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Limits to the world’s green water resources for food, feed, fiber, timber, and bioenergy

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Green water—rainfall over land that eventually flows back to the atmosphere as evapotranspiration—is the main source of water to produce food, feed, fiber, timber, and bioenergy. To understand how freshwater scarcity constrains production of these goods, we need to consider limits to green water availability. Here we expand the debate on water scarcity by considering green water scarcity (WSg). At 5 × 5 arc-minute spatial resolution, we quantify WSg and the maximum sustainable level to this footprint (WFg,m), while accounting for green water requirements to support biodiversity. We then estimate WSg per country as the ratio of the national aggregate WFg to the national aggregate WFg,m. We find that globally WFg,m amounts to 56% of WFg,m and overshoots it in several places, for example in countries in Europe, Central America, the Middle East, and South Asia. The sustainably available green water flows in these countries are mostly or fully allocated to human activities (predominately agriculture and forestry), occasionally at the cost of green water flows earmarked for nature. By ignoring limits to the growing human WFg, we risk further loss of ecosystem values that depend on the remaining untouched green water flows. We emphasize that green water is a critical and limited resource that should explicitly be part of any assessment of water scarcity, food security, or bioenergy potential.

Significance

Precipitation over land partitions into runoff via surface water and groundwater (blue water) and evapotranspiration (green water). We expand the traditional debate on water scarcity, which solely focuses on blue water, by assessing green water scarcity. The current debate on water scarcity is heavily skewed, since it leaves unnoticed the bulk of water availability—which is green—and the bulk of water use—which is also green. Green water is the main source of water to produce food, feed, fiber, timber, and bioenergy. Thus, to understand how freshwater scarcity constrains the production of these vital goods, explicating and including (limits to) green water use is imperative.

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*Blue water can be withdrawn from groundwater or surface water to be added to the green water in the soil by means of irrigation. The resulting evapotranspiration (ET) will then have a green component (ETg) as well as a blue component (ETb). In this paper we refer to the ET of green water (ETg).

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The quantification of green water availability and use: by excluding ET from nonagricultural lands they underrepresent green water availability (5) and by excluding the forestry sector they underrepresent green water use (18).

The objective of this study is to quantify the degree of human appropriation of the world’s limited green water flow. We answer three questions: What is the appropriation of green water by the human economy, specified geographically? What are the geographically explicit limits to the human appropriation of green water? Where are these limits approached or exceeded?

Regarding the first question, we estimate the human appropriation of green water flows as the sum of the green water footprints (WFg) of crop production, livestock grazing, wood production, and urban areas at a 5 × 5 arc-minute grid cell spatial resolution. By doing so, we provide a more comprehensive, spatially explicit estimate of the WFg of humanity than was previously shown by Hoekstra and Mekonnen (8) (which included crop production only).

Regarding the second question, the limits to the WFg are estimated at 5 × 5 arc-minute resolution by quantifying the maximum sustainable WFg (WFg,m) as the total available green water flow minus the green water flow to be reserved for nature (22). In estimating WFg,m, we consider agroecological suitability and accessibility of land, biophysical constraints to intensifying land use, and biodiversity conservation needs. For the latter, we subtract the green water flow from land needed to support biodiversity, using a spatially explicit map of biodiversity conservation areas to achieve the Aichi Biodiversity Target (ABT) 11—which entails expanding the protected area network to at least 17% of the terrestrial world by 2020 (www.cbd.int/sp/targets)—with maximum conservation outcome (26). In doing so, we innovate upon ecological footprint studies, which do not account for conservation needs in the assessment of “biocapacity” (27, 28).

Regarding the third question, we present the global allocation of the green water flow to human activities versus ecosystem services and show the degree of human appropriation and overshoot of the WFg,m on the level of 5 × 5 arc-minute grid cells. Next, we assess green water scarcity (WSg) per country—in a complementary way to common blue water scarcity indicators—as the ratio of the national aggregate WFg to the national aggregate WFg,m, which reflects the degree to which the sustainably available green water flow in a country has already been allocated to human activities. In doing so, we make a contribution to the incorporation of green water in water scarcity assessments.

**Results**

**Human Appropriation and Overshoot of the Limited Green Water Flow.** Fig. 1 shows the allocation of the limited green water flow to human activities and ecosystem services. About 22% of the global green water flow is from land that is set aside for nature so as to effectively achieve ABT 11, while 17% is from nonutilizable lands that are too cold for cropping or grazing, have too steep terrain slopes, or are far from human settlement and infrastructure. The green water flow from the remaining utilizable land (62%) is in part allocated to human activities and in part to ecosystem services like habitat, climate regulation, erosion control, and others (see refs. 29 and 30 for the full list of ecosystem services and descriptions).

The WFg reflects the human appropriation of the green water flow and is made up of 5.7 × 10³ km³ y⁻¹ for crop production (58%), 2.9 × 10³ km³ y⁻¹ for livestock grazing (30%), 0.9 × 10³ km³ y⁻¹ for wood production (9%), and 0.3 × 10³ km³ y⁻¹ for urban areas (3%). A spatially explicit map of the WFg of humanity is included in SI Appendix, Fig. S1.

The WFg,m is estimated at 18 × 10³ km³ y⁻¹. Comparing the global sum of WFg to the global sum of WFg,m, we find that 56%...
the world’s sustainably available green water flow has already been allocated to human activities.

Although on a global level 56% of the sustainably available green flow has been appropriated for human use, locally the ratio ofWFₜ toWFₜₐₐₜ can be much higher or lower (Fig. 2). In places on the map occurring in the darker shades of gray,WFₜ is close toWFₜₐₐₜ, meaning that nearly all of the sustainable available green water flow has been allocated to human use. In places showing lighter shades of gray,WFₜ is still belowWFₜₐₐₜ (Australia, Africa, Canada, Scandinavia, North Eurasia), indicating possibilities to locally increaseWFₜ if local trade-offs with loss in ecosystem service values are deemed acceptable (Discussion).

Furthermore, we find that 18% of the totalWFₜ overshootsWFₚₐₜ by being located in biodiversity conservation areas to effectively achieve the ABT 11 (i.e., the red areas in Fig. 2). Overshoot ofWFₜ (1.8 × 10⁵ km³ y⁻¹ globally) is mainly related to overshoot of theWFₜ of crop production (51%) and grazing (35%), followed by wood production (11%) and urban areas (3%). Over half the overshoot occurs in just 10 countries: United States (8.6%), Brazil (6.9%), Indonesia (6.4%), India (5.2%), China (5.0%), Colombia (4.9%), Philippines (4.4%), Mexico (4.0%), Germany (3.1%), and Malaysia (2.5%).

**WSₕ of Nations.** To assess WSₕ per country, we calculate the ratio of the national aggregateWFₜₐₐₜ to the national aggregateWFₚₐₜ (Fig. 3). WSₕ expresses the degree to which the sustainably available green water flow has already been allocated to human activities. Countries in whichWFₜ closely approaches or exceedsWFₚₐₜ—i.e., where WSₕ is close to or beyond 1—are predominantly found in Europe, Central America, the Middle East, and South Asia (Fig. 3). These include countries known for ample rainfall—and consequently a large green water flow, such as the United Kingdom, Germany, Indonesia, and New Zealand—where presence of WSₕ may sound counterintuitive. However, we show that the sustainably available green water...
flow in these countries is limited and mostly or fully allocated to human activities, with even green water flows to be reserved for nature being appropriated already (mainly for agriculture).

Discussion
The world’s limited green water flow is shared by humans and nature. We have made its allocation explicit and provide an attempt to quantify WS$_g$ as the ratio of actual to maximum sustainable WF$_g$. The value of our assessment lies in raising awareness for the fact that there are limits to the human WF$_g$. We show where these limits are approached or exceeded, i.e., where there is a high degree of WS$_g$.

Uncertainties. Our results should be interpreted with care as they are subject to uncertainties in the estimates of both WF$_g$ and WF$_{g,m}$ (and hence in the WS$_g$ ratio). Uncertainties can be particularly significant at the grid cell level, since uncertainties from random errors tend to reduce when averaged over larger scales (31). Uncertainties in the WF$_g$ of crop production can range in the order of $\pm 20\%$ (32, 33). Our estimate of the WF$_g$ of livestock grazing is within the range of estimates from previous studies (SI Appendix), but nevertheless subject to uncertainties, especially in the estimates of the grazed areas and the value of ecosystems services generated by pastures. Similar uncertainties in the areas used for wood production and the value of forests apply to the WF$_g$ of wood production (see ref. 34). The WF$_g$ of urban areas is so small that any uncertainties hardly affect our total WF$_g$ estimate. The estimates of WF$_{g,m}$ are uncertain (particularly at the smaller scales) due to uncertainties in the land that is set aside for nature (WF$_{g,m}$ equals zero), which we will reflect upon below in Trade-Offs Between Allocating Green Water to Humans Versus Nature.

Implications and Alleviation of WS$_g$. Tensions and trade-offs between green water allocation to humans versus nature are widespread. With our analysis we aim to make these issues part of the debate on water scarcity. For example, to become the European leader in biofuel production, Germany has reconverted vast areas of land to monocultures of bioenergy crops, rappedeseed in particular (35). Germany has already reached the maximum use of grasslands according to Common Agricultural Policy regulations (35) and agricultural intensification is a prime suspect for the major decline in flying insects in protected areas in Germany (36). Also in the United States, bioenergy crops have expanded into previously set-aside land (35) and uncultivated grasslands (37), at the cost of plant, insect, and bird diversity (38). The strong irrigation dependence in the Middle East can be explained by the fact that green water flows for crop production are fully utilized already. The region has seen a huge increase in livestock grazing and associated environmental impacts over the past century (39). Grazing is now a major contributor to range-land degradation in Saudi Arabia (40) and desertification in Israel (41).

Globally, deforestation is primarily driven by land-use change for commodity production (42) and is a major cause of biodiversity loss (43, 44). The relatively fast agricultural expansion in rainforests in the Amazon and in Southeast Asia is to be understood in the context of the global scarcity of still unused lands with sufficient rain. While green water flows are intensively used in most places around the world, the rainforests are among the few places with vast unused green water flows. Primary causes for deforestation across Central and South America are cattle ranching and large-scale agriculture, often for animal feed and bioenergy crops (45). Hotspots are the Atlantic Forest/Gran Chaco in Bolivia (46), Argentina (47–49), and Paraguay (50) [clearing for pasture and overgrazing (51); and agricultural expansion for soj], the Amazon (52, 53) and Cerrado (54) in Brazil (cattle ranching; soy plantations for food, animal feed, and biofuels), and the Chocó-Darién (45, 55) in Colombia and Ecuador (coca production; cattle ranching). In South Asia forest degradation is linked to crop production and wood logging (45). In the Greater Mekong in Cambodia, Thailand, Laos, and Myanmar (56) deforestation pressures include plantations of sugar, rice, rubber (57), and timber production, with logging in protected areas being prevalent across the region (58). On Sumatra and Borneo, wood logging severely degrades forest and leaves them vulnerable for land conversion, particularly for palm oil plantations (44, 59).

The tensions between green water for humans versus nature are intensifying as the green water demand for biomass in the economy grows. This growth is not only driven by population growth, but also by increasing green water demands per capita due to changes in the food and energy mix. Increasing affluence and urbanization are driving a global dietary transition with a higher consumption of animal products (60), which have much larger WF$_g$ than nutritionally equivalent plant-based products (61). Current policies aiming for a higher share of bioenergy in the energy mix will increase the WF$_g$ of the energy sector (16, 62, 63). Averting increased pressure on limited green water resources requires policies to slow down the growth of the human WF$_g$—targeting the consumption of livestock products and increased use of biofuels in particular.

We can hardly “grab” more green water flows for human society at the cost of nature (Trade-Offs Between Allocating Green Water to Humans Versus Nature), and although there is the potential to locally increase the green water availability to some extent by improved soil management (to retain more water in the soil that can then be taken up and transpired by crops), this will reduce beneficial blue water flows. Green- and blue water are communicating vessels and their sum is limited by the available precipitation, which is essentially the resource that is being allocated to competitive uses. For this reason, we deliberately assessed the human appropriation of the green water flow under current land use, for which blue water scarcity has been assessed as well by others (e.g., ref. 13).

Green water productivity can be increased by using the green water flow more effectively through a vapor shift (64), i.e., turning nonbeneficial evaporation from the soil into transpiration that contributes to biomass growth. This can be achieved by soil and crop residue management to maintain the infiltration and water-holding capacity of the soil, particularly by no-till and reduced tillage systems which conserve soil organic matter (65, 66). The transpiration efficiency (the ratio of plant transpiration to total ET from the crop field) will also be higher if the crop has a dense foliage and a well-developed root system (64), which requires proper supply of nutrients and effective control of weeds, pests, and diseases (67). Also, the application of mulches on the field is an effective way to enhance green water productivity by limiting evaporation from the bare soil (68). Closing the yield gap (69) by other means than a vapor shift, e.g., by using well-suited stress-resistant crop cultivars (67), also increases crop water productivity. Adding some blue water (deficit or supplemental irrigation) to bridge short dry spells can also help to achieve higher yields and hence boost green water productivity (64, 70). In some places where we have identified as highly green water scarce, increased use of blue water might offer a solution to increase production in this way (e.g., Northwestern Europe), yet in other places (e.g., the Middle East, Central America, Southern Europe, and India) blue water is severely scarce as well (13).

Assessing the differences and similarities between green- and blue water in terms of appropriation and scarcity, and related conflicts and solutions, remains an interesting avenue of further research. A major difference between the two types of water resources is that green water is landbound and indirectly allocated through land-use decisions (2, 14), while blue water can
be diverted and supplied to other locations. Blue water scarcity (the competition over limited runoff) generally translates to reduced river flows and declining levels in groundwater, rivers, and lakes, which affect ecosystems and people depending on these flows and levels (11). The effects of increasing WS$_g$ (viz. increased competition over limited ET) are not as visible as the effects of increasing blue water scarcity. The reason is that green water use does not change catchment hydrology as blue water use does; green water use just means that a green water flow that was available to natural vegetation before use has now been reallocated to produce biomass for the human economy.

Trade-Offs Between Allocating Green Water to Humans Versus Nature. The current allocation of green water is the result of past land-use decisions, which entailed (implicit) considerations of the trade-off between green water for mankind versus nature, as referred to by Rockström et al. (20). Mostly, these decisions have favored mankind. When natural vegetation was converted to agricultural land, the green water flow was reallocated from supporting biodiversity to supporting human food supply. This has been accompanied by tremendous impacts on habitats and biodiversity (69) with millions of dollars in losses of ecosystem service values (30). Since the green water flow is a limited resource in space and time, increased human appropriation of the green water flow is at the cost of natural ecosystems. This trade-off is always present, even when WF$_g$ remains below the estimated WF$_{g,m}$.

We have estimated WF$_{g,m}$ considering agroecological suitability and accessibility of land, biophysical constraints to intensifying land use, and biodiversity conservation needs (based on ABT 11; Materials and Methods). However, despite this solid basis, limits to WF$_g$ are debatable to some extent, especially at the local level. ABT 11 is a global target that calls for effective conservation of at least 17% of the terrestrial world, especially focusing on areas of particular importance for biodiversity and ecosystem services, but without regional specification of this target. We used the map by Montesino Pouzols et al. (26), who mapped those areas of highest conservation value, thus representing an effective spatial configuration to achieve ABT 11. However, different configurations are possible. Despite uncertainties, we believe that our estimate of the WF$_{g,m}$ of humanity is rather an under- than an overestimation, considering that some have argued for far more ambitious targets to preserve vital ecosystems services (71), or even leave half of the Earth to nature (72). Nevertheless, we recommend future work that aims to improve upon our estimate of WS$_g$ to focus on better estimates of the WF$_{g,m}$ in particular regarding the green water flow that should be reserved for nature.

Conclusions

We have mapped the WF$_g$ of the global economy and compared it to maximum sustainable levels, considering green water requirements to support biodiversity. We find that the total WF$_g$ of humanity currently appropriates 56% of the world’s sustainably available green water flow. About 18% of humanity’s WF$_g$ overshoots local sustainable levels, by being located in biodiversity conservation areas needed to achieve ABT 11. By expressing WS$_g$ per country as the ratio of the national aggregate WF$_{g,m}$ to the national aggregate WF$_{g,m}$, we showed that countries facing high WS$_g$—thus having no or very limited potential remaining to increase rainfed biomass production—are mainly found in Europe, Central America, the Middle East, and South Asia.

The world’s limited green water flow is shared by human society and nature. By ignoring limits to human’s growing WF$_g$—driven by an increased demand for food, feed, fiber, timber, and bioenergy—we risk further loss of ecosystem service values. Green water is a critical and limited resource that should explicitly be part of any assessment of water scarcity, food security, or bioenergy potential.

Materials and Methods

We estimated the human appropriation of the green water flow as the sum of WFD for crop production, WFD for wood production, livestock grazing, and urban areas at a 5 x 5 arc-minute grid cell spatial resolution, using estimates of WF$_g$ of crop and wood production from Mekonnen and Hoekstra (73) and Schyns et al. (34), and our own estimates on WF$_g$ of livestock grazing and urban areas (details in SI Appendix).

Limits to the WFD$_g$ are expressed by WF$_{g,m}$, which we estimate at 5 x 5 arc-minute resolution. To estimate WF$_{g,m}$ we translate limits to land use into limits to the use of the green water flow. We set aside the green water flow (WF$_{g,m}$ = 0) from lands that should be maintained to support natural terrestrial ecosystems (details in SI Appendix), which is similar to the practice of accounting for environmental flow requirements to support natural aquatic ecosystems (74). We set aside lands (WF$_{g,m}$ = 0) that have a protected status (75) or have priority to receive that status to achieve the ABT 11. Priority areas for protection, representing the most suitable 17% of the terrestrial land for protection based on conservation value, were obtained from Montesino Pouzols et al. (26) using the map for present land-use conditions. Furthermore, we estimate WF$_{g,m}$ based on agroecological suitability and accessibility of land, and biophysical constraints to intensifying land use. Therefore, we distinguish between lands that are currently utilized to some extent for agriculture, forestry, or urban areas, and those lands that are nonutilized at the moment but have the potential to be considered under a range of constraints (details in SI Appendix).

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