Green water and African sustainability

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Abstract

Sub-Saharan Africa faces an enormous challenge in meeting the basic needs of a population that will nearly triple between now and the end of the twenty-first century. Managing water effectively, sustainably, and equitably will be a critical component for meeting this challenge, especially in the context of the Sustainable Development Goals (SDGs). We focus on green water (i.e. the water that comprises evaporation and precipitation flows), rather than blue water (i.e. the liquid water flowing in rivers, lakes, and aquifers), since green water is primarily used for food production. We examine three key insights into green water management at their relevant spatial and temporal scales: farm-based food production using the vapor shift (annual, local); landscape and ecosystem interventions (multi-year, national/regional), and moisture recycling (decadal, regional/continental). As such, these insights are organized into a spatial and temporal framework, which helps to clarify how feedbacks within and among these different scales create opportunities for intervention. Our key finding is that green water management at the landscape-scale constitutes the best entry point for providing leverage at both smaller and larger scales, in terms of time, space, and policy. We conclude by highlighting the urgent need for much more resilient, cross-scale green water systems that can accommodate the impending, nonstationary changes related to climate change. This urgency is further underlined by the very short time horizon for achieving the SDGs by 2030.

Keywords Water management · Food security · Africa · Sustainability · SDG · Cross-scale · IWRM · Agriculture · Smallholder farming · Subsistence · Evaporation · Precipitation · Moisture recycling

1 Introduction

Water development in western countries has historically focused on surface runoff and groundwater, so called *blue* water management. Meanwhile, development efforts in semiarid regions in Central Asia and sub-Saharan Africa have drawn attention to the importance of the water in the soil – the *green* water – and the atmospheric branch of the hydrological cycle (L'vovich 1979, Falkenmark 1995; Weiskel et al. 2014). In the world of water management, it is often assumed that water in the soil is the same as water flowing in a river, and that most of the water used for food production comes from irrigation (i.e. blue water). However, this is not the case in practice. Most of

the global water active in agricultural production is in fact green water (Molden 2007), while the agricultural water conventionally discussed by water experts tends to be the blue water used for irrigation, sourced from either groundwater or surface runoff. Rockström and Gordon (2001) estimated the global annual green water flow (i.e. the flow of soil evaporation and plant transpiration), sustaining the major global biomes to be 69,000 Gm³/yr., out of which 9800 Gm³/yr. came from croplands (Fig. 1).

1.1 Alleviating hunger in 12 years?

In the Sustainable Development Goals (SDGs) (United Nations 2015), water is explicitly addressed in goal #6. However, there is no mention of the water required for food production to alleviate hunger (i.e. goal #2), despite water scarcity being the largest constraint for reaching food production goals – truly a fateful blindspot. The fact that the time span allocated for the Sustainable Development Goal Agenda is now only 12 years (United Nations 2015) raises the question – are the core constraints to achieving the SDGs really understood?

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Fig. 1 Most agricultural production is green water based. Map produced using data from Rost et al. 2008

It so happens that the challenge of achieving both poverty and hunger alleviation – two core SDGs – is largest in sub-Saharan Africa (Fig. 2a). Its rapid population growth (Fig. 2b) and generally semiarid climate (Fig. 2c, d) makes its water scarcity a fundamental development problem.

For a multitude of human activities, a human's life is profoundly water dependent (Rockström et al. 2012): *green* water is essential for production of biomass (food, fiber, timber); *blue* water for direct water use in drinking water supply, industry, and energy generation. Consequently, sustainable development profoundly depends on (a) well-functioning biosphere-based life support systems, (b) the underlying water cycling among atmosphere, land, and ocean, and (c) the system's capability to sustain human pressure, as both population and its resource demand continues apace.

Recent work has suggested that the SDGs in fact may belong to different 'spheres' (Rockström and Sukhdev 2016): respectively the biosphere, the social sphere, and the economic sphere. In that representation (Fig. 3), water is a core component of the basic life support system at the bottom, the biosphere, where it appears together with land, aquatic ecosystems, and climate (SDGs 15, 14, 6 and 13).

If there should be even a distant chance of alleviating hunger in sub-Saharan Africa in only a few decades, a basic condition will be a profound awareness of the implications of the severe water shortage that characterizes this region (Rockström and Falkenmark 2015). The large rivers form river corridors carrying runoff from isolated mountain "water towers". Meanwhile, as a consequence of the very large potential evaporation in these dry climate regions, most runoff generated from rain falling over the savanna tends to evaporate before reaching a river. Thus, rain falling over the

landscape is basically partitioned between *blue* liquid water in rivers, aquifers and lakes, supporting the many water supply-dependent activities in society (domestic, industry, energy production), and *green* soil water involved in supporting terrestrial ecosystems and biomass production.

1.2 An arid Achilles heel

Based on an overview of green and blue water in Africa (Schulz et al. 2008), and the particular blue water geography in Sub-Saharan Africa (Vörösmarty et al. 2005), it is not surprising that agriculture remains mostly rainfed. Most subsistence farmers live far away from the large river corridors with very limited possibilities for conventional irrigation. In subsistence agriculture, only some 30% of rainfall is used as productive green water flow in crop production (i.e. plant transpiration), with 50% going to soil evaporation, resulting in very low crop yields (some 1 ton/ha only on average in sub-Saharan Africa) (Rockström and Falkenmark 2000). In the semiarid and dry sub-humid zones (Fig. 2), population growth is very rapid and may, by 2050, host some 1.3 billion persons (Falkenmark and Rockström 2006; Falkenmark and Tropp *In press*).

Thus, in sub-Saharan Africa, green water is the primary way to deliver SDG #2. However, considerable water losses in current rainfed agriculture will have to be met with: a) agricultural upgrading, i.e. turning soil evaporation into productive transpiration (*vapor shift*, Rockström 2003), and b) *water harvesting systems* providing supplementary irrigation using rainwater, harvested from slopes and valley bottoms, and stored in ponds or dams for use during dry spells and drought periods (Oweis et al. 1999; Hussain et al. 2014).

Fig. 2 Savanna landscapes, hydroclimate and population prospects: **a** Undernourishment is highest in sub-Saharan Africa; **b** sub-Saharan Africa will experience some of the highest population growth in the world through 2050; **c** sub-Saharan Africa is dominated by dry-subhumid and

semiarid savannas; and, **d** Precipitation as compared to crop water requirements (plus/minus one standard deviation) in arid, semiarid and subhumid zones, and population 2010, 2030 and 2050. Source: Falkenmark and Rockström 2015

In the vast semiarid and dry sub-humid African drylands (Fig. 2c, d), direct management of green water from scarce rainfall must in other words form an integral part of the development agenda for securing reliable food production to alleviate hunger (Rockström and Falkenmark 2015). On the other hand, drinking water supply, industry, and energy development will all require large amounts of blue water, despite potential transitions to clean energy technologies (e.g. wind, solar). Since both socioeconomic development and food production all critically depend on access to water – blue as well

as green - their sectoral interdependence will make a nexus approach between the two sectors essential. (Falkenmark 2017).

Simply put, good green-water management (Wani et al. 2007) leads to food security, leaving blue-water to help sustain cities, economic modernization, and aquatic ecosystem health (Falkenmark and Rockström 2010). Bad green-water management would require blue water to also be used for irrigation – as well as for cities, industry, energy, and aquatic ecosystems. This type of management can be labeled as ‘bad’ since it is a maladaptive strategy,

Fig. 3 Sustainable Development Goals, organized in three ‘spheres’: from bottom, biological, social and economic spheres. Source: Azote images for Stockholm Resilience Centre

that would entail developing infrastructure and institutions that are unlikely to be appropriate in the near future.

In this paper, in an effort to characterize ‘good’, or sustainable, green water management, we explore key insights related to green water to refine the possibility-space for policy and practice. To avoid serious deviations in the achievement of the SDGs, policy and practice for sub-Saharan African sustainability must build on a realistic understanding of the hydroclimatic conditions on an arid continent. Based on these individual green water insights, we will synthesize how they interact with one another in the context of hydrology generally, and green water management specifically. Likewise, we examine the cross-scale interactions of these insights to reveal entry points or levers of change for water management. Finally, we consider the SDG-benefits of these recent insights, and conclude by outlining pathways for how green water management can contribute to achieving food security for sub-Saharan Africa, and how it ought to be reflected in realistic SDG targets.

2 Recent insights in green water science

We begin by highlighting three key insights from the broad academic study of green water systems: 1) improving food production via the vapor shift, 2) understanding green water from the landscape perspective, and 3) moisture recycling connecting distant locales.

2.1 Improving food production via the vapor shift

2.1.1 Water and biomass production, farming

The green water consumed in rainfed agricultural production (Fig. 4) is partly transpiration and partly soil

evaporation. Thus, from a strict agricultural perspective, the water that evaporates from the soil, or that forms runoff (i.e. blue water), could be transferred to transpiration, increasing the crop yield. However, since blue water is needed for downstream activities, yield increases will primarily require agricultural practices that (a) reduce the water that escapes as soil evaporation (shifting soil evaporation to transpiration through vapor shift), (b) increase infiltration through soil conservation, and (c) increase soil water storage by mulching. This is the so-called ‘vapor shift’ (Rockström and Falkenmark 2000).

The key implications of the vapor shift for water management overall are:

- More water (volumetrically) could be used for producing biomass-based goods for human use, with minimal impacts to the hydrological environment,
- Minimal reliance on blue water (which can be diverted easily and quickly) reduces vulnerability in food-producing systems, and
- ‘Additional’ green water that is captured with the vapor shift can support crop diversification, allowing for both subsistence food crop production as well as cash-crop production for sale at market.

Food production in sub-Saharan Africa remains overwhelmingly small-scale, with nearly 50 million small-holder farming households (<15 ha each), including over 17 million very small farms, of <2 ha each (Samberg et al. 2016). Even though there is a steady flow of migrants from rural areas to urban centers, food production will continue to be an important livelihood strategy, and more importantly subsistence strategy, for millions of people for decades to come (Khan et al. 2014). As such,

Fig. 4 Simplified cross-section of sub-Saharan African partitioning of rainfall into green water (i.e. water available for plant transpiration or soil evaporation) and blue water (i.e. deep percolation and surface runoff). Note the increase in ‘Plant transpiration’ and the decrease in ‘Soil

evaporation’ in the second panel, which would be the primary green water related consequence of the vapor shift. Adapted from Rockström and Falkenmark 2000

it is necessary to find low-cost, low-input methods for improving agricultural yields, given the simple fact that input-heavy agriculture is much less of an option for many poor, subsistence farmers (Rusike et al. 2004; Vanlauwe et al. 2015).

Thus, it remains a key priority to emphasize policy strategies that can improve crop yields and be applied immediately. One of the most promising strategies is the productive vapor shift of a farming landscape (e.g. Rockström 2003). By maximizing the amount of productive transpiration, it is possible to improve yields without overly deleterious impacts on the downstream hydrological cycle, specifically for runoff into blue water systems (Garg et al. 2012).

2.1.2 Farm- to community-scale processes

The scales at which this process occurs are the same scales as that of rainfed food production systems, that is annual to bi-annual time scales and local (i.e. smallholder to community) spatial scales. These two characteristics (fast and small) make this process heterogeneous in space and highly adaptable, providing resources are available. However, there is also very high variability inherent to these systems, which is also related to their being ‘fast and small’.

Subsistence agriculture in sub-Saharan Africa suffers from very limited productive transpiration, with yields often only 1 ton/ha. This implies that modernized approaches, including vapor shifting, will form essential components in moving towards alleviation of hunger.

This insight can help SDG achievement by improving management of farm-scale water resources, primarily the amount of food that is grown using green water without reducing water for downstream needs (e.g. urban drinking supply). Given that the process-scale of green-water management is small (e.g. farm) and fast (e.g. annual), there is a significant opportunity for iterative and adaptive management related to this effort. A secondary or tertiary benefit of the vapor shift could be that by increasing food security at farm-scales, the accelerating flow of migrants from rural-to-urban communities may be reduced, consequently relieving pressure on urban resources and retaining key cultural knowledge to manage landscapes for subsequent generations.

2.2 Green water and the landscape perspective

Cutting edge hydrological research (Weiskel et al. 2014) has developed a novel categorization of landscape units based on the dominant flows of water, in terms of blue water and green water (Fig. 5). It distinguishes between different combinations of water flows as both vertical and horizontal *inflows* and *outflows* within a landscape unit. Weiskel et al. (2014) distinguish between four general system types:

1. Headwater source (i.e. pure-source; precipitation input, surface and groundwater flow out)
2. Headwater no-flow (i.e. pure-green; precipitation input, evaporation output)

Fig. 5 Categorisation of different hydroclimatic landscapes, based on water inflow and outflow (i.e. precipitation, evaporation, and surface and groundwater flows). The four types are indicated in the four

corners of this figure, with a corresponding real-world example. Adapted from Weiskel et al. (2014) with photos used under the Creative Commons license

3. Terminal flow-through (i.e. pure-blue; surface and groundwater flow input, surface flow output)
4. Terminal sink (i.e. pure-sink; surface and groundwater flow input, evaporation output)

Thus, in *humid regions*, landscape units are dominated by blue outflows, whereas in *drylands*, with low runoff generation, vertical *green* water flows (rainfall and evaporation) are dominant. In these dryland settings, development will depend on green water practices to protect or restore soil moisture (the green water reservoir) and to carefully manage green fluxes, i.e. precipitation and evaporation. We note that we use the term *evaporation* instead of *evapotranspiration*, because evaporation refers to total evaporation accounting for all fluxes associated with a landscape, including soil and vegetation interception (Savenije 2004). These two interception fluxes occur much more quickly than soil evaporation or transpiration (Van der Ent et al. 2014). Thus, since we are discussing landscape-scale (or larger) processes in this paper, we use ‘evaporation’ when referring to all fluxes, or the specific portion of evaporation (e.g. transpiration) for specific comments.

In terms of cross-scale relations, management options, and policies, this typology facilitates the categorization of different

landscapes, and makes it possible to zoom out from the farm-scale, and highlight the hydroclimatic realities of what types of agriculture are appropriate for meeting food security goals in different landscapes. Specifically, this research can reveal which regions are essentially green water dominated systems (i.e. precipitation and evaporation constitute the dominant hydrological input and output, rather than surface or groundwater flow). Furthermore, since this classification highlights regions that experience little or no runoff, we want to emphasize that we are referring to different kinds of landscapes, rather than exclusively river basins. This is in large part due to the fact that river basins immediately conjure imagery of surface runoff (i.e. blue water). Our use of ‘landscape-scale’ is analogous in size to what many refer to as ‘basin-scale’, but explicitly includes green water systems that may technically exist across multiple river basins. We note, this classification is inherently based on average flows of water, which can only reasonably be calculated at scales larger than the farm.

Most of the food-producing regions in sub-Saharan Africa exist in the “pure green” domain, where what little precipitation falls on the land, departs almost entirely as evaporation. There is some runoff that is generated (see the red dashed line in Fig. 2d), but this manifests primarily as flash flooding (Rockström and

Falkenmark 2015). Thus, development activities for reducing hunger and poverty must keep in mind the limited availability of blue water resources. Furthermore, while there may be some scope for small-scale rainwater harvesting (e.g. sand dams), the overwhelming emphasis on water management ought to be on how to maximize the productive use of soil water.

In a subsistence or smallholder farming context, land-use decisions are made to gain food security. However, land-use decisions are functionally water-partitioning decisions, with ecosystem dependencies, trade-offs, and potentially co-benefits that can emerge. In other words, the decisions that are made at the landscape-scale have direct consequences for the types of green water food production that are possible at smaller scales. Key landscape-scale considerations include: availability of regional pollination (e.g. Kremen et al., 2007), livestock practices and interaction with crop production (Ran et al. 2016), and ecosystem service trade-offs (Bennett et al. 2009).

The policy environment in which landscape-scale decisions are made, are very likely more complex than at the farm-scale or even community-scale (e.g. Lienert et al. 2013; Lubell et al. 2014). This is partly because landscape-scale processes are driven by many kinds of stakeholders, likely with competing priorities and goals, e.g. foreign companies maximizing short-term agricultural yields versus conservation organizations seeking to limit biodiversity losses versus smallholder farmers in pure green water systems (Porter and Phillips-Howard 1997).

2.2.1 Landscape-scale processes

The scales at which these landscape processes occur and interact with good production are multi-year and across an intermediate domain (e.g. catchment, bioregion, small country). These characteristics (medium term and medium scale) imply that these landscape processes are less variable than the ‘fast and small’ processes discussed above. Likewise, they are natural entry-points for policy intervention since they can align well with administrative units, as well as the windows of time in which policies can reasonably be implemented.

The focus on hydroclimatic landscape differences has clarified the specific characteristics of the tropical savanna landscape, that dominates a zone where poverty, hunger and population growth converge. The fact that most of the savanna rain evaporates, constrains blue water generation and limits irrigation potential (SDG #2). This insight connects to bigger-picture water resource goals of the SDGs, especially those related to ecosystem service generation (SDG #14, #15) and sustainable cities and communities (SDG #11). There are benefits of improving the landscape-scale understanding of green water management, not least considering that much of sub-Saharan Africa is a ‘pure-green’ where land management *is* water management (Falkenmark and Rockström 2010). For example, sustainable management of water and ecosystems in a ‘pure-green’ region is going to emphasize activities that are rainfed, and not activities

that utilize irrigation, given the lack of run-off. These activities include management practices such as reduced soil tillage, mulching of agricultural wastes, appropriate fallowing, and rain-water harvesting. Given that this insight interacts with processes at the catchment or small-country scale, and that they occur at multi-year time-scales, adaptation and policy will be both more stable and more persistent than the vapor shift described above.

2.3 Moisture recycling connects distant locales

Until recently, the atmospheric branch of the water cycle was not really considered as part of the broader agricultural system, except as a loss of water from the system (i.e. soil evaporation) or as a driver of production (e.g. precipitation) (Fig. 6). However, recent work highlights how agricultural and land-use decisions on the land surface have direct impacts on the amount of water that flows into the atmosphere (i.e. transpiration and canopy interception), and how much water flows out of the atmosphere, i.e. precipitation, at local, regional, and continental scales (e.g. Tuinenburg et al. 2011; Lo and Famiglietti 2013; Bagley et al. 2014; Keys et al. 2016; Feng et al. 2017; Wang-Erlandsson et al. 2017).

Some recent work has highlighted the important connection between land-use and the recycling of water vapor from one location to somewhere else. Keys et al. (2016) quantified the extent to which current land-use provides rainfall for downwind regions, by comparing a current vegetation scenario to a hypothetical desert land scenario. In a case study of the Mato Grosso region of Brazil, the authors found that removal of vegetation in Mato Grosso changed the amount of rain that fell downwind, and importantly the seasonality of the rainfall. The authors suggest that vegetation-regulated moisture recycling is indeed an ecosystem service, and that the atmospheric connections may in fact be complemented by social connections that could create feedback loops. These feedbacks could be fast and small, such as land-use policy driven by drought events or floods, or much slower and larger, occurring at the scale of a country and its long-term forest management policy, such as Brazil’s deforestation policy ‘The Forest Code’ (Keys and Wang-Erlandsson 2017).

Additionally, Wang-Erlandsson et al. (2017) explore how distant land-use change can modify precipitation and runoff in distant regions. They found that human modifications to moisture recycling have the potential to significantly impact both green and blue water partitioning in important ways. For Africa in particular, the authors found that land-use change *outside* of the Congo River basin has influenced Congo River runoff more than land-use change within the basin.

The implications of these moisture recycling-related findings are that changes to vegetation in one location can lead to large changes in (a) distant rainfall and subsequently soil moisture (i.e. green water), (b) the productivity of distant landscapes (e.g. crop production), and (c) the amount of water that flows into rivers and lakes (i.e. blue water flows).

Fig. 6 Schematic representation of atmospheric branch of water cycle, emphasizing moisture recycling that occurs over land. Within the orange dashed box, precipitation that is primarily of oceanic origin falls onto land, and the water that evaporates is from the land surface. This water

is transported through the atmosphere, and falls out as precipitation again, and is then re-evaporated on land again. Used with permission from Keys (2016)

2.3.1 Large and slow-scale processes

Moisture recycling as a physical process operates at weekly to monthly time-scales, i.e. the average time a water molecule spends in the atmosphere is around 8–9 days (with a long-tailed distribution stretching out to multiple weeks) (e.g. Van Der Ent and Tuinenburg 2017). However, to modify moisture recycling requires significant changes in land-use and subsequently evaporation, which would likely take place across decadal time-scales (i.e. long-term). Similarly, the scale of the process is detectable at the scale of the small country (e.g. Burkina Faso) to continental scale (large-scale).

Moisture recycling constitutes a necessary condition for water resilience in biomass production (Falkenmark 2017). Not only large scale but also landscape-scale recycling is essential for the generation of rainfall. The latter is fundamental for the generation of local water cycles, supporting convective rainfall (Kravcik et al. 2008). Perhaps unlike farm-scale vapor management and landscape ecosystem decisions, moisture recycling is *biogeophysically emergent*. This means that moisture recycling changes are unlikely to be planned, simply due to the large spatial scales at which they occur. However, that does not imply that it cannot be governed, and recent work has speculated on how institutional and legal options could address the challenges of anthropogenic changes to moisture recycling (Keys et al. 2017). Likewise, given that terrestrial moisture recycling relationships can be simulated in both simple and complex models, it is possible for SDG goals and programs to *respond to* changes in moisture recycling, as well as *anticipate potential scenarios* of land-use change that could impact SDG attainment.

3 Cross-scale interactions

These three insights can be organized conceptually along a temporal and spatial domain, with space on the x-axis and time (in years) on the y-axis (see Fig. 7). Note that the y-

axis is not depicting the time scales at which the phenomena occurs, but rather the time scales across which the process *can adapt or change*. We highlight this aspect of each of these phenomena to draw attention to how quickly certain aspects of the green water system can be expected to respond to specific biophysical or social drivers.

The scales depicted above describe where farm-scale vapor management, landscape-scale green water management, and regional-scale moisture recycling exist in the spectrum of space and time - yet this is a static representation. In reality, the different insights are nested within one another, and thus cross-scale interactions will reflect this nesting. Figure 8 depicts how this nesting may appear using similar (though dimensionless) axes of space and time.

The nested reality of these processes also suggests that changes can propagate, but only in certain directions. Thus, if

Fig. 7 The three core insights represented in space and time, not in terms of the process (e.g. how long it takes for moisture to recycle in the atmosphere), but rather the time and space scales at which these processes adapt or change

Fig. 8 Food production change processes (red loops) occur at the farm-scale and across individual years; landscape and ecosystem processes (green loops) occur at the catchment scale, and over multi-year time-scales; and, moisture recycling change processes (blue loop) occur at regional to continental scales and the longest decadal time-scales

green water management aims to leverage these different scales and interactions, it is important to note how these processes do (and do not) interact. Modifying large-scale moisture recycling patterns will take time and extensive land-use change. So, year-to-year farm changes are unlikely to have a discernible impact on moisture recycling. However, landscape-scale policies that take many years to implement (and manifest in a tangible way) are more likely to have traceable impacts and interactions with moisture recycling. Thus, if an entire region or landscape of farming communities collectively introduces significant changes to how they manage green water, this ought to interact in a noticeable way with moisture recycling patterns. An example of such a change spreading rapidly through communities is the work of Rajendra Singh and his efforts to assist farmers in Rajasthan to construct *johads*, or traditional earthen dams (Hussain et al. 2014). This technology has improved storage of monsoon rainfall, supported infiltration, and subsequently contributed to the doubling of crop yields, increased forest cover, and improved water security.

If we look only at the time dimension of Fig. 8, we can see how many ‘cycles’ of a given process occur relative to others. For example, for every single cycle of moisture recycling, we see three landscape-scale cycles, and nine farm-scale cycles. The intermediate position of landscape and ecosystem stewardship suggests that it might be a good entry point for desirable green water management outcomes, since it has the potential to structure food production at the farm-scale and to shape the emergence of desirable moisture recycling processes. We note that Fig. 8 is conceptual and suggestive of the interactions among these insights, but is not meant to convey absolute relationships.

3.1 SDG considerations

Given the limited timeframe of the SDGs, i.e. less than 15 years, it is worth considering how many adaptation or change cycles

are potentially available for these different processes. For food production there is a maximum of 12 cycles of potential adaptation till 2030, for landscape and ecosystem processes, there are probably about 3 or 4, and for moisture recycling there is likely one. This means that the impacts of changes in both (a) food production and (b) landscape ecosystems, will not be detectable in moisture recycling, likely until 2030 or beyond. This does not mean that change will occur at the same pace everywhere. However, it may provide a sense of the difficulty in detecting the impact of certain development interventions.

This potentially complicates continued achievement of the SDGs beyond 2030, because it is impossible to measure how agricultural and landscape changes will impact moisture recycling. This creates an immediate urgency to explore the consequences of intended changes in sub-Saharan Africa to understand whether and how SDG achievement, particularly in terms of changes to water use between green and blue flows, will affect regional and continental rainfall regimes.

3.2 Integrating with broader forces of development

Successfully managing green water is only one part of the overall sustainable development strategy for sub-Saharan Africa, but it is a necessary part. We discuss below first how these green water insights must be balanced carefully with blue water development, then how green water management interacts with another key necessity for achieving food security, namely market access for smallholder farmers. We finish the discussion with an overview of how these insights specifically, and green water management in general, ought to be brought to the fore in discussions of not only sustainable water management, but sustainable development in general.

3.2.1 Green and blue water have distinct purposes in development

It is critical to manage green water in such a way to reduce ecosystem harm, reduce interference with the hydrological cycle (notably the partitioning of green and blue water, and the volume of water that is sent via terrestrial moisture recycling), and maximize productive human uses (e.g. food/fodder/fiber). As such, ‘good’ green water management will preserve the blue water flows which must be allowed to provide aquatic habitat as well as provide the foundation of urban modernization, industrialization, and economically-robust nations (Falkenmark and Tropp *In press*). This is especially important for nations that must achieve food security via imports, foreign aid, or financial instruments (e.g. options or futures contracts for food commodities) (Woertz et al. 2008).

These sorts of efforts could be achieved by engaging different blue water actors, ranging from international NGOs that are implementing irrigation projects to national water management organizations that are building dams. Likewise, linking

land management efforts explicitly to water management may seem obvious or mundane, but it remains far from common practice in many countries. It is almost impossible to break-down siloed organizational structures, especially in the context of separate governmental ministries. However, it may be possible to build bridges across these siloes, helping to link green water management with corresponding policy actors in land, agricultural, and forest management. Thinking multi-laterally as well as outside-the-box will be critical to integrated success across land and water management.

3.2.2 Balancing an agricultural revolution with ecosystem resilience

Recent analysis finds that much more than just subsistence agriculture will be needed to meet food security goals, and that cash crops for sale at market will also be needed (Frelat et al. 2016). This means roads and other infrastructure, as well as institutional innovation, will be needed to achieve food security.

Farming communities and organizations at the landscape-scale need to connect to markets, but there are important trade-offs between developing infrastructural and institutional connections to markets, namely that there is a risk of opening the door to large-scale farming, that could threaten ecosystem processes upon which smaller-scale farms rely. Thus, the key insight here is that market forces that are ostensibly needed to drive food security goals, must (a) prioritize green water-based food production (rather than blue water systems), and (b) not infringe on the off-farm ecosystem services that are needed for livelihoods, including regulating services such as pollination, as well as complementary sources of income such as livestock forage (e.g. Kremen et al. 2012).

Scientific evidence clearly shows the need for a sustainable, resilience-based agricultural revolution in the vast water-scarce regions in Africa to avoid large-scale famine and food insecurity (Kotir 2011). It will *not* be possible to reach the SDGs in Africa without a uniquely African water revolution - based on green water (SIWI 2016). The 2016 Stockholm call for an African Water Revolution highlights the need for a Green Water Initiative for Africa, to lead the path towards achieving the food security and hunger alleviation SDGs, which in turn are preconditions for achieving all the other SDGs (Mugagga and Nabaasa 2016).

4 Conclusions

Green water must be considered explicitly for there to be any hope of a sustainable future in Africa. This article highlights the different spatial and temporal scales at which recent green water insights can be brought to bear in the realm of sustainable development. We base our conclusions on three key insights: farm-scale improvement in evaporation management,

landscape-scale partitioning of water between green and blue flows, and regional scale monitoring of moisture recycling patterns. These insights provide leverage to integrate green water thinking and management into broader sustainability policy.

More broadly, distinguishing between green and blue water allows for conceptual and practical division of water resources between green water for landscape-scale agricultural and ecosystem initiatives, and blue water for municipal, industrial, and aquatic ecological demands. There are only 12 years remaining to achieve the Sustainable Development Goals by 2030, and distinguishing between green and blue water is prerequisite for success.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflicts of interest.

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