesstra, S.D. & Stroosnijder, L. (2010). Simulating yield response to water of Teff (Eragrostis tef) with FAO's AquaCrop model. *Field Crop Research*. Vol. 116. pp. 196-204. DOI: 10.1016/j.fcr.2009.12.010
	Araya, A., Habtu, S., Hadgu, K.M., Bebede, A. & Dejene, T. (2010). Test of AquaCrop model in simulating biomas and yield of water deficient and irrigated barley (Hordeum vulgare). *Agricultural Water Management.* Vol. 97. pp. 1838-1846.: DOI: 10.1016/j.agwat.2010.06.021
	Temesgen, M., Savenije, H.H., Rockström, J. & Hoogmoed, W.B. (2012). Assesment of strip tillage systems for maize production in semi-arid Ethiopia: Effects on grain yield, water balance and water productivity. *Physics and Chemistry of the Earth.* Vol. 47-48. pp. 156-165. DOI: 10.1016/j.still.2008.09.013
*	Mekonnen, S., Descheemaeker, K., Tolera, A. & Amede, T. (2010). Livestock Water Productivity in a Water Stressed Environment in Northern Ethiopia. *Experimental Agriculture.* Vol. 47(S1). pp.85-98. DOI: 10.1017/S0014479710000852
	Mesfine, M., Abede, G. & Al-Tawaha, A-R.M. (2005). Effect of Reduced Tillage and Crop Residue Ground Cover on Yield and Water Use Efficiency of Sorghum (Sorghum bicolor (L.) Moench) Under Semi-Arid Conditions of Ethiopia. *World Journal of Agricultural Science.* vol. 1(2). pp. 152-160. ISSN 1817-3047
**	Haileslassie, A., Peden, D., Gebreselassie, S., Amede, T. & Descheemaeker, K. (2009). Livestock water productivity in mixed crop-livestock farming systems of the Blue Nile basin: Assessing variability and prospects for improvement. *Agricultural Systems.* vol. 102. pp. 33-40. DOI: 10.1071/RJ09006
	Temesgen, M., Rockström, J., Savenije, H.H.G., & Hoogmoed, W.B. (2007). Assessment of strip tillage systems for maize production in semi-arid Ethiopia: effects on grain yield and water balance. *Hydrology and Earth System Sciences Discussion.* Vol. 4. pp. 2229-2271. DOI: 10.5194/hessd-4-2229-2007.
	Erkossa, T., Awulachew, S.B. & Aster, D. (2011). Soil fertility effect on water productivity of maize in the upper Blue Nile Basin, *Ethiopia. Agricultural Sciences.* Vol. 2(3). pp.238-247.DOI: 10.4236/as.2011.23032

Food category	References
Roots and tubers	Gebremedhin, Y., Bere, A. & Nebiyu, A. (2015). Performance of AquaCrop model in Simulating Tuber Yield of Potato (Solanum tuberosum L.) under Various Water Availability Conditions in Mekelle Area, *Northern Ethiopia. Journal of Natural Sciences Research.* vol. 5. pp. 123-130. ISSN: 2225-0921
**	Haileslassie, *et al* (2009)
Pulses and legumes	Girma, F. & Haile, D. (2014). Effects of Supplemental Irrigation on Physiological Parameters and Yield of Faba Bean (Vicia faba L.) *Varieties in the Highlands of Bale, Ethiopia. Journal of Agronomy.* Vol. 13(1). pp. 29-34. ISSN: 1812-5379
	Worku, W. & Skjelvåg, A.O. (2006). The Effect of Different Moisture and Light Regimes on Productivity, Light Interception and Use Efficiency of Common Bean. *Ethiopian Journal of Science.* Vol. 29(2). pp.95-106.DOI: 10.4314/sinet.v29i2.18264
**	Haileslassie, *et al* (2009)
*	Mekonnen, *et al* (2010)
Vegetables	Haileslassie, *et al* (2009)
Animal products	Alemayehu, M., Amede, T., Peden, D., Kumsa, T., Böhme, M.H. & Peters, K.J. (2016). Assessing Livestock Water Productivity in Mixed Farming Systems of Gumara Watershed, Ethiopia. *Experimental Agriculture.* Vol. (5) pp. 1-14. DOI: 10.5539/jsd.v5n7p1
	Mekonnen, M.M. & Hoekstra, A.Y. (2010) *The green, blue and grey water footprint of farm animals and animal product*s. Delft: UNESCO-IHE. (Value of Water Research Report Series No.48).

Appendix B. Calculated numbers of NWP_{diet} for micronutrients

Dietary Nutritional Water Productivity (NWP_{diet}) for low-income diets (LDI), lower-middle income diet (LMD, equal to middle income diet in Ethiopia and Burkina Faso) and high-income diet (HID) were calculated for the micronutrients calcium, magnesium, iron, zinc, vitamin C, vitamin A and folate. The micronutrients were put as a function of total dietary consumption of the food categories *cereals*, *roots and tubers*, *pulses and legumes*, *oil crops*, *vegetables*, *fruits* and *animal products*, values of Water Productivity (WP) for crops within the food categories and of the crops nutritious content of declared micronutrients. Overall, LID had the highest values of NWP_{diet} while HID had the lowest values. Exceptions are NWP_{diet} values for vitamin C and vitamin A calculated for diets in Burkina Faso where HID had higher productivity values than LMD (Table B17).

Table B17.Calculated numbers of Dietary Nutritional Water Productivity (NWP_{diet}) for diets attributed to population in different socio-economic levels in Ethiopia, Tanzania, and Burkina Faso: low-income (LID), lower middle-income(LMD), upper middle-income (UMD – only included for Tanzania) and high-income (HD). The values of NWP_{diet} are calculated from diet compositions for the different socio-economic levels and from values of Water Productivity (WP [kg m^{-3}] for main crops and food products eaten in the three countries. These values were clustered to WP-values for the food categories cereals, roots and tubers, pulses and legumes, oil crops, vegetables, fruits, and animal products. The WP-values for the food categories showed a range in efficiency whereby the values of NWP_{diet} in the table are divided into the categories inefficient-, median- and efficient $WP_{food\ category}$ indicating which value of $WP_{food\ category}$ which have been used in the calculations of NWP_{diet}

Micronutrient	Calcium				Magnesium				Iron				Zink				Vitamin C				Vitamin A				Folate			
Unit	[mg m^{-3}]																[µg m^{-3}]											
Diet	LID	LMD	UMD	HD	LID	LMD	UMD	HD	LID	LMD	UMD	HD	LID	LMD	UMD	HD	LID	LMD	UMD	HD	LID	LMD	UMD	HD	LID	LMD	UMD	HD
Country	**Inefficient WP**																											
Ethiopia	140	49		13	440	161		44	13	5		1	6	2		1	49	14		2	20	8		3	180	61		15
Tanzania	144	29	18	7	417	83	52	22	13	3	2	1	5	1	1	1	52	9	6	1	46	12	8	3	185	36	23	8
Burkina Faso	96	22		17	359	95		57	10	3		2	4	1		1	14	1		3	38	2		5	106	23		23
	Median WP																											
Ethiopia	282	162		58	889	540		203	27	16		6	11	7		4	100	47		11	40	27		14	364	205		68
Tanzania	288	115	81	35	833	331	229	107	25	10	7	4	11	5	4	3	104	38	25	6	93	47	36	17	369	142	100	41
Burkina Faso	218	87		73	814	387		249	22	11		8	10	6		4	31	9		13	85	8		20	240	93		100
	Efficient WP																											
Ethiopia	624	419		176	1965	1392		616	59	41		19	25	19		11	220	121		35	89	70		44	804	529		205
Tanzania	606	308	230	110	1751	887	649	333	53	27	20	11	23	14	12	9	219	100	72	20,	195	126	102	53	777	381	285	129
Burkina Faso	515	262		212	1923	1158		728	52	32		22	23	16		13	73	11		37	201	25		59	568	278		292

Appendix C: Numbers and information used in calculations of WP_{diet} and NWP_{diet} for Ethiopia, Tanzania, and Burkina Faso

Nutritional values for ingoing crops in the food categories *cereals*, *roots and tubers*, *pulses and legumes*, *oil crops*, *vegetables*, *fruits*, and *animal products* were clustered and the median values of nutritive content for energy, carbohydrates, protein, fibre, fat, calcium, magnesium, iron, zinc, vitamin C vitamin A and folate were calculated and used in calculations of Dietary Nutritional Water Productivity. *Pulses and legumes* have the highest content of most nutrition (protein, fibres, calcium, iron, zinc and folate); cereals had the highest value of *carbohydrates and magnesium*; *oil crops* the highest values of energy and fat; *vegetables* the highest content of vitamin A; and *fruit*s the highest values of vitamin C (Table 18)

Table 18. Median nutritional values of main food categories from diets in Ethiopia, Tanzania, and Burkina Faso. The values are calculated from nutritive content of main crops included in dietary intake in the three countries. .

Food category		Cereals	Roots and tubers	Pulses and legume	Oil crops	Vegetables	Fruits	Animal product
Nutrient								
Energy	*kcal kg^{-1}*	3435	1155	3530	5850	550	1500	1390
Carbohydrates	*g kg^{-1}*	643	254	426	58	45	97	0
Protein	*g kg^{-1}*	117	15	256	118	11	7	168
Fibre	*g kg^{-1}*	93	9	176	46	19	20	0
Fat	*g kg^{-1}*	28	2	19	542	2	2	95
Calcium	*mg kg^{-1}*	315	215	746	380	260	125	110
Magnesium	*mg kg^{-1}*	1620	210	1217	1315	135	100	220
Iron	*mg kg^{-1}*	42	10	61	32	7	3	18
Zink	*mg kg^{-1}*	18	4	36	18	3	1	33
Vitamin C	*mg kg^{-1}*	0	215	68	0	140	298	0
Vitamin A	*µg kg^{-1}*	0	50	71	0	399	66	100
Folate	*µg kg^{-1}*	290	250	2150	360	350	120	60

The food categories have a range of WP values as well as nutrition content depending on ingoing crops in the groups. The largest range of WP was for *cereals* and the least for *oil crops.* The range of energy content was highest for *vegetables* and lowest for *roots and tubers* (Table 19). However, these orders of magnitude are not general but specific to the crops which have been included in the different food categories in this study. Thus, the range will be different depending on included crops and food products.

Table 19. Values of 1st and 3rd quartiles for distributions of water productivity (WP) and energy content for main food categories.

Food category	WP interval [kg m^{-3}]			Energy content [kcal kg^{-1}]		
	Quartile 1	*Median*	*Quartile 3*	*Quartile 1*	*Median*	*Quartile 3*
Cereals	0.30	0.66	2.26	3365	3435	3550
Roots and tubers	2.23	3.14	3.68	1128	1155	1175
Pulses and legumes	0.18	0.37	0.53	3340	3530	3645
Oil crops	0.42	0.47	0.51	5415	5850	6000
Vegetables	0.92	1.49	1.83	298	550	1180
Fruits	0.91	1.24	1.64	1230	1500	2240
Animal products	0.01	0.05	0.18	1165	1390	2460

Import and export of food products are indirectly a trade with water. Of commodities commonly consumed in Ethiopia, Tanzania and Burkina Faso, *cereals* and *fruits* are net-imported goods. Numbers of p*ulses and legumes* shows net-export. Ethiopia and Tanzania do also have net-export numbers for roots and tubers, vegetables, and animal products. Burkina Faso shows a net-import of these food categories, but a net-export of oil crops (Table 20)

Table 20. Net import of agricultural products in Ethiopia, Tanzania, and Burkina Faso. Average values from 2007 – 2016 calculated from FAO Food Balance Sheet. Included crops and products in the food categories are those most commonly consumed as food within the three countries

Food category	Ethiopia	Tanzania	Burkina Faso
		1000 tonnes	
Cereals	1519	836.9	443.9
Roots and tubers	-29.6	-14.3	8.6
Pulses and legumes	-168.3	-125.4	-13.1
Oil crops	4.7	81.1	-31.4
Vegetables	-138.7	-61.6	11.4
Fruits	22.3	7.4	1.1
Animal products	-0.86	-73.4	118.7

The food categories used to put together median nutritional values to use in calculations of NWP_{diet} (*cereals, roots and tubers, pulses and legumes, oil crops, vegetables, fruits,* and *animal products)* where put together by the most commonly consumed crops and animal products in Ethiopia, Tanzania, and Burkina Faso. The highest number of crops were included in the category *fruits* (17) and the least in *roots and tubers* (4) (Table 21).

Table 21. Crops included in calculation of food category nutritive content for energy content, carbohydrates, protein, fibre, fat, calcium, magnesium, iron, zinc, vitamin C, folate, and vitamin A.

Food category	**Crop/product**	
	English common name	**Latin name**
Cereals	Maize	*Zea mays*
	Sorghum	*Sorghum spp.*
	Teff	*Eragrostis teff*
	Wheat	*Triticum aestivum*
	Barley	*Hordeum vulgare*
	Millet	
	Rice	*Oryxa sativa*
	Amaranth (*grain)*	*Amaranthus spp.*
Roots and tubers	Potato	*Solanum tuberosum*
	Sweet potato	*Ipomoea batatas*
	Cassava	*Manihot esculenta*
	Yams	*Dioscorea sp.*
Pulses and legumes	Chickpea	*Cicer arietinum*
	Lentil	*Lens culinaris*
	Horse bean	*Vicia faba*
	Haricot verts	*Phaseoulus vulgaris*
	Green pea	*Pisum sativum*
	Dry pea	
	Soybean	*Glycine max*
Oil crops	Sesame seed	*Sesamum indicum*
	Linseed	*Linum usitatissimum*
	Bambara groundnut	*Vigna subterranean*
	Sunflower seed	*Helianthus annuus*
	Almond	*Prunus dulcis*
	Cashew	*Anacardium occidentale*
	Coconut	*Cocos nucifera*
Vegetables	Tomato	*Solanum lycopersicum*
	Onion	*Allium cepa* L.
	Shallot	
	Lettuce	*Lactuca sativa*
	Avocado	*Persea americana*
	Cabbage	*Brassica oleracea*
	Leek	*Allium ampeloprasum*
	Beetroot	*Beta vulgaris*
	Carrot	*Daucus carota*
	Turnip	*Brassica rapa*
	Pumpkin	*Cucurbita spp.*
	Cucumber	*Cucumis sativus*
	Jute mallow	*Corchorus olitorius*
	Spinach	*Spinacia oleracea*
	Amaranth (*leaves)*	*Amaranthus spp.*
	Squash	*Cucurbita spp.*

Fruits	Banana	*Musa spp.*
	Apple	*Malus pumila*
	Pineapple	*Ananas comosus*
	Grapes	*Vitis spp.*
	Pear	*Pyrus spp.*
	Honeydew melon	*Cucumis melo*
	Cantaloupe melon	*Cucumis melo*
	Watermelon	*Citrullus lanatus*
	Orange	*Citrus x sinensis*
	Mandarin	*Citrus reticulata*
	Mango	*Mangifera spp.*
	Grapefruit	*Citrus x paradisi*
	Papaya	*Carica papaya*
	Lemon	*Citrus limon*
	Peach	*Prunus persica*
	Guava	*Psidium guajava*
	Breadfruit	*Artocarpus altilis*
Animal products	Beef	
	Chicken meat	
	Goat meat	
	Lamb/mutton meat	
	Pork meat	
	Cow milk	
	Goat milk	
	Egg	

Appendix D: References from review of WP used in calculations of WP_{diet} and NWP_{diet}

There were few references found in the review of water productivity (WP) of crops in rainfed agricultural systems in Sub-Saharan Africa (SSA) which were calculated as the ratio between average actual yield (Y_a) and actual evapotranspiration (ET_a). The studies which were review were done in areas both in west-, east-, and southern parts of SSA (Table 22).

Table 22. References for Water Productivity (WP) used in calculations of Dietary Water Productivity and Dietary Nutritional Water Productivity. The table show the reference, which country the studies were done in, location in the countries and values of WP for studied crops

Reference	Country	Location	Crop/product	Values of WP (Y_a ET^{-1})
Temesgen, M., Savenije, H.H., Rockström, J. & Hoogmoed, W.B. (2012). Assesment of strip tillage systems for maize production in semi-arid Ethiopia: Effects on grain yield, water balance and water productivity. *Physics and Chemistry of the Earth*. Vol. 47-48. pp. 156-165. DOI: 10.1016/j.pce.2011.07.046	Ethiopia	Melkawoba	Maize	5.5; 6.4; 5.8; 3.8; 3.1; 3.4; 4.5; 4.1; 4.4
Mo, F., Wang, J-Y., Xiong, Y-C., Nguluu, S.N. & Li, F-M. (2015). Ridge-furrow mulching system in semiarid Kenya: A promising solution to improve soil water availability and maize productivity. *European Journal of Agronomy*. Vol. 80. pp. 124-136. DOI: 10.1016/j.eja.2016.07.005	Kenya	Katumari Research Center	Maize	3.642; 3.36; 2.025; 1.043; 1.49; 1.557; 0.78; 0.323
Kurwakumire, N., Chikowo. R., Mtambanengwe, F., Mapfumo, P., Snapp, S., Johnston, A. & Zingore, S. (2014). Maize productivity and nutrient and water use efficienies across soil fertility domains on smallholder farms in Zimbabwe. *Field Crop Research.* Vol. 164. pp. 136-147. DOI: 10.1016/j.fcr.2014.05.013	Zimbabwe	Wedza District	Maize	0.025; 0.162; 0.091; 0.41; 0.134; 0.4
Mekonnen, S., Descheemaeker, K., Tolera, A. & Amede, T. (2010). Livestock Water Productivity in a Water Stressed Environment in Northern Ethiopia. *Experimental Agriculture.* Vol. 47(S1). pp.85-98. DOI: 10.1017/S0014479710000852	Ethiopia	Lenche Dima watershed	Maize	1.2
			Teff	0.6
			Rice	1.1
			Chickpeas	0.4

Reference	*Country*	*Location*	*Crop/product*	*Values of WP (Ya ET^{-1})*
Haileslassie, A., Peden, D., Gebreselassie, S., Amede, T. & Descheemaeker, K. (2009). Livestock water productivity in mixed crop-livestock farming systems of the Blue Nile basin: Assessing variability and prospects for improvement. *Agricultural Systems*. vol. 102. pp. 33-40. DOI: 10.1016/j.agsy.2009.06.006	Ethiopia	Gumera watershed	Maize	0.36
			Sorghum	0.24
			Teff	0.24; 0.33
			Wheat	0.23; 0.21
			Barley	0.41
			Rice	0.67
			Potato	1.45; 1.46
			Pulses	0.68; 0.18
			Onion	1.76
Nyakudya, I.W. & Stroosnijder, L. (2014). Effect of rooting depth, plant density and planting date on maize (Zea maize L.) yield and water use efficiency in semi-arid Zimbabwe: Modelling with AquaCrop. *Agricultural Water Management*. Vol. 146. pp. 280-296. DOI: 10.1016/j.agwat.2014.08.024	Zimbabwe	Rushinga district - modelled	Maize	2.13; 1.93; 1.79; 1.35; 2.46; 2.29; 2.1; 1.56; 2.59; 2.38; 2.14; 1.59; 2.6; 2.36; 2.11; 1.57; 2.8; 2.55; 2.35; 1.7; 2.76; 2.5; 2.24; 1.65; 2.75; 2.51; 2.23; 1.67; 2.94; 2.61; 2.35; 1.73; 2.8; 2.64; 2.27; 1.65
Cai, X., Molden, D., Mainuddin, M., Sharma, B., Ahmad, M-u-D. & Karimi, P. (2011). Producing more food with less water in a changing world: assessment of water productivity in 10 major river basins. *Water International*. Vol. 36(1). pp. 42-62. DOI: 10.1080/02508060.2011.542403	Volta delta Niger delta	Reviewed data	Maize	0.15
			Sorghum	0.1, 0,1
			Millet	0.08
Mutiro, J., Makurira, H., Senzanje, A. & ;ul, M.L. (2006). Water productivity analysis for smallholder rainfed systems: A case study of Makanya catchment, Tanzania. *Physics and Chemistry of the Earth*. Vol. 31, pp. 901-909. DOI: 10.1016/j.pce.2006.08.019	Tanzania	Makanya catchment	Maize	1.33; 0.44; 0.09; 0.36; 0.06

Reference	Country	Location	Crop/product	Values of WP (Y_a ET^{-1})
Erkossa, T., Awulachew, S.B. & Aster, D. (2011). Soil fertility effect on water productivity of maize in the upper Blue Nile Basin, Ethiopia. *Agricultural Sciences*. Vol. 2(3). pp.238-247.DOI: 10.4236/as.2011.23032	Ethiopia	Caffee Doonsaa - Gimbichu-District	Maize	1.7; 2.4; 2.6
Temesgen, M., Rockström, J., Savenije, H.H.G., & Hoogmoed, W.B. (2007). Assessment of strip tillage systems for maize production in semi-arid Ethiopia: effects on grain yield and water balance. *Hydrology and Earth System Sciences*. Vol. 4. pp. 2229-2271. DOI: 10.5194/hessd-4-2229-2007.	Ethiopia	Melkawoba	Maize	4.1; 3.9; 4.1; 4.0; 3.2; 3.5; 4.8; 5.8; 3.8
Mesfine, M., Abede, G. & Al-Tawaha, A-R.M. (2005). Effect of Reduced Tillage and Crop Residue Ground Cover on Yield and Water Use Efficiency of Sorghum (Sorghum bicolor (L.) Moench) Under Semi-Arid Conditions of Ethiopia. *World Journal of Agricultural Science*. vol. 1(2). pp. 152-160. ISSN 1817–3047	Ethiopia	Melkassa	Sorghum	*0.485; 0.573; 0.655*
Chimonoyo, V.G.P., Modi, A.T. & Mabhaudhi, T. (2015). Water use and productivity of a sorghum-cowpea-bottle gourd intercrop system. *Agricultural Water Management*. Vol. 165. pp. 82-96. DOI: 10.1016/j.agwat.2015.11.014	South Africa	KwaZulu-Natal	Sorghum Cowpeas Bottle gourds	0.589 0.39 0.504
Mulebeke, R., Kironchi, G. & Tenywa, M.M. (2015). Exploiting Cropping Management to Improve Agricultural Water Use Efficiency in the Drylands of Eastern Uganda. *Sustainable Agriculture Research*. Vol. 4(2). pp. 57-69. DOI: 10.5539/sar.v4n2p57	Uganda	Teso region	Sorghum Cassava Cowpeas	0.376 3.438 1.5
Zougmoré, R. Mando, A., Ringersma, J. & Stroosnijder, L. (2003). Effect of combined water and nutrient management on runoff and sorghum yield in semiarid Burkina Faso. *Soil Use and Management*. Vol. 19. pp. 257-264. DOI: 10.1111/j.1475-2743.2003.tb00312.x	Burkina Faso	Sarya	Sorghum	0.51; 0.59; 0.43
Adgo, E., Teshome, A. & Mati, B. (2013). Impacts of long-term soil and water conservation on agricultural productivity: The case of Anjeie watershed, Ethiopia. *Agricultural Water Management.* Vol. 117. pp. 55-61. DOI: 10.1016/j.agwat.2012.10.026	Ethiopia	Gojam, Amhara Region	Teff Barley	0.101; 0.135; 0.042; 0.052; 0.07; 0.02 0.135; 0.18; 0.037; 0.086; 0.011; 0.018

Reference	Country	Location	Crop/product	Values of WP (Y_a ET^{-1})
Araya, A., Keesstra, S.D. & Stroosnijder, L. (2010). Simulating yield response to water of Teff (Eragrostis tef) with FAO's AquaCrop model. *Field Crop Research*. Vol. 116. pp. 196-204. DOI: 10.1016/j.fcr.2009.12.010	Ethiopia	Mekelle & Ilala - modelled	Teff	0.98; 0.53
Zwart, S.J., Bastiaanssen, W.G.M., de Fraiture, C. & Molden, D.J. (2010). A global benchmark map of water productivity for rainfed and irrigated wheat. *Agricultural Water Management*. pp.1617-1627. DOI: 10.1016/j.agwat.2010.05.018	SSA rainfed systems		Wheat	0.4; 0.8
Erkossa, T., Haileslassie, A. & MacAlister, C. (2013). Enhancing farming system water productivity through alternative land use and water management in vertisol areas of Ethiopian Blue Nile Basin (Abay). *Agricultural Water Management*. Vol. 132. pp. 120-128. DOI: 10.1016/j.agwat.2013.10.007	Ethiopia	Blue Nile Basin	Wheat	0.37; 0.58; 0.42; 0.93; 0.54; 0.53; 0.99; 0.49; 0.77; 0.82; 0.5; 0.83
			Rice	0.72
Erkossa, T., Menker, M. & Betrie, G.D. (2011). Effects of Bed Width and Planting Date on Water Productivity of Wheat Grown on Vertisols in the Ethiopian Highlands. *Irrigation and Drainage*. vol. 60. pp. 635-643. DOI: 10.1002/ird.608	Ethiopia	Caffee Doonsaa - Gimbichu-District	Wheat	0.48; 0.56; 0.53; 0.66; 0.63
Araya, A., Habtu, S., Hadgu, K.M., Bebede, A. & Dejene, T. (2010). Test of AquaCrop model in simulating biomas and yield of water deficient and irrigated barley (Hordeum vulgare). *Agricultural Water Management*. Vol. 97. pp. 1838-1846. DOI: 10.1016/j.agwat.2010.06.021	Ethiopia	Mekelle	Barley	0.8; 0.8; 0.75; 0.6; 0.72; 0.59; 0.4
Sivakumar, M.V.K. & Salaam, S.A. (1998). Effect of year and fertilixer on water-use efficiency of pearl millet (Pennisetum glaucum) in Niger. *Journal of Agricultural Science*. Vol. 132. pp. 139-148. ISSN: 1469-5146, 0021-8596	Niger	Sadoré	Millet	0.171; 0.127; 0.282; 0.151; 0.212; 0.406; 0.362; 0.246
Ibrahim, A., Abaidoo, R.C., Fatondji, D. & Opoku, A. (2015). Integrated use of fertilizer micro-dosing and Acacia tumida mulching increases millet yield and water use efficiency in Sahelian semi-arid environment. *Nutrient Cycling in Agroecosystems*. Vol. 103(3). pp. 375-388. DOI: 10.1007/s10705-015-9752-z	Niger	Sadoré	Millet	0.15; 0.18; 0.18; 0.39; 0.24; 0.35; 0.23; 0.36

Reference	Country	Location	Crop/product	Values of WP (Y_a ET^{-1})
Ibrahim, A., Abaidoo R.C., Fatondji, D. & Opoku, A. (2015). Hill placement of manure and fertilixer micro-dosing improves yield and water use efficiency in the Sahelian low input millet based cropping system. *Field Crops Research*. Vol. 180. 29-36. DOI: 10.1016/j.fcr.2015.04.022	Niger	Sadoré	Millet	0.09; 0.09; 0.2; 0.49; 0.78; 0.07; 0.17; 0.41; 0.87
Karunaratne, A.S., Walker, S. & Azam-Ali. S.N. (2015). Assessing the productivity and resource-use efficiency of underutilised crops: Towards an integrative system. *Agricultural Water Management*. Vol. 147. pp. 129-134. DOI: 10.1016/j.agwat.2014.08.002	Botswana	Notwane - modelled	Millet	2.71; 3.03
			Groundnuts	0.53; 0.38
Gebremedhin, Y., Bere, A. & Nebiyu, A. (2015). Performance of AquaCrop model in Simulating Tuber Yield of Potato (Solanum tuberosum L.) under Various Water Availability Conditions in Mekelle Area, Northern Ethiopia. *Journal of Natural Sciences Research*. vol. 5. pp. 123-130. ISSN: 2225-0921	Ethiopia	Mekelle	Potato	2.52; 2.37
Ezui, K.S., Franke, A.C., Leffelaar, P.A., Mando, A., van Heerwaarden, J., Sanabria, J., Sogbedju, J. & Giller, K.E. (2017). Water and radiation use efficiencies explain the effect of potassium on the productivity of cassava. *European Journal of Agronomy*. vol. 83. pp. 28-39. DOI: 10.1016/j.eja.2016.11.005	Togo	Sevekpota & Djakakope	Cassava	3.26; 2.07; 3.73; 3.99; 3.44; 2.23; 3.73; 3.68; 2.66; 2.14; 3.14; 3.74
Girma, F. & Haile, D. (2014). Effects of Supplemental Irrigation on Physiological Parameters and Yield of Faba Bean (Vicia faba L.) Varieties in the Highlands of Bale, Ethiopia. *Journal of Agronomy*. Vol. 13(1). pp. 29-34. ISSN: 1812-5379	Ethiopia	Sinana - Oromia region	Horse beans	0.89
Worku, W. & Skjelvåg, A.O. (2006). The Effect of Different Moisture and Light Regimes on Productivity, Light Interception and Use Efficiency of Common Bean. *Sinet: Ethiopian Journal of Science*. Vol. 29(2). pp.95-106. DOI: 10.4314/sinet.v29i2.18264	Ethiopia	Awassa	Haricot verts	0.76; 1.0
Chibarabada, T.P., Modi, A.T. & Mabhaudhi, T. (2017). Nutrient Content and Nutritional Water Productivity of Selected Grain Legumes in Response to Production *Environment. Environmental Research and Public Health*. vol. 14(11). Article no. 1300. DOI: 10.3390/ijerph14111300	South Africa	KwaZulu-Natal, Umbumbulu & Wartburg	Haricot verts	0.465; 0.756
			Groundnuts	0.453

Reference	Country	Location	Crop/product	Values of WP (Y_a ET^{-1})
Sennenhenn, A., Njarul, D.M.G., Mass, B.L. & Whitbread, A.M. (2017). Exploring Niches for Short-Season Grain Legumes in Semi-Arid Eastern Kenya - Coping with the Impacts of Climate Variability. *Frontiers in Plant Science*. Vol. 8. article no. 699. DOI: 10.3389/fpls.2017.00699	Kenya	Eastern Province: Machakos - Makueni transect	Haricot verts	0.59; 0.4
			Cowpeas	0.53; 0.37
			Lablab	0.51; 0.65
Kadyampakeni, D.M., Mloza-Banda, H.R., Singa, D.D., Mangisoni, J.H., Ferguson, A. & Snapp, S. (2013). Agronomic and socioeconomic analysis of water management techniques for dry season cultivation of common bean in Malawi. *Irrigation Science*. Vol. 31(4). pp. 537-544.: DOI: 10.1007/s00271-012-0333-5	Malawi	Zomba district	Haricot verts	0.28
Adeboye, O.B., Schultz, B., Adekalu, K.O. & Prasad, K. (2017). Soil water storage, yield, water productivity and transpiration efficiency of soybeans (Glycine max L. Merr.) as affected by soil surface management in Ile-Ife, Nigeria. *International Soil and Water Conservation Research*. vol. 5. pp. 141-150. DOI: 10.1016/j.iswcr.2017.04.006	Nigeria	Ile-Ife	Soybeans	0.506; 0.294
Obalum, S.E., Igwe, C.A., Obi, M.E. & Wakatsuki, T. (2011). Water use and grain yield response of rainfed soybean to tillage-mulch practises in south-eastern Nigeria. *Scientia Agricola*. Vol. 68(5). Pp. 554-561. DOI: 10.1590/S0103-90162011000500007	Nigeria	Nsukka	Soybeans	0.116; 0.14; 0.116; 0.138; 0.22; 0.28; 0.168; 0.21
Mzezewa, J., Gwata,E.T. & van Rensburg, L.D. (2011). Yield and seasonal water productivity of sunflower as affected by tillage and cropping systems under dryland conditions in the Limpopo Province of South Africa. *Agricultural Water Management*. Vol. 98. pp. 1641-1648. DOI: 10.1016/j.agwat.2011.06.003	South Africa	Limpopo Province - Thohoyandou	Cowpeas	0.108; 0.022
			Sunflower seeds	0.33; 0.432
Miriti, J.M., Kironchi, G., Esilaba, A.O., Heng, L.K., Gachene, C.K.K. & Mwangi, D.M. (2012). Yield and water use efficiencies of maize and cowpea as affected by tillage and cropping systems in semi-arid Eastern Kenya. *Agricultural Water Management*. Vol. 115. pp. 148-155. DOI: 10.1016/j.agwat.2012.09.002	Kenya	Kampi ya Mawe	Wheat	0.82; 0.48; 0.25; 0.63; 0.19
			Cowpeas	0.34; 0.19; 0.18; 0.38

Reference	**Country**	**Location**	**Crop/product**	**Values of WP (Y_a ET^{-1})**
Anguira, P., Chemining'wa, G.N., Onwonga, R.N. & Ugen, M.A. (2017). Effect of Organic Residues on Soil Properties and Sesame Water Use Efficiency. *Journal of Agricultural Science*. Vol. 9(6). pp.98-107. DOI: https://doi.org/10.5539/jas.v9n6p98	Uganda	Serere	Sesame seeds	0.558; 0.501; 0.49
Agele, S.O., Iremiren, G.O. & Ojeniyi, S.O. (2011). Evapotranspiration, water use efficiency and yield of rainfed and irrigated tomato. International *Journal of Agriculture and Biology*. Vol. 4. pp. 469-476. ISSN: 1560–8530	Nigeria	Akure	Tomatoes	0.2
Karuku, G.N., Gachene, C.K.K., Karanja, N. Cornelis, W. & Verplacke, H. (2014). Effect of Different Cover Crop Residue Management Practices on Soil Moisture Content under a Tomato Crop. *Tropical and Subtropical Agroecosystems*. Vol. 17. pp. 509-523. ISSN: 1870-0462	Kenya	Nairobi	Tomatoes	1.22; 2.04; 1.06
Fanadzo, M., Chiduza, C., Mnkeni, P.N.S., van der Stoep, I. & Stevens, J. (2009). Crop production management practices as a cause for low water productivity at Zanyokwe Irrigation Scheme. *Water SA*. Vol. 36(1). pp. 27-36. DOI: 10.4314/wsa.v36i1.50904	South Africa	Eastern Cape	Pumpkins	2.2
Gudissa, H.D. & Edossa, D.C. (2014). Evaluation of Surge and Cutback Flow Furrow Irrigation Systems for Pepper (Capsicum Annuum) Production. *Irrigation and Drainage*. Vol. 63(4). pp.463-473. DOI: 10.1002/ird.1828	Ethiopia	Echway Kebele, Gambella	Peppers	1.75
Akinro, A.O., lufayo, A.A. & Oguntunde, P.G. (2012), Crop Water Productivity of Plantain (Musa Sp) in a Humid Tropical Environment. *Journal of Engineering Science and Technology Review.* Vol. 5(1). Pp. 9-25. ISSN: 1791-2377	Nigeria	Akure	Bananas	0.9; 0.91
Siebert, S. & Döll, P. (2010). Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology.* Vol. 384. pp. 198-217. DOI: 10.1016/j.jhydrol.2009.07.031	Global values*		Grapes	1.819
			Lemons	1.575

Reference	Country	Location	Crop/product	Values of WP ($Y_a ET^{-1}$)
Alemayehu, M., Amede, T., Peden, D., Kumsa, T., Böhme, M.H. & Peters, K.J. (2016). Assessing Livestock Water Productivity in Mixed Farming Systems of Gumara Watershed, Ethiopia. Experimental Agriculture. Vol. p. 1-14: DOI: 10.1017/S0014479717000321	Ethiopia	Gumera watershed	Cattle	0.0266
			Small ruminants	0.0264
			Equine	0.0149
Mekonnen, M.M. & Hoekstra, A.Y. (2010) *The green, blue and grey water footprint of farm animals and animal products*. Delft: UNESCO-IHE. (Value of Water Research Report Series No.48).			Cattle	0.12; 0.13; 0.22
			Sheep	0.17; 0.37; 0.82
			Goat	0.12; 0.25; 0.57
			Pork	0.21; 0.19; 0.24
			Poultry	0.18; 0.31; 0.5
			Milk	0.97; 1.56
			Eggs	0.16; 0.28; 0.39
van Breugel, P., Herrero, M., van de Steeg, J. & Peden, D. (2010). Livestock Water Use and Productivity in the Nile Basin. *Ecosystems*. Vol. 13(2). pp. 205-221. ISSN:1432-9840	Nile Basin	Modelled	Meat general	0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01
			Milk	0.03; 0.06; 0.01; 0.08; 0.05; 0.03; 0.06; 0.05; 0.08; 0.07
Peden, D., Alemayehu, M., Amede, T., Awulachew, S.B., Faki, H., Haileslassie, A., Herero, M., Mapezda, E., Mpaiwe, D., Musa, M.T., Taddesse, G. & van Breugel, P. (2009). *CPWF Project Report: Nile Basin livestock water productivity*. Colombo: CPWF. (CPWF Project Report Series, PN37).	Nile Basin		Meat general	0.011; 0.01; 0.012; 0.014; 0.011; 0.008; 0.013
			Milk	0.526; 0.082; 0.079; 0.064; 0.05; 0.057; 0.026; 0.041
Ogilvie, A., Mahé, G., Ward, J., Serpantié, G., Leoalle, J., Morand, P., Barbier, B., Diop, A.T., Caron, A., Namarra, R., Kaczan, D., Lukasiewicz, A., Patruel, J-E., Liénou, G. & Clanet, J.C. (2010). Water, agriculture and poverty in the Niger River basin. *Water International*. vol. 35(5). pp. 594-622.DOI: 10.1080/02508060.2010.515545	Niger River Basin		Livestock	0.002; 0.05