Green and blue water demand from large-scale land acquisitions in Africa

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In the last decade, more than 22 million ha of land have been contracted to large-scale land acquisitions in Africa, leading to increased pressures, competition, and conflicts over freshwater resources. Currently, 3% of contracted land is in production, for which we model site-specific water demands to indicate where freshwater appropriation might pose high socioenvironmental challenges. We use the dynamic global vegetation model Lund–Potsdam–Jena managed Land to simulate green (precipitation stored in soils and consumed by plants through evapotranspiration) and blue (extracted from rivers, lakes, aquifers, and dams) water demand and crop yields for seven irrigation scenarios, and compare these data with two baseline scenarios of staple crops representing previous water demand. We find that most land acquisitions are planted with crops that demand large volumes of water (>9,000 $m^3 \cdot ha^{-1}$) like sugarcane, jatropha, and eucalyptus, and that staple crops have lower water requirements (<7,000 $m^3 \cdot ha^{-1}$). Blue water demand varies with irrigation system, crop choice, and climate. Even if the most efficient irrigation systems were implemented, 18% of the land acquisitions, totaling 91,000 ha, would still require more than 50% of water from blue water sources. These hotspots indicate areas at risk for transgressing regional constraints for freshwater use as a result of overconsumption of blue water, where socioenvironmental systems might face increased conflicts and tensions over water resources.

land grabbing | water scarcity | LPJmL | water footprints | irrigation

Increased Competition Over Freshwater Resources

Freshwater is becoming increasingly scarce in many regions of the world, a result of both unsustainable land management and changes in rainfall patterns as a consequence of global and regional climate change (1). Moreover, the demand for water is increasing because of population growth, higher food demand, and changing dietary preferences, as well as increased industrialization and urbanization. Water, food, and energy are closely linked, and fundamental for human well-being, poverty alleviation, and sustainable development (2). As demand for water, food, and energy increases, there is an increased competition for water resources between agriculture, livestock, fisheries, forestry, energy, and other sectors, with unpredictable impacts for livelihoods and the environment.

Globally, agriculture is the most water-consuming sector, responsible for 70% of global freshwater withdrawals and more than 90% of consumptive water use (3). Agriculture's freshwater use is causing severe environmental degradation in many parts of the world (4). This in turn affects local ecosystems and people, especially in countries where the population directly depends on the surrounding environment for their livelihoods. For example, Lake Chad has shrunk by 95% since 1963 as a result of large-scale irrigation projects in Chad, Nigeria, Niger, and Cameroon together with climatic changes (4). This is just one example of how large-scale irrigation has contributed to local water scarcity, and in turn harmed societies and ecosystems.

Large-scale conversion of land to agriculture to provide food, fiber, and energy needs to balance trade-offs between agricultural production, and other societal and ecosystem needs (5). It is important to weigh the benefits of increasing yields through irrigation with the consequences those water extractions might have on local and regional scales. The cumulative effect of local land-use changes also have regional to global consequences, to the degree that regional boundaries of freshwater use are transgressed, thereby increasing the risk for abrupt and irreversible environmental change (6), potentially creating new challenges for food, fiber, and energy supplies.

Green and Blue Water in Agricultural Production

Water embedded in agricultural production can be divided into site-specific precipitation stored in soils and consumed by plants through evapotranspiration (green) and surface and ground water in aquifers, rivers, lakes, and dams that can be extracted from renewable and nonrenewable sources for irrigation (blue) (7). Blue water is sometimes diverted from nonlocal sources to enable agricultural production (8). The volume of blue water required by agricultural systems differs, depending on crops planted, agricultural management, and water lost through evaporation from the water source to the field. The green and blue water concept can help estimate site-specific water demand of agriculture, and refine our understanding of human impacts on freshwater resources. Distinguishing between blue and green water indicates the volume of freshwater needed to meet human demands in addition to what is available through precipitation. These blue water extractions in turn might pose increased competition or conflicts between other water-using sectors.

Significance

Freshwater appropriation can have vast impacts, depending on management and scale of water use. Since 2000, foreign investors have contracted an area the size of the United Kingdom in Africa, leading to increased pressure on water resources. Here we couple site-specific water demand for the crops planted there to the efficiency of different irrigation systems, while relating these estimates to local water availability. This approach enables us to identify "hotspot" areas of freshwater use where crops demand more water from irrigation than can be supplied by soil moisture, where the potential water demands from large-scale land acquisitions pose a risk for increased competition over water resources. Of these land acquisitions, 18% would be hotspots even with the most efficient irrigation system implemented.

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Large-Scale Land Acquisitions and Freshwater Appropriation

Large-scale land acquisitions are areas larger than 200 ha contracted for commercial agriculture, for the purpose of timber extraction, carbon trading, food, feed, and renewable energy production (9). In 2014 the land-monitoring initiative Land Matrix had registered about 47 million ha of land contracted globally since 2000 under such large-scale land acquisitions. All deals in the database have at least one transnational investor from the public or private sector (including individuals, companies, investment funds, and state agencies), and may also include one or more domestic investors. These investors are currently key players in the modernization of African agriculture, and imply a conversion from smallholder production or community use to a commercial use of land and water (10).

The reasons for the rush for land are many, but were partly triggered by the food and energy crisis of 2007–2008 (11). Globalization, market liberalization, and commodification of land and natural resources in combination with the support of international donors have facilitated the implementation of these land contracts (11). Governments in the targeted countries may see foreign investments in land as an opportunity for agricultural modernization (10), as investors often motivate and legitimize their business proposals with rural and national development goals, typically including improved infrastructure, technological transfer, job opportunities, and financial benefits. However, research and nongovernmental organization reports (12–14) point out that large-scale land acquisitions rarely benefit local people, and that the proposed infrastructure is often not developed on the local scale.

Africa is the continent where most land has been contracted (about 22 million ha) because of cheap land and labor costs (15), but also has the potential to boost yields and reduce yield gaps with modern agricultural techniques and irrigation systems (16). However, many of these land deals have been abandoned or are not yet in production (17), and only about 3% of the contracted deals (0.7 million ha) are currently in production (Dataset S1). These numbers are constantly changing, as land acquisitions are expanding, abandoned, or were never implemented. An example of this is the belief that Chinese investors are major actors acquiring large tracts of land in Africa, which has recently been shown to be on a smaller scale than first reported (18).

The rush for water might be just as important for investors as the rush for land (10, 19, 20). Land contracts rarely indicate any limits to water use, which means that investors might choose inexpensive and inefficient irrigation for their operations. The lack of water regulations thereby increases the risk of unsustainable water use, which in turn has the potential to alter the availability and accessibility for local communities, ecosystems, and other water-intensive sectors.

Human appropriation of freshwater can have vast impacts depending on the management and scale of water use (21), highlighting the importance to estimate the growing water demand associated with land transformations in Africa. No study has yet connected the site-specific water demand to water-use efficiencies of different irrigation systems. This connection is vital because it can indicate areas that might experience increased water stress or conflicts over water resources. The objectives for our study, therefore, are: (*i*) to estimate and identify site-specific green and net blue water demand of crops grown on acquired land in production; (*ii*) to calculate yields, as well as green and gross blue water demand, for crops grown on acquired land under seven irrigation scenarios, and for staple crops as a baseline; and (*iii*) to develop a Blue Water Index (BWI) to identify hotspot areas of increased competition for freshwater resources where demand for blue water exceeds green water supply.

We note that previous continental- to global-scale studies of land acquisitions have met serious critique for issues with data selection biases and quality of data sources, therefore producing results of questionable accuracy (22, 23). One notable example found that 310 $\mathrm{km^3 \cdot y^{-1}}$ of green water and 140 $\mathrm{km^3 \cdot y^{-1}}$ of blue water are appropriated globally for crop and livestock production (24). However, this study included contracted global land deals, which likely overestimate the water use on acquired land because few projects are currently in production.

As a response to these critiques, and to meet our objectives, we focus on land deals in production. We model green and blue crop water demand with the dynamic agro-ecosystem and hydrology model Lund–Potsdam–Jena managed Land (LPJmL), and provide a clarification of model assumptions and parameterization for the given crops planted. The model output includes: (*i*) green water demand met by rainfall; (*ii*) net blue water demand that plants need to grow, in addition to rainfall; and (*iii*) gross blue water demand that has to be extracted to fulfill plant requirements, accounting for losses between the water source and the field. Water losses depend on the efficiency of irrigation and their distribution systems (see description in Table 1). Finally, we validate the data by cross-referencing the 54 largest land deals in Google Earth, responsible for 95% of acquired land area in production (*SI Materials and Methods*). Because there is a lack of information about water management of acquired land, we model seven different irrigation systems to obtain a full range of plausible water-use efficiency scenarios.

Table 1. The seven different irrigation scenarios that were run with LPJmL for crops planted on large-scale land acquisitions in Africa

Irrigation scenario	Description
Rainfed	Rainfed agriculture (modeled for crops currently in production on acquired land, and for the staple crop baseline)
Drip (pipelines)	Micro (drip) irrigation with pressurized pipelines for distribution
Sprinkler (pipelines)	Irrigation with sprinklers supplied by pressurized pipes
Mixed	Irrigation with a mix of surface and sprinkler irrigation systems with both open canals and pressurized pipes
One-step improvement	Irrigation and distribution systems that are one step higher in efficiency than current national irrigation efficiencies (e.g., moving from sprinkler to drip systems).
Current irrigation efficiencies	Irrigation under current national irrigation and distribution systems in every country (39) (modeled for crops currently in production on acquired land, and for the staple crop baseline)
Surface (open canals)	Surface irrigation systems (flooding) with water diverted from open canals

Scenarios are presented from most (top) to least (bottom) efficient, based on gross blue water use. The current irrigation efficiency, and therefore also the one-step improvement, varies by country.

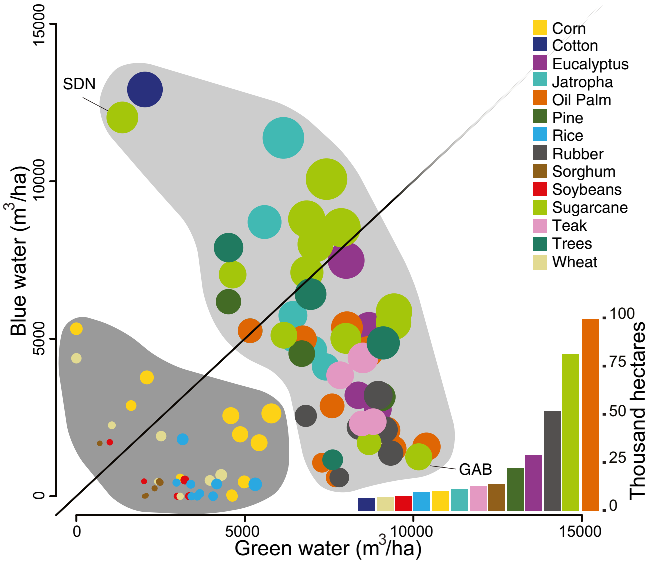

Fig. 1. Average green, net blue, and total water demand (m^3·ha^{-1}) of crops grown on 95% of acquired land currently in production in Africa. The water demand has been averaged to the national level for each crop, the bubbles are scaled to total water demand, and cases mentioned in the main text are labeled with ISO3 country codes (Table S1; for all labels see Fig. S1). The diagonal line indicates where green and blue water demands are equal. Crops are grouped into zones of higher (light gray) and lower (dark gray) water demand. The area of acquired land per crop is shown in the lower right corner, and the largest group "trees" (301,000 ha) has been excluded from the bar chart to see the differences between the other crops.

Results

Land Acquisitions in Africa for Water-Intense Crop Production. More than 60% of the acquired land in production (>418,000 ha) is for forestry purposes (Fig. 1). Most tree species are not specified, but rubber, eucalyptus, pine, and teak are commonly grown for timber or pulp and, in some cases, carbon sequestration (Fig. 1). The next largest crop group is flexible crops, covering 244,000 ha (35% of acquired land). Flexible crops can be used for food, feed, or biofuel; here, these include sugarcane, oil palm, soybean, maize, wheat, sorghum, and cotton. The remaining 5% are acquired for food and beverage crops (tea, coffee, fruits, vegetables), biofuel crops (jatropha), feed, and flowers (Dataset S1).

Our results from LPJmL show that some crops require more water than others (Table S2), but also that the same crop varies in water demand depending on temperature and rainfall. It is possible to distinguish between two crop groups, one with lower water demand (sorghum, soybean, wheat, maize, rice) and one with higher water demand (cotton, eucalyptus, jatropha, oil palm, pine, rubber, sugarcane, teak, trees) (Fig. 1). Within each group, there is a large variation in the amount of green and blue water required to meet the total water demand. For example, sugarcane in the Sudan (green bubble in upper left corner of Fig. 1) has an average net water demand of 13,390 m^3·ha^{-1} (bubble size) of which 90% is blue water and 10% is green, whereas in Gabon the average net water demand is 15% lower, of which 11% is required from blue water sources and 89% supplied from green water (green bubble in the lower right corner of Fig. 1).

Scenarios for Green and Blue Water Demand and Crop Yields. Simulating water demand with LPJmL enables us to compute water demand of land deals for different irrigation scenarios. Irrigating all land acquisitions has the potential to almost double yields for the crops planted on acquired land (from 17 to 28 megatons) compared with purely rainfed management (Fig. 2 and Table S3). However, this would come at the cost of blue water extractions, which in turn require infrastructure for freshwater appropriation from either local or distant water sources, causing negative impacts on freshwater systems. Total water demand for land acquisitions in production ranges between 5.4 (rainfed) and 8.5 km^3·y^{-1}, depending on the water use efficiency of the irrigation system (Fig. 2). If all land acquisitions were irrigated with the most efficient system (drip irrigation with pressurized pipes), the annual gross blue water use would be 2.1 km^3·y^{-1}, compared with 3.5 km^3·y^{-1} if the least-efficient irrigation system (surface irrigation with open canals) were used, leading to a water efficiency improvement of up to 40%.

Producing maximum crop yield (Fig. 2) requires less water for all irrigated cases, ranging from 255 m^3 of water per ton of crop yield for drip irrigation, to 300 m^3·ton^{-1} for open canal surface irrigation, compared with 315 m^3·ton^{-1} for rainfed agriculture (Fig. 2 and Table S3). This means that establishing irrigated agriculture in areas of production would demand more water in total, but require less water per unit of production compared with the rainfed case.

To estimate the added pressure on water resources by land acquisitions compared with previous land use, we provide a baseline of water demand for five staple crops widely grown under small-scale farming systems in the affected countries: maize, wheat, rice, sorghum, and cassava (Dataset S2). We model the most common staple crops grown in that country, at the location of the acquired land, using both rainfed and national irrigation efficiency scenarios for the year 2000. The water requirements for staple crops varies between 2,500 and 14,500 m^3·ha^{-1} (average 5,500 m^3·ha^{-1}), summing up to a total green water use of 3.3 km^3·y^{-1} under rainfed conditions, with an additional 0.5 km^3 of blue water if the staple crops were irrigated with national irrigation efficiencies (Table S3). This finding suggests that green and blue water use is 39% and 76–86% greater, respectively, for crops grown on acquired land compared with the baseline of common staple crops, showing that land acquisitions substantially increase water demands.

Mapping Blue Water Use Hotspots with the BWI. To assess what areas might face increased water scarcity as a result of land acquisitions, we relate crop water demand to the water supply of the specific area in production by calculating the ratio between the gross blue water demand to the total (green + gross blue water) water demand for these crops. We call this the Blue Water Index, which indicates the fraction of water added from irrigation needed to generate maximum yields. An index of 1 indicates that all crop water comes from irrigation, whereas an index of 0 indicates that precipitation is sufficient to achieve maximum yields. The BWI helps identify those land acquisitions that might have large impacts on freshwater availability.

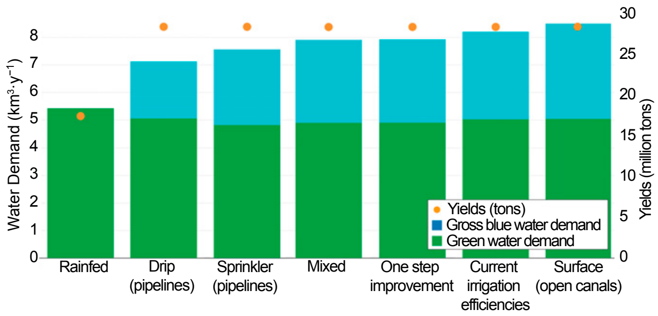

Fig. 2. Total yields for current crops (tons, orange dots, *Right* axis) and green and gross blue water demand (km^3·y^{-1}, *Left* axis) for 121 large-scale land acquisitions in production in Africa for seven irrigation scenarios (Table 1). Local estimates for each deal have been aggregated to a continental scale for each irrigation scenario shown in increasing efficiency. In all cases, irrigation nearly doubles crop production from the rainfed scenario, but at the cost of 2.1–3.5 km^{-3} of blue water per year, a variation within irrigation systems of 40%.

For all irrigation scenarios, land acquisitions in production with a BWI lower than 0.5 (less than 50% of water demand from blue water sources) are distributed in tropical and temperate climate zones of sub-Saharan Africa (Fig. 3 and Dataset S3), whereas land acquisitions with a BWI above 0.5 (more than 50% of water demand from blue water sources) are scattered throughout all climate zones from dry to tropical (Fig. 3).

These blue water hotspots are mapped in Fig. 4, which shows the effect of irrigation system on blue water use. Under current national irrigation efficiencies, 35% of all land deals in production would be hotspots (Dataset S3), with 33 land deals using 50–75% blue water and 9 using >75%. The remaining 46 deals using 25–50% blue water and 33 deals using <25% (Dataset S3) may still stress local water systems. If more efficient sprinkler or drip irrigation were applied, hotspot areas would drop to 22% and 18% of total deals in production, respectively (red and yellow dots in Fig. 4). Even under the most efficient drip irrigation system, there will still be 22 land acquisitions where more than 50% of water would be drawn from blue water sources to meet demand, most in Central and Eastern Africa (red dots in Fig. 4).

Discussion

Water Intense Crop Production of African Land Acquisitions. As shown in this study, most acquired land in production is for forestry and flexible crop production for crops with high water demand (e.g., sugarcane, jatropha, trees, and eucalyptus). It is relevant to consider site-specific green and blue water demands of individual land acquisitions to identify land deals that might induce water stress, and cause water-related conflicts between different water users. Blue water demand depends on crop choice and location. From a water-efficiency perspective, for example, it is better to grow sugarcane in the Congo than in the Central African Republic, but in the context of food security it might be better to develop the land for food crops that require less water, like maize, rice, sorghum, and wheat (shown in the light gray zone in Fig. 2). However, in reality, low water demand is not the primary driver of crop choice, but rather local to global demand, market prices, and nutrient calorie content play more dominant roles in deciding crop production (25).

Scenarios for Green and Blue Water Demand. Green water demand from crops now planted on acquired land (5.4 $km^3 \cdot y^{-1}$) is substantially higher than it would be for traditional staple crops (3.3 $km^3 \cdot y^{-1}$). It is important to consider the scale of production when calculating blue water use, and to assess how blue water demands differ depending on the irrigation system implemented. Irrigating all crops currently in production for land acquisitions on a continental scale would require 2.1–3.5 km^3 of blue water per year in addition to what is supplied naturally from rainfall. By adding this amount of blue water, it is possible to maximize and almost double yields compared with rainfed agriculture. It is reasonable to assume that investors irrigate acquired land because they want to guarantee high agricultural productivity and reduce the risk of crop failure because of erratic rainfall (10). Land acquisitions in semiarid regions are, however, more likely to be irrigated than in tropical regions, as a result of crop type and relative availability of green water. Note that this is accounted for in LPJmL, as blue water requirements are only added if needed to avoid soil water deficit.

Improving water-use efficiency, while also considering the purpose of production (food, feed, or fuel) and the location of consumption, is essential for developing more sustainable agricultural systems. Efficiently irrigated agriculture contributes to increased yields and also allows allocation of water to other sectors, like sanitation and health, but for already water-scarce regions, the additional extraction of blue water might be substantial even if the most efficient irrigation system is implemented. If water is available and free of charge, investors will probably prefer cheap and inefficient irrigation systems, such as surface irrigation ($600–800/ha) or sprinklers ($3,000–5,000/ha) rather than expensive but efficient drip irrigation systems ($10,000/ha) (26). In reality, the irrigation scenarios are linked to factors like economic costs, labor

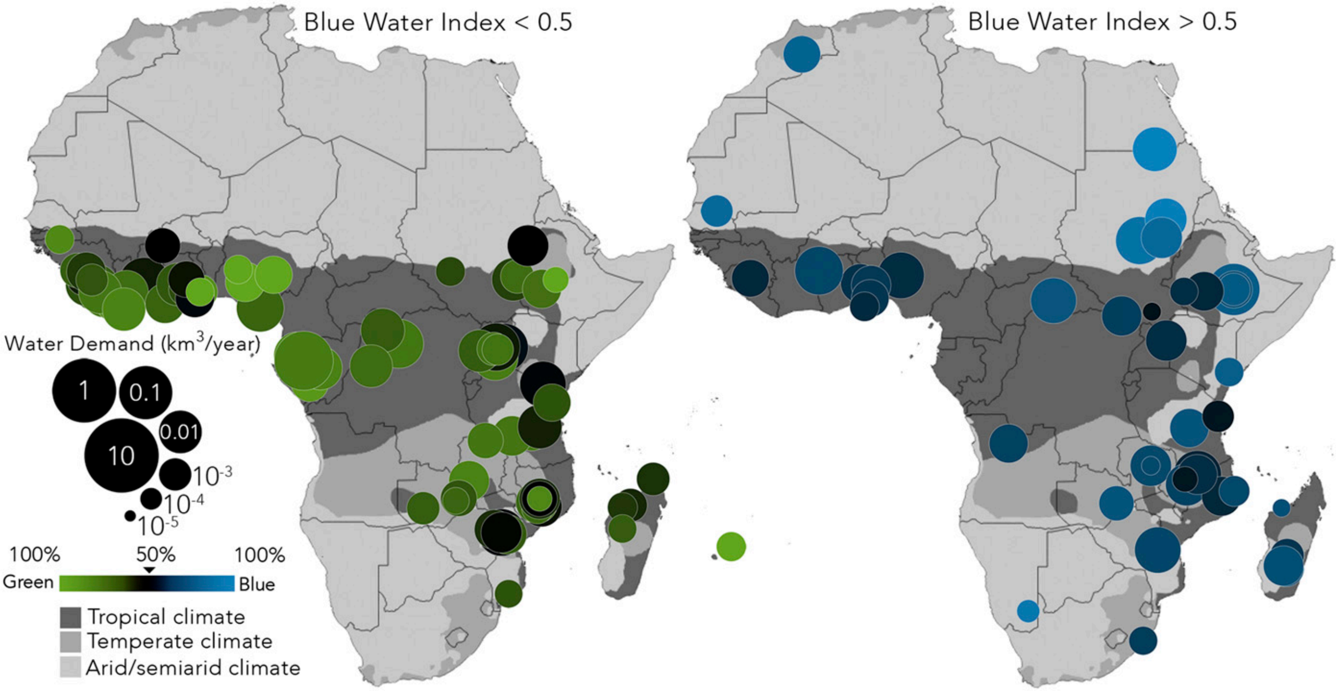

Fig. 3. Individual land acquisitions with a BWI less than 50% (*Left*, 79 land deals now in production where the majority of water demand is met by precipitation), and land acquisitions with a BWI greater than 50% (*Right*, 42 land deals where the majority of water demand would be extracted from irrigation). The BWI in this figure is based on the current national irrigation efficiency scenario (39) for crops grown there.

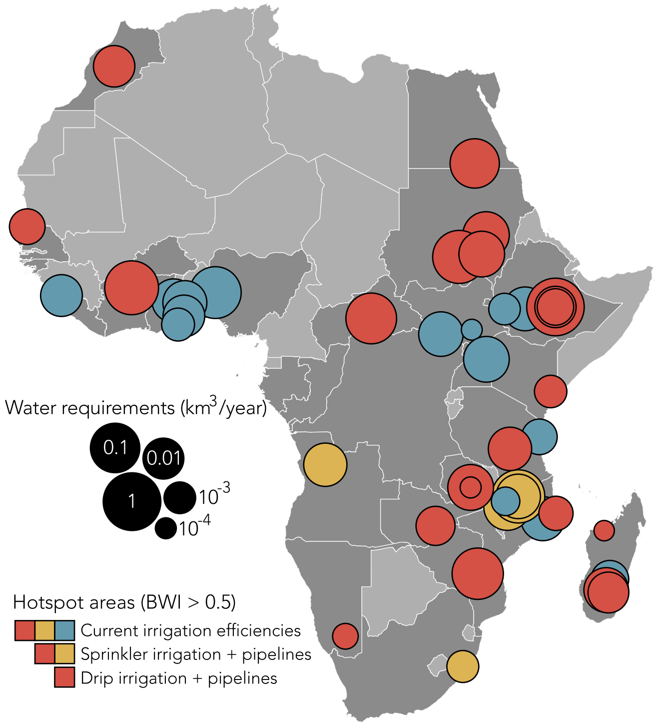

Fig. 4. "Hotspot" land acquisitions in production (countries in dark gray) where blue water use is more than 50% of crop demand across three different irrigation scenarios: drip irrigation (red, 22 locations), sprinkler irrigation (yellow, an additional 5 locations beyond the drip irrigation locations), and current irrigation efficiencies (blue, an additional 15 locations beyond the drip and sprinkler locations). The size of the circles indicates the total water demand (green + gross blue). These land deals have been highlighted to identify hotspot areas that might experience increased competition between sectors over freshwater resources.

intensities, water rights, and governance. However, these factors could not be considered in the present biophysical framework, where our goal was to bracket the range in water use given a variety of irrigation scenarios.

Blue Water-Use Hotspots. The BWI was developed to delineate hotspot areas of blue water demand, and to indicate areas where increased freshwater use potentially creates tensions and conflicts between different water users. We find that 22% of land acquisitions in production (for the sprinkler irrigation scenario) require more than 50% of their water from blue water sources. Land acquisitions with a BWI above 0.5 are scattered over all climate zones, from dry to tropical, which indicates that it is not only the lack of rainfall that gives rise to water-scarcity hotspots, but also crop choice and scale of production. For example, both West Africa and Madagascar are tropical zones where there are land deals with both high and low BWI.

Beyond Water. Just because a crop planted on acquired land is suitable to grow in that area does not mean that the area is suitable for large-scale agriculture. There are several other risks to be considered, including biodiversity loss from land conversion, and loss of land-rights for people who are engaged in small-scale farming (among others). For example, Central Africa has the second-largest rainforest in the world and is rich in biodiversity (27). Until recently, forests there have remained largely intact because of low demographic pressure and limited accessibility (28), but deforestation has increased in recent years as a result of the rush for farmland (29). Consequently, large areas of forests and people's access to land are threatened (30).

Many investors claim to stimulate local and national development, thereby reducing rural poverty and food insecurity (11, 25); however, optimizing yields for timber or biofuel crops for export might not be the most suitable option to do so (31). Even though socioeconomic benefits in terms of infrastructure and employment might contribute to food security on the local scale (25), case studies have found that this has not been realized on the ground (32, 33). Therefore, there is a need to further examine local implications for rural societies and ecosystems, and whether the crop production is of benefit to the national or local population. This approach would shed light on the trade-offs between the purpose of production and increased yields at the cost of ecosystem health (e.g., water pollution, reduction of wildlife, and deforestation), as well as local to national socioeconomic trade-offs regarding infrastructure development and employment.

Data Limitations and Key Assumptions. There are several data limitations for the land deals themselves, as well as current water management in the study area. Although Land Matrix is the most extensive dataset currently available, it is continuously being updated as a result of the rapidly changing nature of the land deals, highlighting issues of uncertainty (34, 35). Nevertheless, these data are suitable for showing general trends and patterns.

Additionally, there is a lack of information about water management for current land deals, which is why we modeled different irrigation scenarios. To refine this measure, there is a need for additional research on the types of irrigation systems that are implemented, the source of blue water, as well as on how the water is diverted to the irrigation system. It is also a challenge to estimate the added pressure on freshwater use by land acquisitions, because there is a lack of data about previous land use. This is a research gap that needs to be filled to assess changes in water use with greater confidence.

This study is an estimate of how much water the plantations on acquired land might require for different types of irrigation systems. We assume (using LPJmL) that irrigation requirements can always be met. This assumption is reasonable, given the additional assumption that investors are likely to assess the availability of water (and potential for profit) associated with leasing or purchasing land. It is worth noting that the aggregate figures of land and water use from land acquisitions are likely to be an underestimate because of the conservative assumptions made in this analysis.

Finally, crops that are not specifically parameterized in LPJmL were modeled as crops with similar behavior (*SI Materials and Methods*). The class "managed grasslands" was used as a proxy for 21 crops covering 31% of acquired land (Table S4). Although uncertainties introduced by this procedure may be low for crops like alfalfa, uncertainties will be higher for tree crops. Consequently, estimates for water use and crop production should be treated with care for these crops. Future model development should focus on parameterizing the most widespread crops not currently in LPJmL: oil palm (14.3% of planted area) and rubber (7.5% of planted area).

Conclusions

Our study quantifies water demand of land acquisitions in Africa as a function of crop choice, local climate, and irrigation scenarios. As such, it advances the field by detailing the implications of crop choice and irrigation techniques on water demand. It also highlights areas that might experience conflicts and tensions over freshwater use between sectors, especially hotspots using more than 50% blue water for crop production.

We show that there is potential to boost yields through irrigation, but that blue water demand varies with irrigation system (because of water use efficiencies). Even if the most efficient irrigation system is used for land acquisitions in production, 18% would require more than 50% of water from blue water sources. If land acquisitions are to benefit local communities, investors need to re-evaluate the purpose of production together with local decision makers and communities while also considering crop water demand to minimize negative trade-offs between water users and ecosystems.

Materials and Methods

Data on Land Acquisitions. We used the collection of large-scale (>200 ha) land deals from Land Matrix (Retrieved in July 2014; www.landmatrix.org/en/). The Land Matrix database contained a total of 1,795 land-deals with an emphasis on food, fuel, and forestry crops. Of these, 747 deals were contracted in Africa, of which 121 were currently in production (Dataset S1). The dataset has geographical coordinates for each specific deal. We cross-referenced the Land Matrix data by observing the 54 largest land acquisitions in Google Earth, representing 95% of acquired land area (Fig. S2).

Simulation of Agricultural Production and Water Demand with LPJmL. There is no information about the irrigation systems the investors use in the existing datasets, prompting the use of the LPJmL (36, 37) to estimate the green and blue water demand for seven different irrigation scenarios, at the site-specific locations given by land-deal coordinates. All scenarios include simulations of vegetation growth, phenology, and agricultural yield (*SI Materials and Methods*).

For LPJmL simulations, we assume that deals are managed intensively; that is, efficient pest and disease control, high-yielding varieties, mechanization, homogenous fields, and no nutrient limitations (see ref. 38 for details on the management parameters). Second, we assume that irrigation water is always available in the irrigated scenarios, if not locally, then by developing water infrastructure that would divert water from local or nonlocal sources. Finally, many crops that are grown on acquired land in Africa were not specifically parameterized. Instead, they were simulated by using a proxy crop with similar characteristics (*SI Materials and Methods*).

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