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The role of rainfed agriculture in securing food production in the Nile Basin

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ABSTRACT

A better use of land and water resources will be necessary to meet the increasing demand for food in the Nile basin. Using a hydro-economic model along the storyline of three future political cooperation scenarios, we show that the future of food production in the Basin lies not in the expansion of intensively irrigated areas and the disputed reallocation of water, but in utilizing the vast forgotten potential of rainfed agriculture in the upstream interior, with supplemental irrigation where needed. Our results indicate that rainfed agriculture can cover more than 75% of the needed increase in food production by the year 2025. Many of the most suitable regions for rainfed agriculture in the Nile basin, however, have been destabilized by recent war and civil unrest. Stabilizing those regions and strengthening intra-basin cooperation via food trade seem to be better strategies than unilateral expansion of upstream irrigation, as the latter will reduce hydropower generation and relocate, rather than increase, food production.

1. Introduction

Major socioeconomic and geopolitical transformations are affecting the allocation of one of the world's most disputed resources: the water of the Nile River. At present, most water in the Lower Nile is being utilized, mainly for irrigation by downstream Egypt. Attempts to convert existing water allocation, primarily based on the 1959 treaty between Egypt and Sudan, to a more equitable share for all countries have not been successful (Nicol and Cascão, 2011). The regional balance of power is, however, changing: (i) the political upheaval after the Arab spring has weakened the dominance of Egypt (Nicol and Cascão, 2011); (ii) in an increasingly multi-polar world, access to infrastructure loans to build dams and irrigation infrastructure upstream has diversified (Broadman, 2008; Foster et al., 2009); and (iii) foreign investors have taken a renewed interest in the basin's agricultural resources, buying and leasing agricultural land all over the basin (Cotula et al., 2009; von Braun and Meinzen-Dick, 2009). Amid these transformations, reallocation of Nile water is a hot issue (Cascão, 2009; Waterbury, 2002; Whittington et al., 2005), with many countries seeking to utilize more water for hydropower and food production.

Increased food availability in the basin is urgent. According to the 2012 report of the United Nations, "The State of Food Insecurity in the World" (FAO et al., 2012), 100 million people in the countries of the basin are undernourished, which amounts to almost a third of the local population. Undernourishment has increased in northern and sub-Saharan Africa over the past decade, bucking the world-wide trend. Except for Egypt, none of the 11 Basin countries are self-sufficient in food (Omiti et al., 2011). Within the context of high and volatile commodity prices that favour net producers over buyers (Breisinger et al., 2010; Swinnen and Squicciarini, 2012), this reliance on global markets is a dangerous gamble: recent political instability in the Nile region has been directly linked to food price hikes (Arezki and Bruckner, 2011), and these risks will only increase. The population of the Basin countries is expected to grow by a third, from 367 million in 2012 to 488 million in 2025 (UNDP, 2011). At the same time, world-wide competition for land, water, energy, and, ultimately, food is increasing (Godfray et al., 2010). Developing countries like those in the Nile, with purchasing powers much lower than that of other

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major food importing countries, are most vulnerable to global shortages (Rutten et al., 2013).

We aim to support the complex policy challenge of the Nile basin by clarifying the science behind the discourse on water, energy and food security, exploring the possibility of national to regional food self-sufficiency as alternatives to an increasing reliance on global markets. We approach this from a hydro-economic perspective and argue that with the water resources of the Nile itself almost fully and productively allocated, the real solution to future food self-sufficiency for the Basin lies outside the domain of water allocation and irrigated agriculture and in the rainfed areas of South Sudan and the Lake Victoria region. According to the United Nations Food and Agriculture Organization (FAO), the potential area suitable for cultivation in South Sudan alone is as high as 30 million hectares, which is ten times the cropped area of Egypt. Only about 10% of that potential is currently being used for agriculture. Recent world-wide assessments of food production have stressed intensification in existing areas, rather than expansion to new areas, as the best way of increasing food production (Foley et al., 2011; Godfray et al., 2010; Tilman et al., 2011). The Nile basin seems to be an important exception, with a combination of both intensification and expansion being warranted.

2. Methods

2.1. Approach

For our research, we derived a baseline of water use (Fig. 2), agricultural crop production and gross margin (GM) in the Nile basin around the year 2005, using an area-based hydro-economic model in *simulation mode* (WaterWise (Siderius et al., 2016); see Section 2.2 and SI1). For this, a present–day spatial distribution of land use systems (FAO, 2009) was made consistent with country-specific FAO crop statistics (FAO, 2004) on actual cropped area (SI2). Crop production and agricultural gross margin (GM) of the water-limited production was then calculated for both rainfed and irrigated crops.

Next, we estimated food requirements in the basin for the year 2025. Future food self-sufficiency correction factors per country were based on the projected population increase up to 2025 (UNDP, 2011) and a population-average calorie requirement of 2300 kcal/person per day (Tontisirin and de Haen, 2001). As such, a minimum intake was imposed, without regard for household access, dietary preferences, or nutritional value. We assumed that agricultural production in the Nile catchment part of each country will grow at the same pace as each country's average and that the proportion of food crops to cash crops remains the same. Future food self-sufficiency targets for the Nile basin could then be derived by multiplying baseline agricultural production with these correction factors (Table 2).

Finally, we applied the hydro-economic model in *optimization mode*, to select those investments in agriculture (area-wise expansion or intensification of rainfed agriculture and new irrigation schemes) and hydropower (new reservoirs) that generate the highest GM using the available land and water resources. We explored where and how food production can best be increased and whether food self-sufficiency for the basin and its individual countries can be achieved by the year 2025.

2.2. WaterWise model

Our model resembles existing hydro-economic models developed for the Nile (Block and Strzepek, 2010; Block et al., 2007; Jeuland, 2010; Whittington et al., 2005; Wu and Whittington, 2006). Similarly to the model of Whittington et al. (2005) it describes the whole Nile basin, including all existing irrigation schemes and hydropower reservoirs, and most of the proposed hydropower plans. Water gets transmitted through the river network using a routing scheme in combination with the variable storage method for the dynamics of large water bodies (swamps, reservoirs), with use in one location limiting options elsewhere. Economic parameters, like the pricing of hydropower, are like those in earlier optimization studies. However, in contrast to the latter we did not limit our analysis to the river system alone, i.e. optimizing hydropower and irrigation yields, but included yield from rainfed land use. Land use is an endogenous variable in our model and land-use changes and the impact on downstream flows are thereby integrated into the optimization. The general idea behind the model is that it should be capable of exploring a wide range of land and water management options, for various scenarios with respect to basin cooperation. Such an exploratory functionality necessitates a relatively simple model formulation for both hydrology and agronomy. It should then be realized that the model results are just indicative of a search direction. Further studies are needed for more accurate assessments.

The model optimizes GM by choosing the optimal combination of land and water use options for each of 1371 so-called hydrotopes, units of similar soil and meteorological characteristics, given available water resources:

$$Y_{TOT} = Y_{LU} + Y_{HP} - C_{LWM}$$

with

$$Y_{LU} = \Sigma_{\mathrm{z,u,y}}(Prod_{\mathrm{z,u,y}} \times P_{\mathrm{y,u}} - C_{\mathrm{LUu}} \times Ac_{\mathrm{z,u,y}})$$

$$C_{LWM} = \Sigma_{\mathrm{z,u,y}}(C_{IRRIz,u} \times Ac_{\mathrm{z,u,y}})$$

where Y_{TOT} represents total gross margin (in USD/yr), Y_{LU} the profit from land use (USD/yr) based on production (*Prod*, in ton) times price of product (*P*, USD/ton) minus non-water costs (C_{LU}, USD/ha) times the cropped area (*Ac*, in ha), in year *y* per land use *u* in hydrotope *z*. Y_{HP} is the GM of hydropower (USD/yr). C_{LWM} are the costs of local water-management measures for supporting land use, i.e., the variable costs of local irrigation measures (in USD/ha), depending on the amount of water used. Variable costs of water relate to pumping costs, which is a combination of labor, capital and energy costs. For the variable costs of water we used a regional estimate of 0.01 USD/m^3 (Hellegers and Perry, 2006).

Crop production and related water fluxes for all land and water use options in each hydrotope are pre-processed by water-crop modules run in an offline mode (SI2). In the Nile application a soil moisture accounting model of the bucket type is used, very similar to the AQUACROP model of the FAO (Raes et al., 2011), but more advanced in simulating soil storage and drainage, while simplifying the dynamic crop growth. Rainfall can contribute to runoff, drainage, or groundwater storage, after correcting for evapotranspiration. The calculation scheme for the evapotranspiration follows the FAO single crop coefficient method (Allen et al., 1998), applied separately to the vegetated and non-vegetated part. Crop production is simulated with a slightly modified form of the K_y approach of FAO (Doorenbos and Kassam, 1979), where the ratio between actual and potential evapotranspiration is translated into a mean yield ratio. Actual yield in each hydrotope is then calculated by multiplying this mean yield ratio with a predefined potential yield. This relatively simple method has the advantage of being robust and requiring a minimum of data.

WaterWise optimizes GM of food production by i. converting non-arable land into arable land, by ii. converting existing arable land into high-intensive variants and/or iii. by increasing the area under irrigation in predefined existing and new large-scale irrigation areas, depending on irrigation water availability and availability of investments. GM from hydropower can be increased by routing more water through existing hydropower schemes, if turbine capacity allows, or by investing in new ones.

Investment costs for the conversion to irrigated area were based on a comprehensive study on the cost of irrigation by IFPRI (Inocencio et al., 2007). We took the value for 'success' projects, under the optimistic assumption that new irrigation systems will be designed, constructed and maintained according to the latest knowledge and standards. There is a clear difference between north Africa and sub-Saharan Africa: the latter having, at 3552 USD/ha, only about half the conversion costs as North Africa. Conversion to arable land was made possible at an investment of 2174 USD/ha, assuming that conversion to rainfed arable land is similar to land preparation for irrigation, but without the additional hardware costs. Investments costs in new hydropower were mainly based on grey literature (see SI2). All major planned hydropower plants, including Ethiopia's highly controversial Grand Renaissance Dam, were offered as options.

The optimization was performed on the basis of two representative climate years—a relatively wet year (1999) followed by a dry year (2000). We did not explicitly include water demand from other sectors like household and industry, being relatively small compared to agricultural demand, nor the economic benefits of flood or sediment control, or environmental flows. Climate change was left out from the analysis. Within the time-frame considered, we expect that any climate change trend will be overshadowed by existing natural variability. However, rainfall projections for East Africa do show a large spread between climate models for the periods beyond 2025, adding considerable uncertainty to any long-term investment decision.

2.3. Data and schematization

Rainfall from the tropical rainfall measurement mission (TRMM) (Kummerow et al., 1998) and daily reference evapotranspiration from ECMWF (Uppala et al., 2005) were used as meteorological inputs, with soil properties coming from FAO-UNESCO's 1974 Soil Map of the World(1:5,000,000), soil classes aggregated based on maximum soil moisture storage and surface slope. A present-day spatial distribution of land use systems (FAO, 2009) at 5 arc minutes spatial resolution was made consistent with country-specific Food and Agriculture Organization crop statistics (FAOSTAT) (FAO, 2004) on actual cropped area by correcting for fallow area. Estimations of arable land were only available at national level. Simply correcting based on land area would lead to an underestimation of arable land within the Nile basin, the Basin part being wetter, in general. A Nile basin estimate was derived by multiplying the national average with the relative proportion of humid zone within the Basin area, as proposed by the FAO (Appelgren et al., 2000). A more detailed mapping of the irrigated areas was achieved by a supervised classification of Landsat images in combination with a FAO map indicating regions with a certain percentage of irrigation (Occurrence of irrigated areas (FGGD); (FAO, 2007; Siebert et al., 2005)). Training sites (areas in the map that are known to be representative) for the irrigated area class were determined based on prior knowledge of the location of some of the major irrigated areas in Egypt and Sudan. The irrigated area was then based on the classification of the high-resolution (30m) Landsat images, but only in regions where irrigation has been reported according to the lower-resolution (~10 m) FAO irrigated area map. The major irrigated areas in the Nile delta, in the Nile valley and in Sudan could be well identified, with their area matching the area as reported in FAOSTAT (Fig. 1).

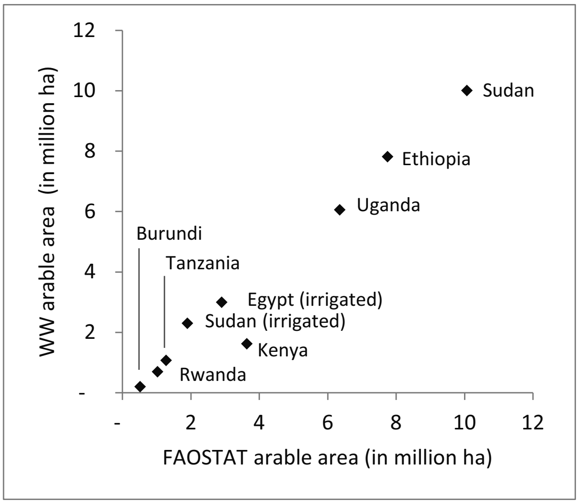

Fig. 1. WW-Nile arable land vs FAOSTAT arable land estimates (with irrigated area from AQUASTAT). 'Sudan' includes both Sudan and South Sudan, but excludes irrigated area in Sudan.

For arable land in each country we defined a unique country-specific cropping system, CCSs, representing a range of crops. Only crops that occupy each at least 10% of the arable area in at least five countries according to FAOSTAT (FAO, 2004) were included. This resulted in seven main crops: bananas, beans, maize, sorghum, sweet potatoes, vegetables and wheat. Because of the importance of groundnuts for Sudanese agriculture and rice for Egyptian agriculture these two crops were added. For each country, five dominant crops were selected from this subset and based on these five crops an average price per ton produced and cost per ha were derived for each country-specific cropping system. This resulted in a total of seven rainfed and two irrigated CCSs for the basin as a whole (Table 1). Crop growth periods and monthly crop factors, to multiply the daily reference evaporation with, were derived from Allen et al. (1998). Except for the sorghum cropping pattern in Sudan we assumed a double crop rotation in each country.

A uniform region-specific potential yield of 4 ton/ha was derived by correlating country-specific crop yields on rainfed arable land (in ton/ha, from FAOSTAT, 2004) with the ET_a/ET_p ratio of each country (AQUASTAT) ($R^2 = 0.7$). While this is a gross simplification of the diversity in crop production, a potential yield of 4 ton/ha does correspond well with earlier estimates (e.g. Penning de Vries et al., 1997). By using a region-specific potential yield, limiting factors other than water, for example, phosphate shortages, pests, or Nile region-specific restrictions in the agro-food chain infrastructure, are implicitly taken into account. Economic parameters in terms of crop prices and costs per hectare do differ per country. Average costs and prices for each CCS were calculated using area averaging of the FAOSTAT data, thereby ignoring any price fluctuations or uncertainty.

Large scale irrigation was separately schematized and parameterized. This type of irrigation in the Nile Basin is currently concentrated in Egypt and Sudan. Especially in Sudan and Ethiopia there is the land potential to increase the area irrigated (Block and Strzepek, 2010; Block et al., 2007). Irrigation from the main water courses was only allowed in predefined large-scale irrigation schemes, currently located in Egypt and Sudan. Yield, price and cost data per hectare for Egypt could be derived directly from FAOSTAT data (FAO, 2004), but for Sudan these were available only as an average of irrigated and rainfed areas combined. Sudan's irrigated agriculture is known to underperform because of the siltation of irrigation canals, waterlogging, and general deterioration of operation and maintenance (Plusquellec, 1990). Sudan's

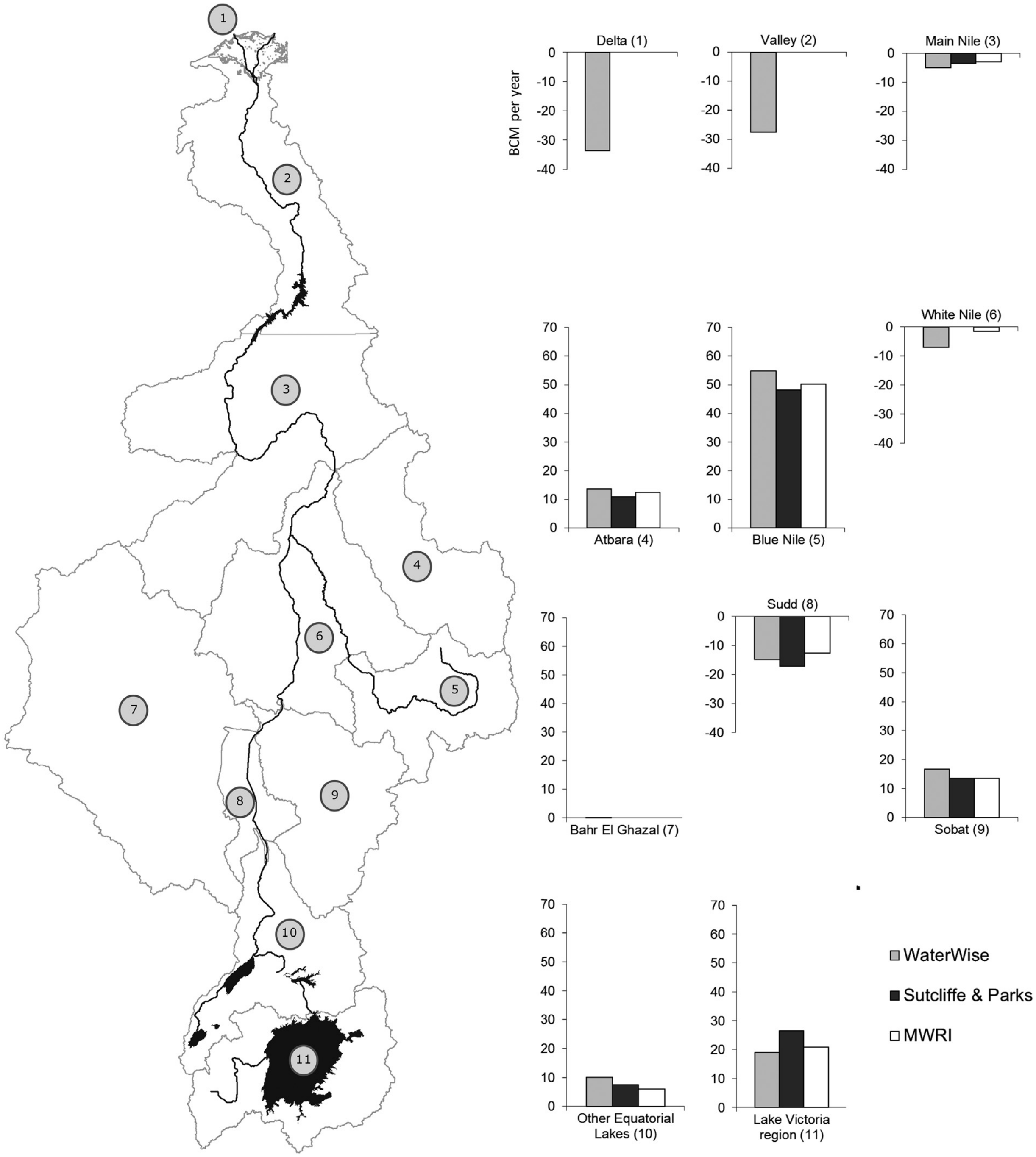

Fig. 2. Comparison of WaterWise-Nile runoff contribution and abstraction with modelled runoff (MWRI, 2005) and runoff derived from water balance estimates (Sutcliffe and Parks, 1999) for the main water balance areas of the Nile (in billion m^3/yr). The water demand of the Delta and Valley was not available for the latter two studies and therefore omitted. No figures for the White Nile are available from Sutcliffe & Parks because of the different catchment schematization. WaterWise-Nile was validated on the wet, average, and dry years of 1999–2001; Sutcliffe and Parks have determined the runoff based on measurement data of the period 1905–1995. The period of the MWRI study represents 1991–2001. Water abstractions of 70 billion M^3 to Egypt support unofficial estimates, suggesting that actual releases at Aswan are higher for the period evaluated than the, often reported, officially allocated 55.5 billion M^3 (Nicol and Cascão, 2011) even after correction for return flows.

yield per hectare was assumed to be half that of Egypt, but with the same costs, and cropping intensity at only half of its potential. With regard to new irrigation schemes in Sudan and Ethiopia, we assume that investors, water managers and irrigation engineers have learned from past mistakes and that productivity will match that of irrigated agriculture in Egypt.

2.4. Scenarios

We evaluated the target of food self-sufficiency under three transformative scenarios with varying degrees of cooperation, which are currently under debate. A hydro-economic model like WaterWise searches, if unrestricted, for a basin-wide optimum, thus reflecting complete cooperation and sharing of GM. This

Table 1
Cropping system characteristics for the dominant crops as derived from FAOSTAT (current) and estimates for future.

	Current Yield ton/ha	Potential yield ton/ha	Price US$/ton	Cost US$/ha	Potential GM US$/ha	Dominant crops in the cropping system	Double cropping
Current							
Burundi	3.6	4.0	216	122	736	Beans–Bananas	Yes
Egypt (irrigated)	19.5	19.5	122	183	2197	Wheat–maize	Yes
Ethiopia	1.5	4.0	149	92	499	Sorghum–wheat	Yes
Kenya	2.4	4.0	125	106	390	Beans–maize	Yes
Rwanda	3.9	4.0	218	136	730	Beans–bananas	Yes
Sudan	0.6	4.0	152	92	510	Sorghum	No
Sudan (irrigated)	9.7	9.7	122	183	1007	Sorghum–wheat	Yes
Tanzania	1.7	4.0	147	96	486	Maize–s. potatoes	Yes
Uganda	2.9	4.0	218	123	743	Beans–Bananas	Yes
Future							
Future intensive		4.0	218	123	743	Not specified	Yes
Ethiopia (newly irrigated)		19.5	122	123	2256	„	Yes
Sudan (newly irrigated)		19.5	122	183	2196	„	Yes

cooperation can then be restricted by specific boundary conditions or objective targets. With the model we focus on the allocation of land and water resources. The third production factor, labour, is assumed to be available and was not taken into account.

The background of the “National Food Self-Sufficiency” scenario is a future where cooperation and trade of agricultural produce is limited and food self-sufficiency is a target of each country individually; GM will drop once supply exceeds demand since transaction costs will increase once products have to be transported to other markets. To mimic this behaviour to the extreme in the model, the weight of land use revenues above a country’s target is reduced to nil in the objective function. In the “Upstream Hegemony” scenario, Ethiopia and Sudan maximize their agricultural GM for international export, irrespective of any downstream demands. All new irrigation schemes and the rehabilitation of existing irrigation schemes in Ethiopia and Sudan are forcefully implemented in the model at the investment cost required. In addition, the model maximizes agricultural GM of the major irrigation schemes in these two countries via the objective function. The “Basin Cooperation” scenario represents a future of enhanced trade in agricultural commodities within the basin, underpinned by infrastructural developments and political, economic, and financial cooperation. In the model this is implemented by solving the objective function for the basin as a whole, giving total freedom to maximize land use throughout the basin to reach the food self-sufficiency target for the basin as a whole. One country can offset shortages in another.

Our model includes both expansion of agricultural area and intensification with higher profits and costs per hectare, with investments in agriculture competing with investments in hydropower. The difference between expansion and intensification in the model needs to be interpreted with care. Especially small-scale agriculture is likely to be clustered with non-agricultural land uses in the present day land use classification. In addition, in war-torn regions, many fields have been temporarily abandoned or left fallow. In these areas, ‘expansion’ will refer more to a leap in production from low-yield agriculture to a form of commercial agriculture connected to regional markets, rather than an agricultural development from scratch.

Livestock was not explicitly included in our analysis, as we focused on arable farming, which has a far larger claim on land and water resources. We assumed livestock raising to be integrated with arable farming in mixed agricultural systems, without explicit additional land and water demands. An exception to this in the Nile Basin could be the large grazing areas in Sudan and South Sudan. Conversion of these existing pastoral lands to arable lands was not restricted in the model. However, in general, the model did not select these areas for arable expansion. The mere existence of pastoral lands can, in itself, be an indication that biophysical circumstances make such lands less suitable for arable farming for example, because of erratic or strong seasonality in rainfall.

We focused on the near future, in which we assume gradual autonomous technological progress in rainfed farming practices in those countries currently producing at a GM level below the

Table 2
Food self-sufficiency and the contribution of irrigated agriculture to food self-sufficiency targets for the main food-producing countries in the Nile basin (Nile basin area); baseline (2005) and three future scenarios.

	Baseline		Future Target 2025	Scenarios					
				National Food Self-Sufficiency		Upstream Hegemony		Basin Cooperation	
Country	Contribution of irrigation to food self-sufficiency	Overall food self-sufficiency	Needed increase in agriculture GM	Contribution of irrigation to food self-sufficiency	Overall food self-sufficiency	Contribution of irrigation to food self-sufficiency	Overall food self-sufficiency	Contribution of irrigation to food self-sufficiency	Overall food self-sufficiency
Egypt	100%	135%	17%	85%	85%	57%	57%	78%	78%
Ethiopia	0%	78%	117%	16%	100%	16%	80%	16%	80%
Sudan	28%	92%	83%	~0%	100%	122%	237%	93%	223%
Uganda	0%	102%	91%	0%	100%	0%	111%	0%	111%
Other	0%	75%	165%	0%	66%	0%	96%	0%	98%
Basin	48%	111%	74%	27%	92%	36%	103%	38%	107%

Sudan includes both Sudan and South Sudan, but changes in the contribution of rainfed production to GM refer mainly to South Sudan, while changes in irrigation are restricted to Sudan, which contains all the large-scale irrigated areas.

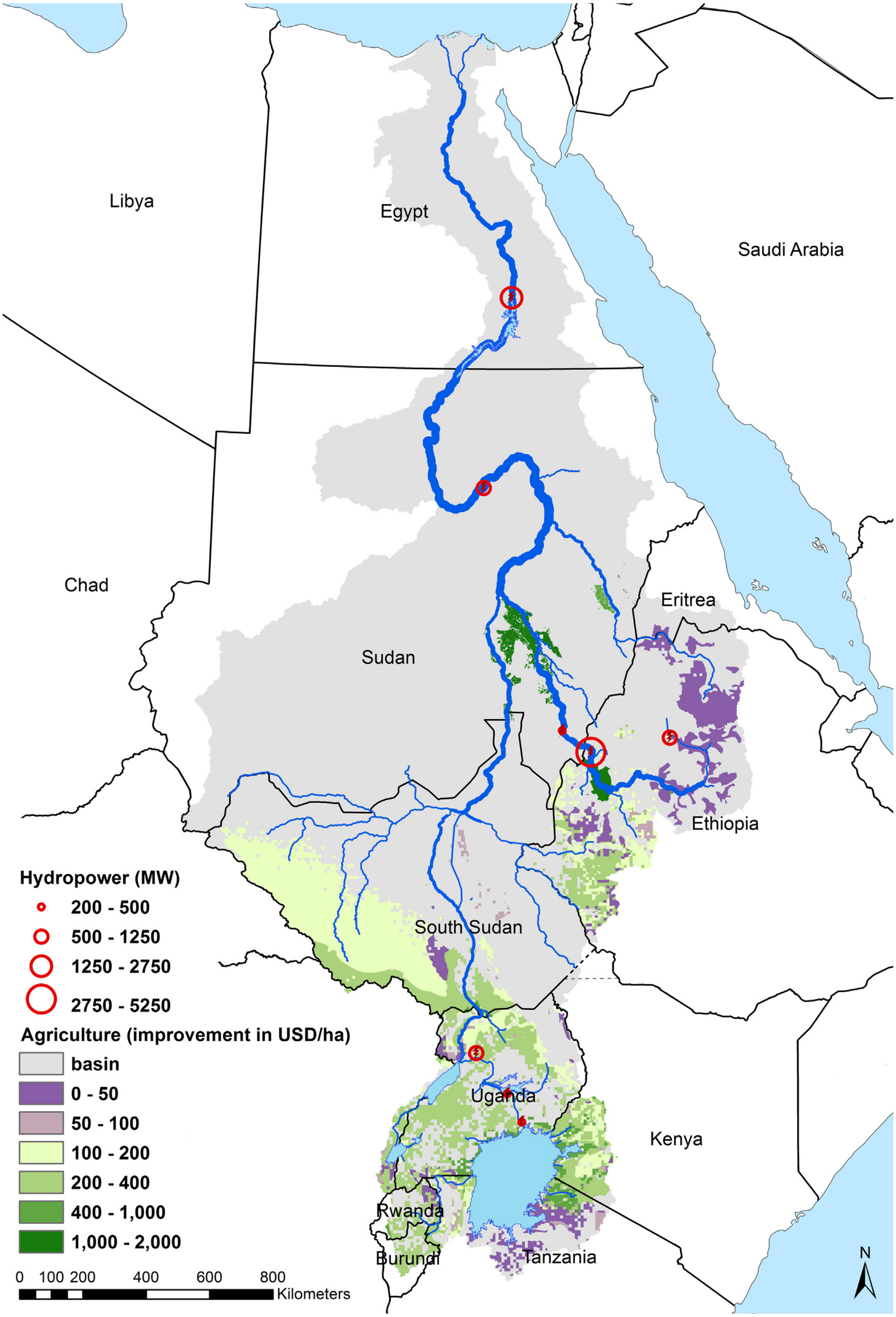

Fig. 3. Increase in annual agricultural gross margin (in USD/ha) between baseline (2005) and 2025 (in a scenario of full "Basin Cooperation" on investments in land use change and water resource allocation for agriculture and hydropower). The regions in dark green represent increase in gross margin in the rehabilitated irrigated areas of Sudan and the new irrigated areas in Ethiopia, under the assumption that they reach the same productivity as Egypt's irrigated areas. The drawn river width is proportional to annual mean discharge in this scenario, with a maximum of 2622 m^3/s after confluence of the main Nile with the Atbara in Sudan. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

regional maximum (Uganda, according to FAO). Such productivity-based growth, currently estimated at 1.3% for Sub-Saharan Africa (Fuglie and Rada, 2013), was represented by an optional 'future intensive' cropping system, activated under conditions of sufficient water availability (SI). No investments were required for conversions to more intense cropping systems, as they are assumed to be an autonomous development within the boundaries of current agronomic practices in the Basin.

3. Results

Comparison of WW-Nile runoff and abstraction with modelled runoff (MWRI, 2005) and runoff derived from water balance estimates (Sutcliffe and Parks, 1999) for the main water balance areas of the Nile shows there is quite a good match between the studies, especially considering the complexity of the hydrology in the basin (Fig. 2). Just like our study, these other studies are constrained by data availability and conceptual limitations. Despite these limitations, the runoff pattern is similar in the various subcatchments—even the evaporative losses in the Sudd match rather well. The largest differences can be found in subcatchments with significant irrigation water abstractions. The two other studies lack data on irrigation abstractions, focussing primarily on natural flow, i.e. runoff, from the different subcatchments.

Our baseline value of annual agricultural GM of 15.4 billion USD per year is about 35% lower than the single available FAO estimate for the basin (Appelgren et al., 2000). The inclusion of livestock in the latter figure, estimated at 18–35% of African agricultural GDP (Ehui et al., 2002; Sansoucy, 1995), can explain a large part of the difference. To accommodate the growth of the population and meet a minimum food supply of 2300 kcal/p/day, total food requirements are expected to rise by 75% over the 2005–2025 period, according to our calculations. A major shift occurs in Egypt, which goes from food surplus to shortage.

Our results show that under the "National Food Self-Sufficiency" scenario, when none of the countries is stimulated to have surpluses due to lack of trade, investments shift towards generating higher hydropower revenues and the basin as a whole will fail to become food self-sufficient (Table 2). Egypt, Rwanda, and Eritrea are unable to produce enough food for their growing populations because of the restricted availability of water or agricultural lands. Under the "Upstream Hegemony" scenario, when there is no restriction on trade within the basin, food self-sufficiency can be realized in 2025 in the Nile basin at a total investment cost of 100 billion USD. As imposed in the scenario, Ethiopia and Sudan expand their irrigated agriculture. However, this is achieved at the expense of increasing the vulnerability of Egypt, with the flow of water downstream being reduced by almost 40%, as Sudan and Ethiopia fully develop their irrigation potential. Egypt will be able to produce only half its needed food requirements, increasing inequality in food self-sufficiency among countries.

Under the "Basin Cooperation" scenario, the basin attains self-sufficiency in a manner that is profoundly different from that of "Upstream Hegemony". Here, the Lake Victoria region and South Sudan are responsible for the bulk of the increase in food production through intensification and expansion of the areas of rainfed agriculture (Fig. 3), while allowing Egypt's highly productive irrigation schemes still to receive a large amount of water. Interestingly, Ethiopia can be food self-sufficient, but does not need to be so under the 'Basin Cooperation' scenario, where climatic circumstances for rainfed agriculture are more favourable in South Sudan and investments there are prioritized. A limited reallocation of irrigation water toward Ethiopia is warranted though, as the country has the comparative advantage of more favourable rainfall and temperature conditions than Egypt or Sudan. Rehabilitating the currently underperforming schemes of Sudan is also prioritized, but additional expansion further north near the Merowe Dam is not, as irrigation there has no advantage over the existing schemes in Egypt. Water allocations of 59 billion m^3 to Egypt remain above its share of 55.5 billion m^3 of the 1959 treaty, a number often quoted. The construction of large hydropower reservoirs, like the Grand Renaissance Dam, does not affect Egypt's share, neither does conversion of land to rainfed agriculture.

Rainfed agriculture contributes over 75% of the additional food requirements in all scenarios. Expansion of rainfed agriculture is suggested primarily in unstable regions of South Sudan and northern Uganda, where the causes of underdevelopment are largely socio-political as opposed to biophysical. Many parts of Africa are characterized by high inter-annual and intra-annual variability in rainfall (Cooper et al., 2008). A reliable rainfed agriculture will require investments in local water harvesting and site-specific supplemental irrigation (Rockström and Falkenmark, 2015), in the long run supported by more accurate regional weather forecasting and smart forms of crop, water and soil monitoring and management. However, the pessimistic view of the whole of East African agriculture being drought-stricken needs refinement as well. Fig. 4, which compares seasonal rainfall totals with crop water demand, indicates suitability for rain-fed agriculture, with country regions lying within the Nile basin being wetter than the countries' total averages. Potential new agricultural areas identified in this study have a total crop season precipitation of about 900 mm, more than double the country's average and well above crop water requirements. Our model suggests investments in a total area of around 11 million ha in South Sudan, about a third of the potential identified.

If not all countries are self-sufficient in food, as is the case under the "Basin Cooperation" scenario, then regional trade is required to deliver food to where it is needed. Food surplus regions in the basin are situated in the south, whereas the largest shortages will occur in the north: in Egypt and Eritrea. While basic transport infrastructure is present in the form of river connections and railroads, historic trade routes need to be revived. To make optimal use of comparative advantages, staple food suitable for long-distance transport to Egypt could be produced in upstream areas, while Egypt could specialize in fresh produce for its urban population and European markets (Wichelns et al., 2003). Export of agricultural produce from South Sudan, which, according to our calculations, could amount to 1.8 billion USD a year at farm-gate level, will provide diversification to this young economy, lessening its dependence on oil. Ethiopia's hydropower revenues could give the country access to food markets, should it choose not to develop its vulnerable highland regions to the maximum. The recent integration of energy grids in the region shows that such cooperation is possible.

4. Discussion

This study focusses on the potential to reach national to regional food self-sufficiency in the Nile basin, as an alternative to an increasing reliance on global markets. This focus on food self-sufficiency gave us a framework to assess the contribution of rainfed agriculture compared to that of irrigated agriculture and the impact of different scenarios on the allocation of Nile waters. We do not, however, wish to advocate basin cooperation and self-sufficiency as the only solution or criticise a reliance on global markets. For this, a different type of study including an analysis of the costs and benefits of regional to global food imports and exports would be required.

Similar to earlier studies that focused solely on irrigated agriculture and hydropower (Whittington et al., 2005; Wu and Whittington, 2006), we find that basin cooperation will provide the most benefit to the basin—a result to be expected given the nature

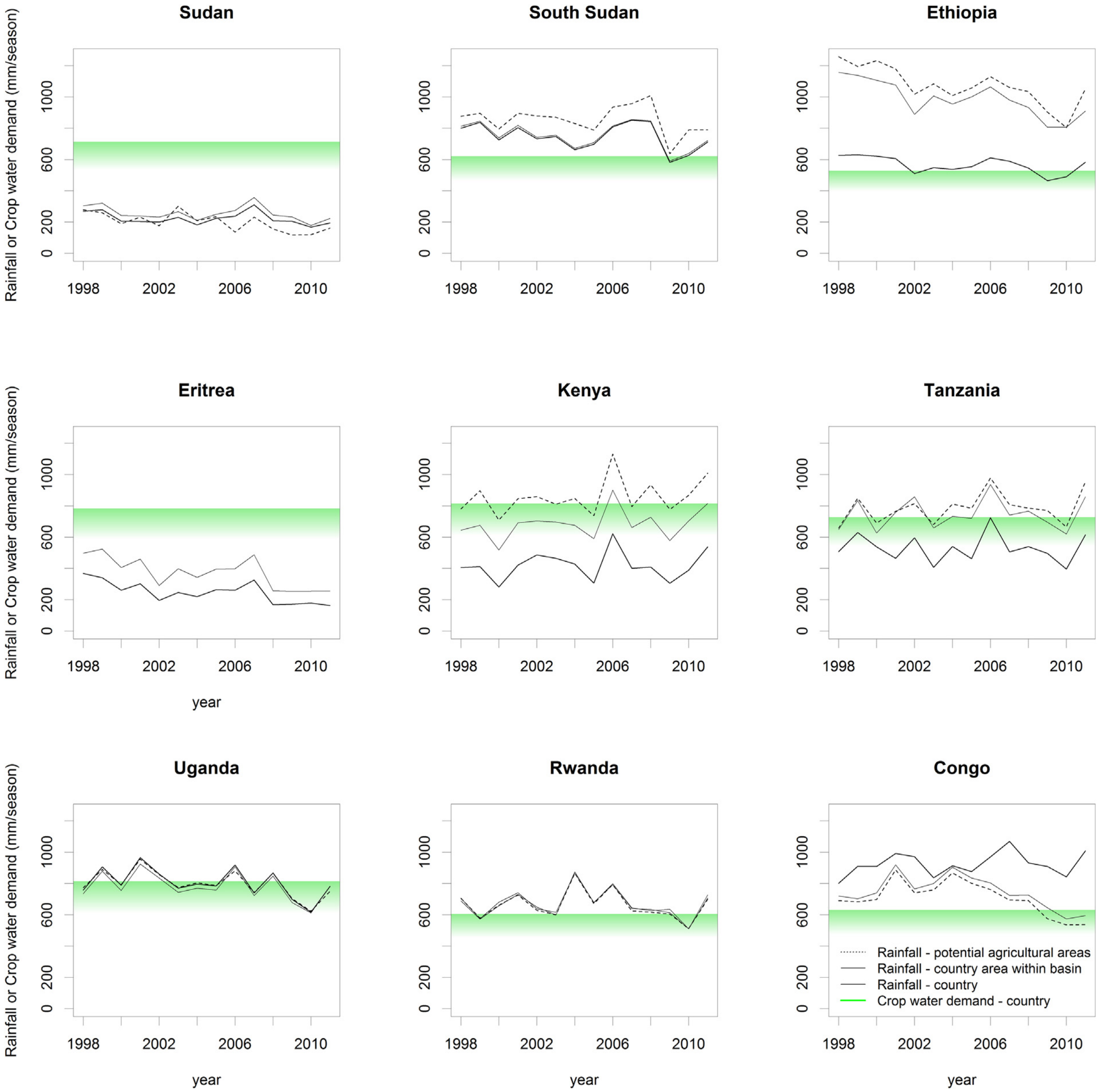

Fig. 4. Satellite-derived country-specific rainfall (source: Tropical Rainfall Measurement Mission [TRMM] data (Kummerow et al., 1998)) for various spatial delineations for the main cropping seasons (JJASO for Sudan, South Sudan, Ethiopia and Eritrea; MAM and SON for all other countries) in relation to average crop water requirements of rainfed agriculture during these months (set equal to potential crop evapotranspiration, based on average ECMWF reference evapotranspiration (Uppala et al., 2005) and FAO crop factors, see SI). Green shades indicate a range between 75% and 100% of crop water requirements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the model used. Integration of rainfed agriculture in the objective function, however, greatly changes the solution space available. Earlier (non-)cooperation studies with their strong focus on Nile water allocation tend to emphasize potential conflicts between Egypt, Sudan and Ethiopia and highlight the role of Egypt as the main hegemon and the unequal distribution of water (Cascão, 2008, 2009; Whittington et al., 2005; Wu and Whittington, 2006). In our study we show that a different distribution will merely shift production, which will not be sufficient to feed a growing population. In rainfed agriculture areas, however, there still is potential to increase production.

An integrated analysis of this kind faces numerous data uncertainties. Several (the yield of hydropower, the yield of the current irrigation system in Sudan and the investment cost of land cover change) were assessed in a partial sensitivity analysis (SI5). Changes in these variables did not change the results such that the main conclusions had to be revised. Inevitably, caveats remain. Our study aims to explore different solutions from a hydro-economic perspective, thereby simplifying the diversity of crop production. Limitations, e.g. in terms of soil nutrient conditions, farmers' knowledge levels and access to markets, were not explicitly addressed, but implicitly included in a potential rainfed yield that is lower than what would be expected from crop and soil and meteorological characteristics alone.

For agriculture in the political and socio-economic unstable regions of South Sudan and north Uganda to approach this potential yield requires considerable effort in creating the infrastructure to make knowledge, technology and inputs–seeds, fertilizers and pesticides–available to farmers. This study did not assess the likelihood of such developments, but rather advocates increased effort to make this happen. Environmental consequences of such development should be thoroughly assessed. We did not include environmental limitations to agricultural intensification or expansion. But a sustainable intensification (Godfray et al., 2010), with proper land management to reduce negative externalities of increased production will be required in the Nile basin as much as elsewhere.

Agricultural intensification and expansion did not lead to significant changes in downstream runoff. We found that seasonal evapotranspirative demand from arable lands was similar to that of the original vegetation in most locations. Crop factors between natural vegetation and arable crops do not differ much during the peak growing season, when it rains most. Small variations in evapotranspirative demand can be buffered by the soil column, resulting in even smaller differences in runoff at the aggregated time steps of a couple of days as is used in the model. In addition, swamps in the main surface water system, located mainly in South Sudan and evaporating a large fraction of runoff, further attenuate any change in runoff from the white Nile part of the basin. It is in this region where most land use changes were projected by the model. In literature, increases in runoff after deforestation are reported, but mainly for temperate regions. Results from the tropics are mixed (Brown et al., 2005; Bruijnzeel, 1989). One of the few extensive empirical studies from the Nile basin itself, by Hurni et al. (2005),suggests that intensification of land use on small test plots has lead to increased surface runoff, but possibly also to decreased baseflow, while soil conservation measures might have led to less runoff in semi-arid regions, but not in the humid parts, in the Ethiopian highlands. More in general, any change in land use on less than 20% of the catchment area appears hard to detect in runoff (Bosch and Hewlett, 1982; Brown et al., 2005; Stednick, 1996). Still, further study on the local and regional impact of upstream land use changes and/without associated soil and water conservation measures using a model with a more detailed vegetation and land management parameterization would be required to verify these initial findings.

In addition, a more detailed analysis of the impact of intra-seasonal droughts on food production is needed to further verify whether rainfed agriculture is sustainable. This should ideally be supplemented with an analysis of the robustness of agriculture and hydropower development under a range of future climate scenarios, given the diversity in both magnitude and direction of change in projections for this part of the world. Ultimately, a comparison of regional versus global climate variability would shed more light on whether the region would be better off cooperating rather than depending on volatile global markets. Although regional cooperation makes countries more vulnerable to regional climate extremes, the region would still have a safety net during such periods of basin-wide scarcity: the global market. If the Nile region were to rely on the global market in the first place, it could no longer act as a safety net.

Finally, our study explored the possibility of different forms of cooperation from a hydro-economic point of view, but did not assess the likelihood of one form of cooperation versus the other or the required political and institutional setting. One such institutional option would be to reinvigorate and broaden the scope of the Nile Basin Initiative (NBI), which aims to stimulate cooperation by the nine Nile riparian countries. For the NBI to transit from a project towards a River Basin Organisation, a Cooperative Framework Agreement (CFA) has been outlined and a permanent institutional mechanism should be established, the Nile River Basin Commission (NRBC). In recent years, however, the NBI has been struggling to define and agree on the CFA and to establish the NRBC. Another option would be to embed negotiations on sharing the Nile waters within East African trade blocks, like COMESA, the Common Market for Eastern and Southern Africa. A focus on broader economic cooperation, as also suggested by Wichelns et al. (2003) and Hilhorst and Schütte (2010) and further explored and quantified in this paper, can provide a new perspective on the issue of sharing water resources by defining common benefits and a new angle for cooperation within existing initiatives.

5. Conclusion

We argue that rainfed agriculture in unstable regions like South Sudan and North Uganda is key to food self-sufficiency in the Nile basin and that the heated debate on water allocation should be put into perspective. Conflicts over allocation can only hinder cooperation on food production and trade, thereby hampering the Basin's development.

Egypt's policy stand in particular seems to resemble a risky strategy: obstructing cooperation within the basin and hindering upstream water infrastructure development, as it has done in the past, gives Egypt the most water. But if this lack of cooperation leads to unilateralism, increased and uncoordinated upstream abstractions will have serious consequences for Egypt's agriculture and hydropower sectors. The resulting more unequal distribution of food self-sufficiency among basin countries will jeopardize regional stability. However, we also show that a more equitable solution is available, should countries choose to cooperate on basin-wide food production and trade, albeit with some, but rather limited, loss of water allocations for Egypt. This will require old policy dogmas to be relinquished and a change of perspective both on the basin itself and on the utilization of its land and water resources.

Such a change in perspective asks for a different, more integrative approach to basin governance and investments, away from the current focus on large water infrastructure projects. Investments for supporting a transition towards a climate-smart sustainable agriculture are needed, with technology improvement and technology adaptation and transfer essential to reduce the environmental impacts of increased production in the basin. The alternative is an increased dependence of Nile basin countries on volatile global food markets.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2016.03.007.

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