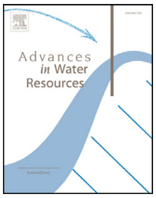
Advances in Water Resources 94 (2016) 231–237

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres



Climate change and large-scale land acquisitions in Africa: Quantifying the future impact on acquired water resources

Davide Danilo Chiarelli[a,*], Kyle Frankel Davis[b], Maria Cristina Rulli[a], Paolo D'Odorico[b,c]

[a] *Department of Civil and Environmental Engineering, Politecnico di Milano, Milan I-20133, Italy*
[b] *Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904, United States*
[c] *National Socio-Environmental Synthesis Center, University of Maryland, Annapolis, MD 21401, United States*

ARTICLE INFO

Article history:
Received 18 January 2016
Revised 24 May 2016
Accepted 25 May 2016
Available online 26 May 2016

Keywords:
Crop water requirement
Climate change
Large-scale land acquisition
Blue and green water
Water resources
Biofuel crops

ABSTRACT

Pressure on agricultural land has markedly increased since the start of the century, driven by demographic growth, changes in diet, increasing biofuel demand, and globalization. To better ensure access to adequate land and water resources, many investors and countries began leasing large areas of agricultural land in the global South, a phenomenon often termed "large-scale land acquisition" (LSLA). To date, this global land rush has resulted in the appropriation of 41 million hectares and about 490 km^3 of freshwater resources, affecting rural livelihoods and local environments. It remains unclear to what extent land and water acquisitions contribute to the emergence of water-stress conditions in acquired areas, and how these demands for water may be impacted by climate change. Here we analyze 18 African countries – 20 Mha (or 80%) of LSLA for the continent – and estimate that under present climate 210 km^3 $year^{-1}$ of water would be appropriated if all acquired areas were actively under production. We also find that consumptive use of irrigation water is disproportionately contributed by water-intensive biofuel crops. Using the IPCCA1B scenario, we find only small changes in green (−1.6%) and blue (+2.0%) water demand in targeted areas. With a 3 °C temperature increase, crop yields are expected to decrease up to 20% with a consequent increase in the water footprint. When the effect of increasing atmospheric CO_2 concentrations is accounted for, crop yields increase by as much as 40% with a decrease in water footprint up to 29%. The relative importance of CO_2 fertilization and warming will therefore determine water appropriations and changes in water footprint under climate change scenarios.

1. Introduction

The past 15 years have seen unprecedented changes in the global agricultural system. Food calorie demand has risen by more than 20% as a result of demographic growth and dietary changes (D'Odorico et al., 2014; FAO, 2015b), while the production of crop-based biofuels has increased more than 6-fold since the year 2000 (OECD/FAO, 2014). In addition, food prices have become increasingly volatile with dramatic spikes in 2007–2008 and 2010–2011 (Rezitis and Sassi, 2013; Brown, 2012). The confluence of these factors has heightened demand for land and brought a wave of land investment to the developing world (Deininger et al., 2011). While this phenomenon of large-scale land acquisition (LSLA) has been acclaimed as a means to improve land productivity and enhance rural development in underperforming agricultural areas through investments in modern technology, many of these land deals occur with no informed consent of prior land users, little or no involvement of local communities, and without accounting for the potential environmental and social impacts (Cotula et al., 2009). To date, over 41 million hectares (ha) worldwide are under transnational contract globally: only 5.1% of the land is currently under production (Land Matrix, 2016). While some of these investments are purely speculative – and will likely never be put to productive use – many more have simply yet to begin production (Zoomers and Quak, 2013). Thus, there is a large potential for land acquisitions to greatly impact natural resources (Rulli and D'Odorico, 2013a), the local environment (Rulli and D'Odorico, 2013a; Davis et al., 2015a, 2015b) as well as the food security (Rulli and D'Odorico, 2014) and livelihoods (Davis et al., 2014) of rural communities.

Recent work (Davis et al., 2015a) has also suggested that land acquisitions may be driven – in part – by investors' anticipation of future climatic changes. This is because the effects of climate change on crop production – both positive (e.g., CO_2 fertilization, longer growing season) and negative (e.g., crop water stress, decreasing yields) – are expected to be heterogeneously distributed

---

[*] Corresponding author.
E-mail address: davidedanilo.chiarelli@polimi.it (D.D. Chiarelli).

http://dx.doi.org/10.1016/j.advwatres.2016.05.016
0309-1708/© 2016 Elsevier Ltd. All rights reserved.

across the world's agricultural areas (Wheeler and von Braun, 2013). For resource-poor countries especially, land acquisitions offer a way to increase the natural resources available to them for food production and may in turn act as a buffer to potential future climate impacts on food security (Harvey and Pilgrim, 2011; Davis et al., 2015a). While the control of agricultural resources has been the focus of recent studies (Rulli and D'Odorico, 2013a; Rulli and D'Odorico, 2014), little work has been done to date to quantify the role of climate in the global land rush. It is unclear how climate change is expected to affect the countries targeted by land investments and whether agribusiness corporations are investing in countries that will be substantially or minimally affected by climate change, particularly with respect to crop water stress and crop requirements for both rainfed and irrigated agriculture. To that end, we examine to what extent water resources in Africa – the continent most targeted (Land matrix, 2015) by the global land rush (46.8% of all acquired area globally, 4.6% of which are already in production) – may be affected by future climate. Specifically, we combine a crop water use model (AquaCrop 5.0) (FAO, 2015c) with long term climate change projections for precipitation and temperature to examine the current and future crop water requirements (water use per unit area) and crop water footprints (water use per unit crop mass) in 18 African countries, which account for over 80% of the total large-scale land acquisitions in the continent. Unlike previous efforts, this analysis is performed at the sub-national time scale using site specific soil, climate and crop data rather than country averages.

2. Method

2.1. Data

Data on land acquisitions were taken from the Land Matrix Database (Land Matrix, 2016), which reports for every target country the acquired area, intended crop, investing country and negotiation status of each deal. A deal could be intended, concluded or failed and the area of the acquired land is reported specifying whether the deals are intended, contracted or in production. Land deals are notoriously un-transparent and negotiations are not always public. Furthermore the landscape of LSLA is very dynamics as deals are often changed, annulled or new ones spring up. Reliability is quantified by Land Matrix by assigning a score to each data entry based on how the data have been verified (Land Matrix, 2015). We stress that even after these quality checks the dataset could remain affected by a few biases resulting from the lack of transparency inherent to the LSLA phenomenon.

We examined 18 African countries which account for more than 80% of agricultural land acquired in this continent by large-scale land investors. We only considered concluded land deals (i.e. deals for which the land has been successfully leased or sold to an investor). For those deals for which the intended crop was not reported we used a weight average of all intended crops reported for all the other areas acquired in that country.

2.2. Present crop water use

Acquired water was determined based on a crop's evapotranspiration (i.e. a crop's consumptive water use), following the methods of Rulli et al. (2013b). The crop water use requirement was estimated using the FAO's AquaCrop 5.0 model (FAO, 2015c). AquaCrop 5.0 is a program for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data. The development of irrigation schedules in AquaCrop 5.0 is based on a daily soil-water balance using various user-defined options for water supply and irrigation management conditions. Scheme water supply is calculated according to the cropping pattern. (FAO, 2012).

We approach a site specific evaluation of the crop water requirement for each plant reported in each deal by assigning the necessary required information for the calculation referred to the exact location of the deal.

Data on soil type, in particular, came from the FAO's Harmonized World Soil database (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) with a resolution of a grid cell size of 30 arc seconds of longitude and latitude (approximately, 1 km).

Climatic data are from the CLIMWAT station (FAO, 2009) closest to the deal coordinate. If more than one location was reported for a given land deal, the total acquired area for that deal was equally divided between each of the stations. For example, if there is a 1000 ha deal with four locations reported, 250 ha would be assigned to each location and its corresponding weather station. Wind speed, relative humidity and hours of sunshine were taken from the meteorological station in CLIMWAT 2.0 (FAO, 2009).

Information on crop coefficient (K_c), growing stage, yield response and critical depletion were taken from values reported by Chapagain and Hoekstra (2004). One limitation of this model is that it evenly distributes monthly rainfall values, so that the modelled crop regularly receives water inputs every 4 to 5 days. Because of this assumption, it is not possible to incorporate certain types of climate extremes (e.g. prolonged dry periods) which are expected to become more frequent with climate change (IPCC, 2012), and may, in turn, increase the amount of blue water crops need to avoid water stress.

As an output, the AquaCrop model gives the crop water requirement (CWR), partitioned into precipitation (i.e. green water) and irrigation (i.e. blue water). Required blue water is simply the additional water (after accounting for precipitation's runoff, deep percolation and productive use) required to keep soil moisture levels above a crop's wilting point. Thus, crop water requirements are estimated with respect to an irrigation scenario that does not expose crops to water stress conditions. Because this study was only concerned with consumptive water use, we do not evaluate the grey water footprint (i.e. the amount of water required to dilute nutrient concentration in runoff water to an acceptable or standard level). Finally, the water acquired in a given land deal was calculated as the product of the area of the deal and the crop water use ($m^3\ ha^{-1}\ year^{-1}$ of water) of the intended crop.

To evaluate the impact of potential blue water consumption for irrigation on the volume of freshwater accessible by humans in each country, we calculated the total available freshwater resources (TAWR) for each targeted country as 40% of the total renewable freshwater resources (RWR) of that country (FAO, 2015a), based on a similar assumption proposed by Fader and colleagues (2013).

2.3. Future scenarios of crop water use

To examine sensitivity to future changes in climatic conditions, we evaluated the effect that changes in precipitation (±10% change from present) and temperature (+1, +2, +3 and +4 °C) could have on the crop water requirements (CWR) of 7 main crops – maize, oil palm, jatropha, rice, sugarcane, wheat and soybean – which account for 31.6% of total acquired land (61.5% of the acquired area where the intended crop was reported, excluding trees). We also evaluated a possible future climate scenario using the IPCC's A1B monthly (8 global model ensemble) projections for temperature and rainfall (NCAR community, 2004). The A1B scenario describes a future world undergoing very rapid economic growth, with global population peaking in mid-century and declining thereafter, and affected by the rapid introduction of new and more efficient technologies. Because the temperature and precipitation values from climate change simulations were reported in a grid format, for the location of each land deal, we used the temperature and precipitation values from the closest grid cell. These

Table 1
LSLA contract size area and acquired water in the 18 studied countries.

Country	Contract size [ha]	% of total LSLA contract	Green Water [km^3]	Blue Water [km^3]	CWR [km^3]	% CWR
Angola	1.30E+05	0.7%	0.58	0.52	1.1	0.52%
Benin	3.21E+04	0.2%	0.2	0.07	0.27	0.13%
Cameroon	1.25E+05	0.6%	1.47	0.16	1.63	0.78%
Congo	2.11E+06	10.8%	19.73	2.85	22.58	10.74%
DR Congo	2.79E+06	14.3%	31.89	0.94	32.83	15.61%
Ethiopia	1.05E+06	5.4%	4.92	8.73	13.65	6.49%
Gabon	4.74E+05	2.4%	6.58	0.03	6.61	3.14%
Liberia	1.81E+06	9.3%	18.15	2.78	20.93	9.95%
Madagascar	6.58E+05	3.4%	6.17	1.86	8.03	3.82%
Morocco	7.02E+05	3.6%	1.3	5.69	6.99	3.32%
Mozambique	2.30E+06	11.8%	17.31	3.21	20.52	9.76%
Nigeria	7.40E+05	3.8%	5.52	3.63	9.16	4.36%
Sierra Leone	1.08E+06	5.5%	9.93	2.13	12.07	5.74%
South Sudan	3.64E+06	18.6%	14.7	24.29	38.99	18.54%
Sudan	1.30E+06	6.6%	4.23	5.07	9.3	4.42%
Tanzania	3.32E+05	1.7%	2.43	0.83	3.26	1.55%
Uganda	1.40E+05	0.7%	0.65	0.98	1.63	0.78%
Zimbabwe	1.20E+05	0.6%	0.53	0.18	0.71	0.34%
Total Domestic LSLA	12%		13%	14%	13%	
Total	1.95E+07	100%	146.3	63.96	210.26	100%

temperature and precipitation values were averaged over the period 2080–2099.Temperature was corrected as:

$$T_{fc} = T_{fs} - (T_{ss} - T_{so}) \tag{1}$$

where T_{fc} is the corrected future monthly temperature, T_{fs} is the simulated future monthly temperature (year 2080–2099 average) (NCAR community, 2004), T_{ss} is the simulated historical monthly temperature (year 2000–2010 average) (NCAR community, 2004) and T_{so} is the observed historical temperature (year 2000–2010 average) (Watanabe et al., 2012). Precipitation was similarly corrected as:

$$P_{fc} = P_{fs} * \left(\frac{P_{ss}}{P_{so}}\right) \tag{2}$$

where P_{fc} is the corrected future monthly precipitation, P_{fs} is the simulated future monthly precipitation (year 2080–2099 average) (NCAR community, 2004), P_{ss} is the simulated historical monthly precipitation(year 2000–2010 average) (NCAR community, 2004) and P_{so} is the observed historical monthly precipitation (year 2000–2010 average) (Watanabe et al., 2012). CWR, green and blue water demand for future scenarios were evaluated with AquaCrop 5.0 (FAO, 2015c) using corrected projection data for precipitation and temperature, as described above. We assumed that wind speed, relative humidity and hours of sunshine remained the same as 2000–2010.

2.4. Present and future water footprint

The water footprint for the 7 main target crops was evaluated as the ratio of the total volume of water, blue and green, in the 18 analyzed countries and the average yield. For the present scenario, data on yield from FAOSTAT (FAO, 2015b) were averaged for the period 2000–2012. For future projections (2080–2099) three different scenarios were evaluated (based on data availability) for three main crops (maize, rice and wheat): a 3 °C temperature increase scenario (no changes in precipitation and without accounting for CO_2 increase), the IPCC A1B scenario with and without the effect of increasing CO_2 concentrations (in agreement with the scenario's projection). In all cases the total volume of water was recalculated for the crops of interest due to changes in climatic conditions. Yield calculations were estimated both for the present scenario and future projections using AquaCrop5.0 (FAO, 2015c).

3. Results

We estimate that 210 km^3 year^{-1} of water (blue + green) would be used by land investors in the targeted countries if all the acquired areas were actively used for agricultural production under current climate conditions (Table 1). Land deals in South Sudan, Democratic Republic of Congo and Congo alone comprise 44% of this total acquired water. In partitioning between rainfall and irrigation, we find that nearly half of the potential blue water appropriation (BW) occurs in just two countries –South Sudan and Ethiopia – while green water acquisition is distributed more evenly amongst targeted countries. While the appropriation of green water resources (i.e., evapotranspiration of water received by vegetation as precipitation) is directly related to the location of acquired land and to the cultivated crops, the use of blue water depends on whether the investors will develop irrigation infrastructure, and on blue water availability. Due to data limitations on irrigation investments and current levels of production, it was not possible to calculate the actual blue water appropriation for land acquisitions. Our analysis therefore focused on the calculation of the "potential blue water appropriation", defined as the amount of water that would need to be supplied by irrigation to prevent the emergence of crop water stress and therefore maximize crop production. We calculated this potential blue water appropriation for both acquired areas currently under production and for all acquired area. We find that the amount of total potentially acquired blue water (BW) in all contracted areas is 64 km^3 year^{-1} of water, comparable to the gross virtual water export (i.e., export of "embodied water" associated with international trade of food commodities) from the entire continent of Africa in the year 2000 (65 km^3 year^{-1}of water (Hoekstra and Hung, 2002)). In four countries (Uganda, Mozambique, Democratic Republic of Congo and Angola) the amount of blue water potentially acquired by investors under present climate conditions ranges between10 and 100 times the volume of irrigation water (IWR, 2015; FAO, 2015a) currently used in agricultural production (or "current blue water use") in the same countries. Additionally, in Congo, Liberia, and Sierra Leone, the potentially acquired blue water within each country's acquired areas exceeds their current national blue water use by more than two orders of magnitude (Table 2). This large potential increase in consumptive blue water use would be largely contributed by water-intensive biofuel crops such as oil palm, sugar cane and jatropha (these three crops covered 80% of the total contracted area devoted

Table 2
Blue water resources in targeted countries. RWR is the total renewable freshwater resources of a country. Irrigation water requirement (IWR) came from the FAO's AQUASTAT database (2015). BW is the current acquired blue water.

Country	RWR [km^3]	IWR [km^3]	BW [km^3]	IWR/RWR	(IWR+BW)/RWR	BW/IWR
Angola	148	0.04	0.52	0.03%	0.38%	13.1
Benin	26	0.011	0.07	0.04%	0.31%	6.3
Cameroon	286	0.201	0.16	0.07%	0.13%	0.8
Congo	832	0.001	2.85	0.00%	0.34%	2854.3
DRC	1283	0.02	0.94	0.00%	0.07%	47.1
Ethiopia	122	1.475	8.73	1.21%	8.36%	5.9
Gabon	164	0.011	0.03	0.01%	0.03%	2.5
Liberia	232	0.003	2.78	0.00%	1.20%	928.3
Madagascar	337	4.398	1.86	1.31%	1.86%	0.4
Morocco	29	5.823	5.69	20.08%	39.70%	1.0
Mozambique	217	0.183	3.21	0.08%	1.56%	17.5
Nigeria	286	1.695	3.63	0.59%	1.86%	2.1
Sierra Leone	160	0.011	2.13	0.01%	1.34%	194.1
Sudan and South Sudan	65	8.015	29.36	12.43%	57.50%	3.7
Uganda	66	0.063	0.98	0.10%	1.58%	15.5
Tanzania	96	0.973	0.83	1.01%	1.88%	0.9
Zimbabwe	20	0.836	0.18	4.18%	5.08%	0.2
Total	4340	17.936	63.96	1.32%	7.25%	240.8

Table 3
Large-scale land acquisition data arranged base on intention of investment.

Intention of investment	Contract size [ha]	% in production	Green Water [km^3]	Blue Water [km^3]	CWR [km^3]	% Area	% CWR
Agriculture	1.09E+06	5.5%	11.63	2.77	14.41	5.6%	6.9%
Biofuel	1.93E+06	5.0%	16.18	10.20	26.38	9.9%	12.5%
Conservation	1.64E+06	0.6%	8.72	9.64	18.36	8.4%	8.7%
Food crops	3.97E+06	2.6%	15.42	17.00	32.41	20.3%	15.4%
For carbon sequestration/REDD	1.16E+06	13.8%	10.19	1.87	12.06	6.0%	5.7%
Wood and fibre	6.07E+06	3.4%	63.28	2.85	66.13	31.1%	31.4%
Industry	1.06E+04	14.1%	0.05	0.11	0.16	0.1%	0.1%
Livestock	2.48E+05	2.5%	1.40	0.65	2.05	1.3%	1.0%
None	6.07E+05	0.2%	2.97	4.19	7.16	3.1%	3.4%
Non-food agricultural commodities	7.32E+05	8.1%	5.53	2.86	8.39	3.7%	4.0%
Other	1.10E+05	1.5%	0.72	0.51	1.23	0.6%	0.6%
Renewable energy	5.70E+05	1.9%	4.34	1.43	5.77	2.9%	2.7%
Tourism	1.38E+06	0.3%	5.86	9.89	15.75	7.1%	7.5%
Total	1.95E+07	4.6%	146.30	63.96	210.26	1.00	1.00

to biofuel production). Our results show that the total volume of water per unit area used by biofuel crops is 67% higher than the one necessary for food crops (Table 3). Thus it is apparent that the water appropriation associated with large-scale land investments greatly depends not only on the area of the acquired land but also on the type of crop. 31.1% of the total area acquired in the 18 African countries is then devoted to wood and fiber production, with a water requirement that is 31.4% of the total water acquired (Table 3).

We also examined the impact of climate change on crop water requirements (CWR) in the acquired lands. Using the climate change projection for the IPCC A1B scenario (NCAR community, 2004) –for the period 2080–99 – resulted in only small changes in overall green (−1.6%) and blue (+2.0%) water demand in the targeted areas for the African countries analyzed. To better understand the influence of temperature and precipitation change on the crop water requirements (CWR) we also run the AquaCrop model under four climate warming scenarios (i.e., increasing temperature by +1 °C to +4 °C with increments of 1 °C) and with two scenarios with changes in precipitation (±10% of mean annual precipitation). We found that elevated temperatures increased CWR by 2%, 5%, 7% and 9% averaged among crops, respectively, while the above changes in precipitation had a negligible effect on CWR (Fig. 1). We also analyzed potential changes in water footprint for three main crops, as yield seems to be differently affected by climate change projection, depending on whether changes in atmospheric CO_2concentrations are accounted for or not (Fig. 2). With an increase in temperature and keeping constant the amount of carbon dioxide in the atmosphere, yields are expected to drop by up to 20% in the case of the 3 °C warming scenario, which a consequently increase the water footprint. Conversely, when an increase in atmospheric CO_2 is accounted for crop yields increase, thereby reducing the water footprint of crops. In particular, C3 crops (i.e. wheat, and rice) may increase their yields by up to 40%, while C4 plants such as maize are expected to exhibit a lower increase in the production up to 6%. We evaluated that in the absence of crop adaptation to the new climatic conditions and without accounting for the impact of elevated CO_2 concentrations on crop yields, substantial increases in water footprint are expected to occur for maize (+3%), rice (+22%) and wheat (+50%) with an increase in 3 °C. When the impact of increasing CO_2concentrations is accounted, a decrease in water footprint is expected to be of 7.5%, 28.0% and 28.9% for maize, rice and wheat respectively (Fig. 2).

4. Discussion

Climate change has the potential to greatly affect future food security and agricultural production (Schmidhuber, 2007). While our study shows that crop water demand in the African regions targeted by large-scale land acquisitions is expected to remain relatively unchanged under a variety of climate change scenarios, numerous studies show that major crop yields will be significantly and adversely impacted by future climate change (Wiebe et al, 2015; Challinor et al., 2014; Kang et al., 2009). Therefore, even though the amount of water transpired per unit area (i.e., the CWR,

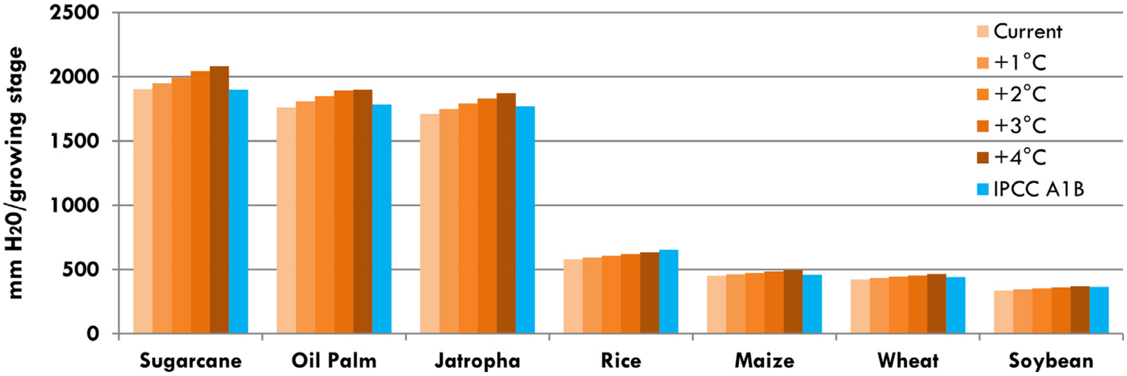


Fig. 1. Crop water requirement for main crops under increased temperature. IPCC results – which have a slight change in precipitation in addition to more elevated temperature – are included for comparison. Projections with changes in precipitation (±10%) are not shown here, as we only found a negligible impact on crop water requirements relative to current levels.

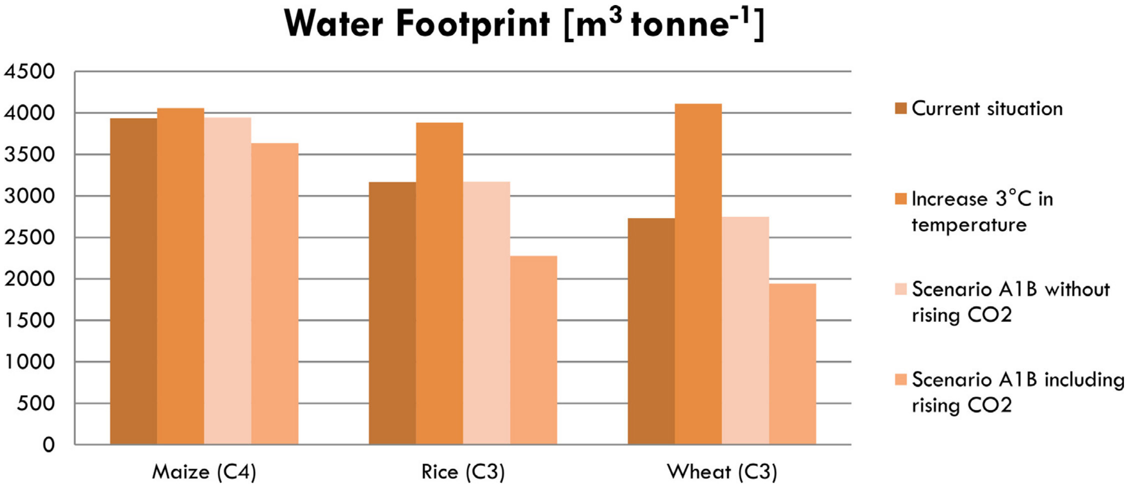


Fig. 2. Water footprint for maize, rice and wheat in the current situation, under increased in temperature and in the future A1Bscenario with and without the effect of increasing CO_2 concentrations. With increasing temperatures, the water footprint is expected to increase, which means that the same amount of irrigation water can sustain lower levels of production, while the opposite is expected as an effect of elevated CO_2 concentrations.

volume of water per unit area) will remain unchanged, the water footprints of crops (i.e., volume of water used per unit crop mass) is expected to increase. Thus, in the target countries the overall water demand for agriculture will likely increase as a result of impacted crop yields. It has been argued (Anseeuw et al., 2012; Mehta et al., 2012; Rulli et al., 2013b) that the acquisition of water resources for agriculture is likely a strong motivation for investing countries because many of the targeted nations are relatively water-rich, while some of the major investors' countries are water stressed. Indeed, of the top five countries (in terms of acquired land) from which investments originated (USA, United Arab Emirates, Great Britain, Saudi Arabia and Egypt, which account for 48% of all the land acquired in Africa), four (excl. USA) are either in arid regions where water limitations constrain crop production or have limited arable land. Because of these limited resources, the food security of these countries may be threatened by climate change. This is especially true for countries in the Middle East, where crop yields are expected to be especially affected by climate change (Wheeler and von Braun, 2013; World Bank 2010). When the impact of increasing CO_2 concentrations is accounted for, the yields of the 7 main crops are simulated to increase. Thus, a reduction in the water footprint is expected to occur, with a consequent overall decrease in water demand for agriculture.

While our study here does not establish causality for land deals being motivated by the need to cope with climate change, it furthers recent work by Davis and colleagues (2015a) which suggested that certain countries may use the global land rush as a mechanism for increasing their resilience to climate change. As noted earlier though, the crop water requirement (CWR) model used here does not capture the potential for more frequent climate extremes and increased variability in temperature and precipitation expected to occur under climate change. Increases in future crop demand for blue water may therefore be larger than estimated here (IPCC, 2012). While there is a level of uncertainty in the estimate of changes in CWR resulting from climate trends, it is apparent from this study that the crop type is a more important determinant of CWR than climate effects. For instance, the CWRs of the biofuel crops considered here were approximately three times greater than those of the main staple food crops (Fig. 1). Thus renewable energy and climate mitigation policies in investing countries can greatly influence the water demand in the acquired lands. Recent biofuel mandates in the EU (EU, 2009) and USA (EISA, 2007) have heightened demand for bio-ethanol and biodiesel, thereby further contributing to the increased demand for land in sub-Saharan Africa and Southeast Asia (Von Witze and Noleppa, 2010; Kugelman and Levenstein, 2009). This is particularly true in the case of biodiesel, the production of which strongly depends on imports (Rulli et al., 2016; Antonelli et al., 2015). More generally, by increasing the human pressure on freshwater resources in the target regions, international investments in agricultural land contribute to an increased global displacement of water use

(Carr et al., 2012, 2013). Our findings also add to recent work (Rulli et al., 2013b) that has shown how land acquisitions can greatly increase freshwater use in target countries. While we find that in most cases the potential water use of land deals would likely not induce water stress conditions in the regions affected by large-scale land acquisitions, most of targeted countries would see tremendous potential increases in blue water consumption (Table 2). Our analysis shows that almost all of the targeted countries are relatively water-rich in that the water resources domestically available are more than sufficient to meet human and environmental demands. Thus, based on the country averages (Table 2), it appears that the production of crops – especially water-intensive biofuel crops– in the acquired land can mitigate water stress in investing countries without necessarily having detrimental effects on water availability in the target areas. With that stated, the local effects on water resources and the livelihoods depending on them can be dramatic. However, these local impacts of large-scale land acquisitions and associated water appropriation cannot be captured by the country-scale analysis reported in this study. The absence of potential detrimental impacts on water resources at the country-scale is not the case however for Sudan and South Sudan. In these countries, potential blue water demand (BW) is almost half of the renewable water resources (RWR) because of their drier climatic conditions and the large total land area acquired in these two countries. Because about 60% of RWR is typically considered (Fader et al., 2013) to be inaccessible to humans (either as a result of geographic constraints or environmental demand), complete productive use of acquired lands in Sudan and South Sudan would likely encroach on "environmental flows" with negative effects on the functioning of stream and riparian ecosystems or downstream communities.

5. Conclusion

To date, most of the acquired land has not been put under production likely because of financial speculations or delays in the process of land acquisition and development. Should investors start using the land for agricultural production, it is expected that they would introduce more advanced technology (including irrigation) to sustain relatively high crop yields. Investments in irrigation increase the human pressure on freshwater resources in the target countries. Thus, water appropriation through large-scale land acquisitions likely contributes to the globalization of water and a displacement of water use, whereby crop demand in the global market acts as a distal driver of water use in the target countries.

We estimate that water appropriation associated with large-scale land acquisitions in Africa accounts for about 210 $\text{km}^3\ \text{year}^{-1}$ of water (including both blue and green water) if all the acquired areas were actively used for agricultural production. This potential increase in agricultural water demand is disproportionately contributed by biofuel crops. The impact of climate change resulted in only small increases in overall green and blue crop water requirements in the targeted areas, while CO_2 may substantially enhance crop water use efficiency. Thus, the relative importance of CO_2 fertilization, changes in precipitation patterns and increased temperature will ultimately determine whether crop water footprints in acquired lands can remain stable under climate change. Regardless, the fact that these targeted countries are rich in water resources likely makes them attractive locations for land investments and for investing countries to increase the pool of agricultural resources under their control. There is therefore an urgent need to incorporate the needs of all stakeholders, to better ensure that the potential benefits of such land deals are more equitably distributed between local communities and distant investors.

Acknowledgments

Data used in this manuscript are from the Land Matrix and FAOSTAT databases. We thank both organizations for making these data publicly available online. This work was partially supported by the U.S. National Science Foundation (NSF) Graduate Research Fellowship Program (Grant #DGE-00809128) and the National Socio-Environmental Synthesis Center (NSF Grant #DBI-1052875).

References

Anseeuw, W., Alden Wily, L., Cotula, L., Taylor, M., 2012. Land Rights and the Rush for Land: Findings of the Global Commercial Pressures on Land Research Project. ILC, Rome.

Antonelli, M., Siciliano, G., Turvani, M.E., Rulli, C., 2015. Global investments in agricultural land and the role of the EU: drivers, scope and potential impacts. Land Use Policy 47, 99–111.

Brown, L.R., 2012. Full Planet, Empty Plates: The New Geopolitics of Food Scarcity. W. W. Norton & Company, New York.

Carr, J.A., D'Odorico, P., Laio, F., Ridolfi, L., 2012. On the temporal variability of the virtual water network. Geophys. Res. Lett. 39, L06404. http://dx.doi.org/10.1029/2012GL051247.

Carr, J.A., D'Odorico, P., Laio, F., Ridolfi, L., 2013. Recent history and geography of virtual water trade. PLoS ONE 8 (2), e55825. http://dx.doi.org/10.1371/journal.pone.0055825.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Climate Change http://dx.doi.org/10.1038/nclimate2153.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations, vol. 2: appendices Value of Water Research Report Series No. 16.

Cotula, L., Vermeulen, S., Leonard, R., Keeley, J., 2009. Land grab or development opportunity? Agricultural Investment and International Land Deals in Africa. IIED/FAO/IFAD ISBN: 978-1-84369-741-1.

Davis, K.F., Rulli, M.C., D'Odorico, P., 2015. The global land rush and climate change. Earth's Future 3, 298–311. http://dx.doi.org/10.1002/2014EF000281.

Davis, K.F., Yu, K., Rulli, M.C., Pichdara, L., D'Odorico, P., 2015. Accelerated deforestation by large-scale land acquisitions in Cambodia. Nat. Geosci. 8, 772–775. http://dx.doi.org/10.1038/ngeo2540.

Davis, K.F., D'Odorico, P., Rulli, M.C., 2014. Land grabbing: a preliminary quantification of economic impacts on rural livelihood. Popul. Environ. 36, 180–192. http://dx.doi.org/10.1007/s11111-014-0215-2.

Deininger, K., Byerlee, D., Lindsay, J., Norton, A., Selod, H., Stickler, M., 2011. Rising Global Interest in Farmland, Agriculture and Rural Development. The World Bank.

D'Odorico, P., Carr, J.A., Laio, F., Ridolfi, L., Vandoni, S., 2014. Feeding humanity through global food trade. Earth's Future http://dx.doi.org/10.1002/2014EF000250.

EISA 2007, Energy Independence and Security Act of 2007, Pub L No. 110–140.

EU 2009, Directive 2009/28/EC of the European Parliament and of the Council.

Fader, M., Gerten, D., Krause, M., Lucht, W., Cramer, W., 2013. Spatial decoupling of agricultural production and consumption: quantifying dependence of countries on food imports due to domestic land and water constraints. Environ. Res. Lett. 8, 014046.

FAO, 2009. CLIMWAT 2.0 for CROPWAT. FAO, Rome (available at http://www.fao.org/nr/water/infores_databases_climwat.html).

FAO, 2012. AquaCrop Version 4.0 Reference Manual D. Raes, P. Steduto, Theodore C. Hsiao, and E. Fereres with Contributions of the AquaCrop Network FAO. Land and Water Division Rome, Italy.

FAO (2015a), AQUASTAT website, Food and Agriculture Organization of the United Nations (FAO), Website accessed on June 2015.

FAO (2015b), FAOSTAT website, FAO Statistic division, Website access on June 2015.

FAO, 2015c. AquaCrop5.0 Decision Support System. FAO, Rome (Available at http://www.fao.org/nr/water/infores_databases_AquaCrop.html).

FAO/IIASA/ISRIC/ISSCAS/JRC (2012) Harmonized World 1 Soil Database (version 1.2) (FAO, 2 IIASA 2012). Available at http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil3database/HTML/. Accessed April, 2012.

Harvey, M., Pilgrim, S., 2011. The new competition for land: food, energy, and climate change. Food Policy 36, S40–S51 Pergamon.

Hoekstra, A.Y., and P.Q. Hung (2002) Virtual water tradeAquantification of virtual water flows between nations in relation to international crop trade, IHE Delft.

IPCC, 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, p. 582. New York, NY, USA.

IWR (2015), Michigan State University, Institute for Water Research.

Kang, Y., Khan, S., Ma, X., 2009. Climate change impacts on crop yield, crop water productivity and food security. Prog. Nat. Sci. 12 (12), 1665–1674. http://dx.doi.org/10.1016/j.pnsc.2009.08.001.

Kugelman, M., Levenstein, S.L., 2009. Land Grab The Race for the World's Farmland. Woodrow Wilson International Centre for Scholars.

Land matrix, 2015. The Land Matrix Global Observatory. International Land Coalition (ILC), Centre de Coopération Internationale en Recherche Agronomique pour le Dévelopement(CIRAD), Centre for Development and Environment (CDE), German Institute of Global and Area Studies (GIGA) and Deutsche (GIZ) Web. Accessed June 2015.

Land Matrix, 2016. The Land Matrix Global Observatory. International Land Coalition (ILC), Centre de Coopération Internationale en RechercheAgronomique pour le Dévelopement(CIRAD), Centre for Development and Environment (CDE), German Institute of Global and Area Studies (GIGA) and Deutsche (GIZ) Web. Accessed March, 2016.

Mehta, L., Veldwisch, G.J., Franco, J., 2012. Introduction to the Special Issue: water grabbing? Focus on the (re)appropriation of finite water resources. Water Altern. 5 (2), 193–207.

NCAR community (2004), Community Climate System Model, version 3.0 (available at http://www.cesm.ucar.edu/models/ccsm3.0/NCAR/UCAR.). GIS data services are provided by NCAR GIS Program through Climate Change Scenarios, version 2.0, 2012. URL: http://www.gisclimatechange.org. Data June 2013.

OECD/FAO, 2014. Agricultural Outlook 2014–2023: Biofuels. OECD-FAO, Rome.

Rezitis, A.N., Sassi, M., 2013. Commodity food prices: review and empirics. Econ. Res. Int. 2013, 15 http://dx.doi.org/10.1155/2013/694507 Article ID 694507.

Rulli, M.C., D'Odorico, P., 2013a. The water footprint of land grabbing. Geophys. Res. Lett. 40, 1–6.

Rulli, M.C., Saviori, A., D'Odorico, P., 2013b. Global land and water grabbing. Proc. Natl. Acad. Sci. U.S.A. http://dx.doi.org/10.1073/pnas.1213163110.

Rulli, M.C., D'Odorico, P., 2014. Food appropriation through large scale land acquisitions. Environ. Res. Lett. 9, 064030.

Rulli, M.C., D. Bellomi, A. Cazzoli, G. De Carolis, P. D'Odorico (2016), The water-land-food nexus on first generation biofuel, doi 10.1038/srep22521.

Schmidhuber, J., Tubiello, F.N., 2007. Global food security under climate change. Proc. Natl. Acad. Sci. U.S.A. 104 (50), 19703–19708. http://dx.doi.org/10.1073/pnas.0701976104.

Von Witze, H., S. Noleppa (2010), EU agricultural production and trade: can more efficiency prevent increasing land grabbing outside Europe?

Watanabe, S., Kanae, S., Seto, S., Yeh, P.J.-F., Hirabayashi, Y., Oki, T., 2012. Intercomparison of bias-correction methods for monthly temperature and precipitation simulated by multiple climate models. J. Geogr. Resour. http://dx.doi.org/10.1029/2012JD018192.

Wheeler, T., von Braun, J., 2013. Climate change impacts on global food security. Science 341, 508–513. http://dx.doi.org/10.1126/science.1239402.

Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., van der Mensbrugghe, D., Biewald, A., Bodirsky, B., Islam, S., Kavallari, A., Mason-D'Croz, D., 2015. Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. Environ. Res. Lett. 10, 085010.

World Bank, 2010. World Bank Development Report 2010: Development and Climate Change. World Bank, Washington, DC 2010.

Zoomers, A., E. Quak (2013), Untangling the myth of the global land rush. Land Grabbing threatens food security and increase inequality.