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From blue to green water and back again: Promoting tree, shrub and forest-based landscape resilience in the Sahel

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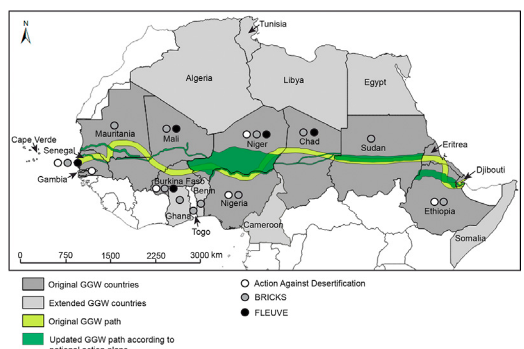
HIGHLIGHTS

- Mitigation aside, tree, shrub and forest-based landscape restoration can help provide landscape resilience in the Sahel
- Resilient ecosystem restoration is best understood on the basis of the *forest-water and land-atmosphere interaction lens*
- Tree, shrub and forest cover provide landscape resilience and agroforestry-related production benefits in the Western Sahel
- The *forest-water and land-atmosphere interaction lens* improves knowledge about the precise roles for tree and forest cover
- Large-scale, forest-water interaction-based processes must be incorporated into landscape restoration strategies

GRAPHICAL ABSTRACT



Source: Goffner et al. 2019.

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ABSTRACT

Enjoying the potential climate benefits of restoration requires linking key forest-water and land-atmosphere interactions to the existential benefits provided on the ground. We apply what we call the *"forest-water and land-atmosphere interaction lens"* to current strategies for improving landscape resilience in the West African Sahel and the concept of the Great Green Wall (GGW). The severe and extensive drought of the 1970's–1990's led many to assess future climate and promote strategies to counter the gradual southward expansion of the Sahara. The idea for the GGW, a wall of trees intended to slow desert encroachment, grew out of this period of tremendous upheaval and human tragedy. Despite partial recovery in the local rainfall regime, we know far too little about whether the GGW strategy can even work. Further, it seems disingenuous to ignore the climatic envelope, which sets the boundaries within which forest-water and land-atmosphere interactions occur. Applying the "*forest-water and land-atmosphere interaction lens*" to landscape restoration as a tool for achieving improved resilience and human welfare in the Sahel provides meaningful input for re-thinking the GGW strategy. We upgrade current knowledge with the specific biophysical conditions likely to better support appropriate forest-water and land atmosphere interactions in the region and further fit such approaches within the context of the climatic envelope. The principal components of an improved strategy include a focus on large scale precipitation recycling all the way from the West African coast on into the Sahel, as well as improved tree, shrub and forest cover in the Sahel proper to promote infiltration, groundwater recharge, rainfall triggering potential and land

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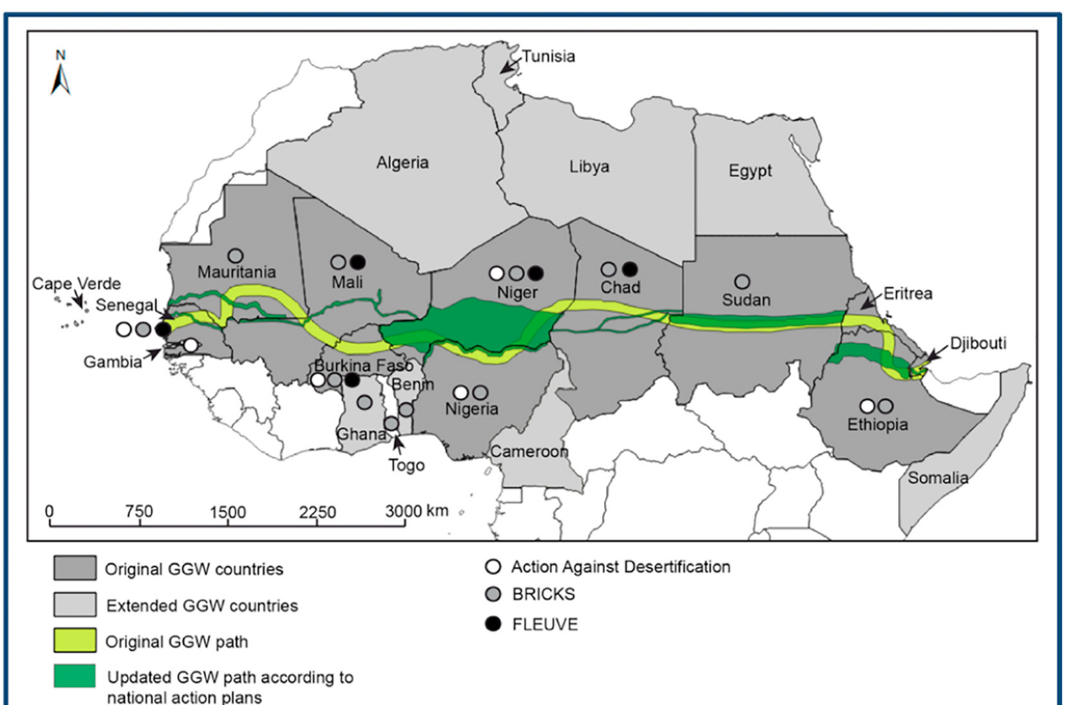
surface cooling. Agroforestry can further broadly promote landscape resilience in the greater region. Strategies broadly focused on increasing rainfall recycling, water availability and the promotion of landscape resilience appear more likely to steer future efforts in useful directions.

1. Introduction

The Sahel has attracted significant attention, in particular due to the extensive drought in the late 60's and early 70's, continuing through the early to mid-90's (Descroix et al., 2018; Nicholson et al., 2018; Vischel et al., 2019). Rainfall deviated sharply from historical patterns, exhibiting one of the most negative rainfall trends in the world (Trenberth et al., 2007). In the late 80's, at the height of the drought, the Sahel was designated one of the most water-challenged regions on the planet (Falkenmark, 1989). Tremendous upheaval and human tragedy emerged from this period of extreme climate adversity, leaving many wondering what the future might hold. Land degradation, persistent poverty, dependence on rain-fed crop and livestock production, rapid population growth and rising temperatures further deepen concerns about this region (Graves et al., 2019). Various strategies for enhancing landscape resilience and improving dependent livelihoods have been proposed. One such initiative, the Great Green Wall (GGW), conceived as a pan-African tree-based land restoration project in 2005, became an official pan-African goal in 2007. Built loosely upon several related re-greening projects that emerged during the comparatively water abundant 1960's and 1970's, the GGW expanded upon the idea of "green belts" around cities and "green dams" (Goffner et al., 2019). Placing obstacles in the desert's path was initially considered sufficient to slow and, more importantly, even reverse desertification. The GGW project thus envisioned a "wall of trees" some 15 km's wide, more than 7000 km long (Goffner et al., 2019) and was designed, in particular, as a strategy for slowing southward desert expansion (Fig. 1).

Much in line with concepts about *Natural Climate*, and *Nature-Based Solutions* (Griscom et al., *2017;* Cohen-Shacham et al., *2019;* Ellison et al., *2019)*, the restoration of tree, forest and vegetation cover is frequently seen as a strategy for restoring resilience in the Sahel. Foley et al., for example, present one of the early reviews defending the position that the restoration of degraded forest and vegetation landscapes could have a positive impact on reducing temperatures and returning additional precipitation to the Sahel (Foley et al., 2003). Yet, while tree and forest cover may well have a positive effect on temperature, rainfall and water availability (Ellison et al., 2017; Ellison, 2018; Creed and van Noordwijk, 2018), when and how this might happen in the context of the Sahel remains largely unexplained, thereby obscuring the biophysical dimensions of the forest-water role. Discussion on the role of tree, forest and vegetation cover in the Sahel runs the gamut of land-atmosphere and forest-water-based interactions. For some, tree planting and landscape restoration in the Sahel are the ultimate goal (Foley et al., 2003; Sendzimir et al., 2011; Behnke and Moritmore, 2016; Reij and Garrity, 2016), while others also point to deforestation further South along the West African coast (Abiodun et al., 2008; Keys et al., 2014; Monteny, 1986; Monteny and Casenave, 1989;



Source: Goffner et al. 2019.

Fig. 1. Original and Current Plans for the Great Green Wall. Note: Action Against Desertificaiton, (The Building Resilience through Innovation, Communication and Knowledge Services (BRICKS), regional project funded by the Global Environment Facility (GEF) and implemented by the World Bank) and (The Front Local Environnemental pour une Union Verte (FLEUVE), a European Union-funded Great Green Wall project implemented by the Global Mechanism of the UN Convention to Combat Desertification (UNCCD)) are related landscape restoration projects with similar goals. However, we do not explicitly review these programs herein.
Source: Goffner et al. 2019.

Savenije, 1995). Others, however, highlight the potentially symbiotic role of trees with agricultural systems (van Noordwijk, 2019; van Noordwijk, 2018), while entirely neglecting other hydrologic landscape features. Thus, the explicit linkage to rainfall, water availability, the synthesis of ideas and the prioritization of policy goals remain obscured in deep disciplinary contemplation.

Climate benefits from massive global re- and afforestation goals (Bastin et al., 2019; Houghton et al., 2015; Houghton and Nassikas, 2018; Chen et al., 2019) will only emerge if such strategies can be adequately linked with rapidly improving knowledge on forest-water interactions (Ellison et al., 2019; Ellison et al., 2017; Creed and van Noordwijk, 2018; Sheil et al., 2019). One of the peculiarities of the original GGW tree-planting idea is its almost blind faith in the view that a wall of trees would be enough to strengthen or reinforce the hydrologic cycle, restrict and even reverse the southward progress of the Sahara and thereby secure landscape resilience (Woodfine and Jauffret, 2009). Conventional knowledge on forest-water interactions suggests building a barrier wall serves no easily comprehensible 'forest-water interaction'-based goal. Experience with the many failed re-greening projects (Morrison, n.d.), as well as with successes in other parts of the Sahel (Sendzimir et al., 2011; Reij and Garrity, 2016), may have had a moderating impact on current plans for the GGW. Goffner et al. note, e.g. that the initial GGW concept as a barrier against desert expansion has shifted in the more general direction of 'promoting landscape resilience' (Goffner et al., 2019; Woodfine and Jauffret, 2009), and away from the comparatively simplistic vision of a tree-based barrier wall. Some of the more successful, ongoing re-greening in the region has largely occurred through farmer-based efforts to bring trees back into the landscape in order to improve agricultural productivity. Despite the physical and conceptual distance between farmer managed natural regeneration (FMNR) and the GGW goals, FMNR appears more successful at returning trees to the landscape and improving resilience than ongoing projects promoted by the GGW strategy (Reij and Garrity, 2016; Reij et al., 2009; Tappan et al., 2016).

A second peculiarity arises from the conflict between emerging concepts of the power of landscapes to restore local resilience and the limitations on such strategies imposed by climate change. For some, the relentless southward advance of the Sahara and the increasing severity of drought in the Sahel may, primarily, be a function of historical deforestation and land degradation. To these authors, desertification is a "myth" (Sendzimir et al., 2011; Morrison, n.d.; Thomas and Middleton, 1994). Behnke and Mortimore, for example, argue desertification is a Western invention imposed on places like the Sahel: decades of deforestation and landscape degradation are the mechanisms driving progressive desiccation and vegetation loss (Behnke and Moritmore, 2016). Yet while measures to restore the landscape and improve resilience may limit desert expansion, these approaches turn a blind eye to the ongoing problem of climate change affecting both the region and the globe. In this sense, two operative questions and discussions are frequently conflated in the Sahel literature at the cost of ignoring threats related to the continued impact of global warming and climate change.

Our goal is to examine the existing, multi-disciplinary strains of analysis through the tree/forest-water and land-atmosphere interaction lens (Ellison et al., 2017; Ellison, 2018; Creed and van Noordwijk, 2018), in order to derive a more coherent picture of sustainable and more resilient development pathways for the Sahel. At the same time, however, we highlight the limitations to this strategy imposed both by extensive and ongoing deforestation and landscape degradation in the region, as well as progressive climate change.

In what follows, we focus first on describing and explaining change in rainfall in the Sahel region. Second, we zero in on the forest-water and land-atmosphere interaction lens and the multiple roles played by tree and forest cover in improving the quality of the hydrospace landscape, land-atmosphere and forest-water interactions. Third, we address each of the major components of the forest-water interaction lens in turn in the context of current and potential reforestation and resilience promotion efforts in the Sahel. Finally, we conclude with a broader discussion both of the challenges imposed by deforestation and landscape degradation in the context of forest-water and land-atmosphere interactions, as well as the persistent and worsening problems imposed by progressive and persistent change in the climatic envelope.

2. Deconstructing rainfall

2.1. The rainfall record

As the principal key to survival in the Sahel region, rainfall imposes existential limits on human and plant survival, and thus on landscape resilience. Hence, future projections of, and change in rainfall in the coming decades provides an important foundation for better understanding the potential to promote landscape resilience in the Sahel. We focus first on; 1) the historical rainfall record, 2) future rainfall projections, 3) current explanations for variation in total annual rainfall, and 4) ongoing discussion of the potential role trees, forest and vegetation cover might play in promoting both rainfall and water availability in the greater Sahel region.

Estimates of changing rainfall in the Sahel are complex. Several authors find Sahel rainfall, beginning in the mid-90's, has improved since the period of extreme and recurrent drought (Descroix et al., 2018; Nicholson et al., 2018; Held et al., 2005; Lee et al., 2015; Biasutti, 2013). On the other hand, projections of future rainfall are highly dependent on the length of the historical record to which current patterns are compared, as well as on how one interprets the existing rainfall record. Nicholson et al. provide what appears to be the longest available historical record (Fig. 2) (Nicholson et al., 2018), though Descroix et al. include a few more recent years (Descroix et al., 2018).

Perhaps the most important finding in Nicholson et al. is the conclusion that rainfall patterns may not entirely have "recovered" from the drought period in the 70's–80's. Descroix et al., for example, indicate that since the drought period, rainfall has varied 'around the mean' (Descroix et al., 2018). However, over the entire period from 1854 to 2014, there are clearly many more years in which total annual rainfall has exceeded the long-term average (equal to 0 in Fig. 2). In this sense, the current period (1995–present) has significantly fewer years of rainfall above the mean and Biasutti and others, on average, find a moderate decline in rainfall over the 1901–2005 period (Biasutti, 2013; Giannini and Kaplan, 2019). On the other hand, while rainfall has clearly not been as heavily or consistently positive as in previous years, rainfall has not, at the very least, returned to the strongly negative values experienced in the 70's and 80's. The general image of relative improvement in the rainfall record is further reflected in data from research on changes in soil moisture and terrestrial water storage, as measured by GRACE satellite imagery, which witnesses an increasing trend in Sahelian soil moisture content and terrestrial water storage from 2000 to 2014 (Ndehedehe et al., 2018; Rodell et al., 2018).

The current period, however, has few data points from which to draw firm conclusions. And data from early years is significantly spottier, suggesting some trends may not be adequately revealed. Moreover, the "wet period" (1951–1967), to which the current period is frequently compared, itself appears an anomaly compared to the remaining historical record (Hulme, 2001). On the other hand, the dry period during the 70's and 80's also appears anomalous compared to the remaining dataseries. Across the longer historical record, most dry periods are of much shorter duration and magnitude. However, an even longer record based on fewer measurements may suggest this most recent drought period was significantly shorter than an extended drought period in the early 1800's (Nicholson et al., 2012). Thus, both what is really an anomaly, and whether these two most recent anomalous wet and dry periods suggest other more dramatic changes may be afoot, or whether they reflect some element of long-term climate variability, is impossible to tell

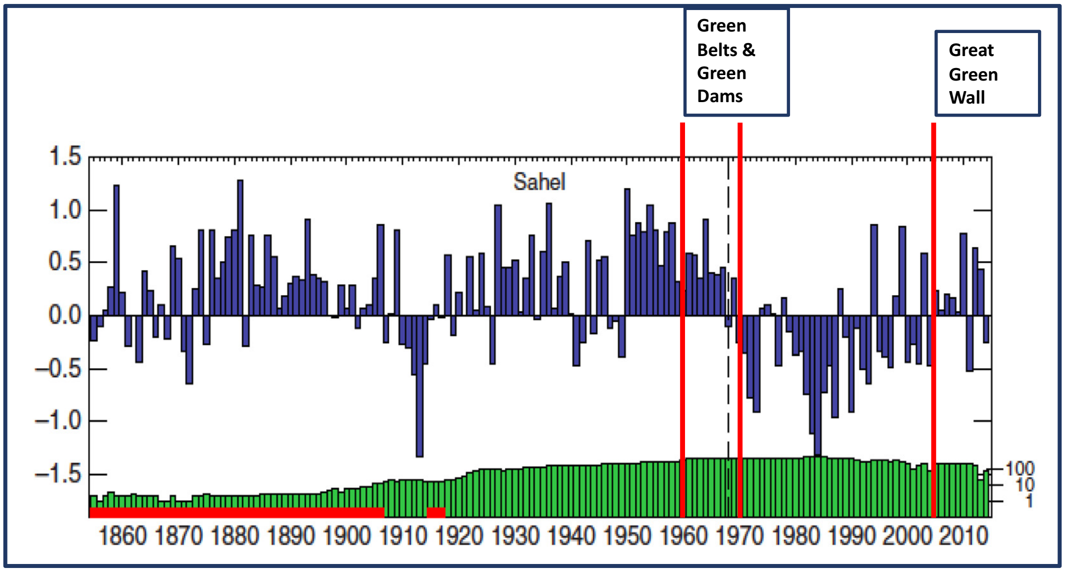


Fig. 2. The Long-term Rainfall Record in the Sahel, 1854–2014. Source: adapted from Nicholson et al. (2018). Blue rainfall bars indicate the number of standard deviations from the long-term mean (1854-2014). Nicholson et al. apply a scaling factor to early years (indicated in red horizontally along the x-axis). Data in earlier years are based on significantly fewer rain gauge measurements (green bars), highlighted by the logarithmic scale on the right-hand side for the number of gauges. Most measurements from about 1854-1895 derive from approximately 1-10 rain gauges. Throughout much of the postwar period, measurements are based on more than 100 gauges. We add information on the timing of the Green belt, Green dam and Great Green Wall discussions (vertical red lines).

from rainfall data alone. The back-to-back occurrence, as well as the repetition, of the two recent anomalies may further suggest some kind of regime change is afoot. Moreover, given that climate change contributes both to the increased occurrence of drought and to the emergence of extremes (Fischer and Knutti, 2015), it is possible the relative length and/or severity of "wet" and "dry" periods will become more pervasive and extreme.

2.2. Future rainfall projections

Consensus on future rainfall in the Sahel is hard to come by. Much like the Dai findings on future drought potential (Dai, 2013), Hill et al., for example, assess estimates from 17 different global circulation models (GCMs) and find evidence for continued drying and warming, and thus likely declining rainfall (Hill et al., 2018). These authors simultaneously raise doubt, however, about the veracity of these findings due to the technical difficulties within the GCM framework of measuring and assessing the impact of land-atmosphere interactions, surface cooling and possible vegetation- and landscape restoration-related increases in rainfall. Though this gap may open an opportunity for promoting the benefits of tree and forest cover, Keys et al. likewise find significant biome shift is likely to negatively affect the Sahel region, suggesting the desert will continue its southward crawl, further reducing tree and vegetation cover in its path (Keys et al., 2019). Several authors, however, find evidence to support a likely increase in future rainfall in the Sahel (Giannini and Kaplan, 2019; Biasutti, 2019).

Paleoclimatic studies link the weakening of the West African monsoon and associated severe droughts to the last deglaciation period that was characterized by a rise in sea levels (Itambi et al., 2009; Stager et al., 2011). Defrance et al., (2017) explore the effects of a "Greenland flash melting scenario" on the Sahelian ecosystem using the representative concentration pathway RCP 8.5 and find that freshwater discharge and associated sea level rise are likely to decrease West African monsoon rainfall, subsequently causing drought and the loss of arable lands, which could trigger large population migration. On the other hand, other studies have predicted brief, but short-lived periods of increased greening due to increasing CO^2 fertilization (Bathiany et al., 2014).

2.3. Explaining rainfall patterns

The attempt to *explain* changing rainfall patterns raises considerably more complexity than the historical record (Biasutti, 2019). Generally speaking, there is broad agreement in the Sahel literature that change in rainfall is largely driven by two phenomena; change in sea surface temperatures (SSTs), and change in land-atmosphere interactions, in particular in the Sahel. Change in SSTs has been variously estimated to predict anywhere from 60 to 70% of variation in Sahel rainfall, while the role of land-atmosphere interactions (possibly as a function of local vegetation cover) has been estimated to explain anywhere from 30 to 40% (Wang and Eltahir, 2000; Wang et al., 2016; Los et al., 2006).

Regarding SSTs, Ndehedehe et al. find positive phases of the Atlantic multidecadal oscillation (AMO) are linked to above-average rainfall (Ndehedehe et al., 2017). Likewise, the El Niño southern oscillation is thought to be important in the promotion of positive rainfall activity, while the Indian ocean dipole (IOD) appears to play a minor role. Nicholson provides similar findings, arguing rainfall in the Sahel exhibits very strong correlations with change in the AMO and that larger AMO changes appear closely correlated with wet-to-dry and dry-to-wet regime shifts in rainfall patterns (Nicholson et al., 2018). Moreover, AMO shifts are considered linked to movements in the ITCZ (the Inter-Tropical Convergence Zone, discussed at greater length below). Thus, a warming AMO contributes to more rainfall, in part by causing the ITCZ to shift further north (Vischel et al., 2019), and vice versa. Nicholson suggests there is evidence for a regime shift driven by changing SSTs and occurring around 1968, which appears to prelude the period of extensive drought from the 1970's–1990's. More importantly, perhaps, for this paper, Nicholson further suggests these regime shifts from wet to dry (and vice-versa) occur with great regularity. This observation accords well with other observations that the Sahel is characterized by long term decadal shifts from "wet" to "dry" periods, and that these shifting regimes have shaped long-term rainfall variability in the region for some 5000+ years (Foley et al., 2003).

However, many argue that global warming and warming SST's impact rainfall occurring over oceans and land surfaces in different ways (Biasutti, 2013; Giannini, 2010). In some senses, the Nicholson findings may be eclipsed by several studies highlighting the differentiated impacts of aerosols (in particular sulfates from energy production in

North America and Europe), which have potentially contributed to ocean cooling and extended drought and, on the other hand, greenhouse gas (GHG)-based warming that has led to rising SSTs (Biasutti, 2013; Giannini and Kaplan, 2019; Biasutti, 2019; Biasutti and Giannini, 2006; Ackerley et al., 2011). These authors ascribe the extensive Sahelian drought of the 70's–90's to sulfate-forced SST cooling in the North Atlantic and warming in the South Atlantic. As sulfate aerosols dissipate, these authors expect GHG effects to predominate, driving increased SST warming and continuous increases in rainfall across the remainder of the 21st century. Dong and Sutton, likewise link climate forcing and global warming to rising SSTs and improved rainfall in the Sahel (Dong and Sutton, 2015). Many also find climate change is increasing rainfall intensity, extending dry season periods and shifting initiation and cessation of the rainy season (Sylla et al., 2015; Ibrahim et al., 2014; Panthou et al., 2018), as well as driving a decline in rainfall in the Western and an increase in the remaining part of the Sahel.

Comparing these more positive projections to the most recent parts of the rainfall record, however, may lend a degree of caution to suggestions rainfall will continuously increase over much of the 21st century. To-date, these projections are not clearly reflected in the most recent rainfall records.

2.4. Tree, forest and vegetation feedbacks

While SSTs appear to play an important role in regime shifts, SSTs alone, are seen as insufficient to shift the system from wet to dry or dry to wet without the contribution of change in tree and vegetation cover (Foley et al., 2003). Wang et al., for example, find earth system modeling of simulated rainfall and drought projections over the Sahel is sensitive to the inclusion of vegetation feedbacks and that vegetation has the effect of diminishing drought persistence (Wang and Eltahir, 2000; Wang et al., 2004). Moreover, although these authors suggest local climate transitions from wet to dry are reversible, such transitions may require several years for the landscape to fully recover from an extended dry period (Foley et al., 2003), suggesting active (human-assisted) regeneration may provide positive benefits. Thus, changing vegetation cover may play an important role in the overall length of the transition to landscape recovery.

Analyses of the role of tree, shrub and forest cover and land-atmosphere interactions for rainfall in the Sahel are increasingly complex. While some literature suggests tree and vegetation cover may matter for rainfall in the Sahel, significantly less is said about how and why this might be true, as well as under what specific circumstances additional tree and vegetation cover might be useful or meaningful. Moreover, the focus on where the principal land-atmosphere interactions occur, how they impact rainfall, what precisely the role of tree, forest and vegetation cover in that feedback effect might be, all of these questions remain the subject of ongoing debate. Abiodun et al. and others (Abiodun et al., 2008; Keys et al., 2014; Monteny, 1986), for example, highlight a long-standing debate over whether the principal drivers of landscape change and rainfall loss should be associated with the process of *deforestation* (occurring primarily toward the Southern part of West Africa, from the coast all the way to the Sahel), or with the process of *desertification* (occurring primarily across the Sahel).

Failure to adequately understand the dynamics of forest-water interactions and their implications for landscape resilience can have profound ramifications. Thus, for example, afforestation in the Loess plateau region of China has tended to threaten the available water supply and thus the limits of sustainable water use (Feng et al., 2016), despite simultaneous increases in local rainfall supply (Gao et al., 2017). While analyses that adequately address the atmospheric dynamics of moisture supply in the Loess plateau region are sorely lacking, the evidence highlights the importance of considering the broad range of forest-water interactions and their potential impacts on promoting local landscape resilience. Unintended and potentially disastrous outcomes are the likely consequence of both reforestation strategies that fail to adequately consider either catchment-level water balance dynamics (Schwärzel et al., 2020; Filoso et al., 2017; Falkenmark and Rockström, 2006), as well as deforestation and land conversion strategies that fail to fully understand the role and importance of atmospheric moisture supply and other forest water interactions (Ellison et al., 2017; Ellison, 2018).

In what follows, we define and apply a *forest-water and land-atmosphere interaction lens* and investigate its potential to highlight the positive (and negative) impacts of land-atmosphere and forest-water interactions on rainfall and water availability. We then highlight the relative importance of distinguishing between different forest-water and land-atmosphere interactions in the context of the Sahel as a foundation for identifying appropriate landscape restoration strategies.

3. The forest-water and land-atmosphere interaction lens

Scientists now know significantly more about forest-water and land-atmosphere interactions than a decade ago. In this sense, our understanding of the relative importance of forest-water interactions has evolved beyond the conventional perspective based on catchment-bounded blue and green water dynamics (Falkenmark and Rockström, 2006; Calder et al., 2007). In this perspective, rainfall is partitioned into evapotranspiration (green water) and downstream flows (blue water). The forest-water interaction lens, on the other hand, employs a more complex understanding of hydrologic space involving the role of precipitation recycling and other forest-water and land-atmosphere interactions (Ellison et al., 2019; Ellison et al., 2017; Ellison, 2018; Creed and van Noordwijk, 2018; Ellison et al., 2012; Dalton et al., 2016). This evolving strategy requires being attentive not only to the catchment-bounded water balance, but also to the atmospheric contribution embodied in the recycling of green water back into the atmosphere where it can again become available as rainfall (Ellison et al., 2019; Creed and van Noordwijk, 2018; Ellison et al., 2012; Sheil and Murdiyarso, 2009; van der Ent et al., 2010; Keys et al., 2016; van Noordwijk et al., 2014).

Thus, in contrast to the Great Green Wall vision of tree and forest landscape restoration as a first line of defense against desert encroachment, we instead emphasize the importance of being attentive to the broad range of forest-water interactions, encompassing both the green and blue water paradigm at the catchment scale and the precipitation-recycling perspective, as well as additional interactions. Though neither the blue-green water paradigm nor atmospheric precipitation recycling can be called upon to support the GGW vision, holistically engaging the broad range of forest-water interactions provides an improved framework for analyzing the potential benefits of tree and forest-based landscape restoration. Combined, these perspectives suggest it makes more sense to encourage the progressive restoration of degraded tree and forest landscapes across a significantly broader North/South expanse, in order to bring more atmospheric moisture into the Sahel region. Thus, instead of building a barrier wall, we suggest incorporating ‘forest-water interactions’, as currently understood, more directly into the logic supporting landscape resilience goals. In part, this requires re-thinking and ultimately reconnecting the blue and green water paradigm (Falkenmark and Rockström, 2006) with its impact on and the role of atmospheric moisture flows (Ellison et al., 2012; van Noordwijk et al., 2014).

Previous work highlights four situations in which potential advantages from forest and landscape restoration likely emerge (Ellison et al., 2017; Ellison, 2018; Creed and van Noordwijk, 2018; Dalton et al., 2016). One of these, the role of high altitude, montane and cloud forests is not relevant to the Sahel region and is ignored in the discussion below. The other three are of potential relevance for the Sahel (we have subdivided the 2nd category into two separate categories); 1) the promotion of precipitation-recycling through increased tree and forest cover, 2) the role of tree and forest cover in the promotion of infiltration, and soil and groundwater recharge, 3) agroforestry (the benefits are primarily dependent on Point #2), and 4) the terrestrial surface cooling potential of tree and forest cover. Building on these forest-water interactions would appear to provide the most likely positive impacts in the Sahel:

1) **Cross-Continental Transfer of Atmospheric Moisture, Precipitation Recycling, Wind and Weather Patterns** (Ellison et al., 2019; Ellison et al., 2017; Ellison et al., 2012; Sheil and Murdiyarso, 2009; van der Ent et al., 2010; Keys et al., 2016; van Noordwijk et al., 2014): Additional tree and forest cover can and probably should be used as a strategy for moving water through the atmosphere, across terrestrial surfaces, to downwind locations. Though it is difficult to specify the amount of forest required to achieve specific amounts, and thus to target specific areas with additional rainfall, forests can be used as a tool for redistributing water away from locations where it is more abundant and dispersing that water in the general direction of locations where it is potentially more urgently required. Thus, by way of example, the restoration of forest landscapes across flood prone regions represents one potentially important strategy for increasing the amount of water returned by such basins to the atmosphere, thereby improving hydrologic intensity (the rate of precipitation recycling) across terrestrial surfaces. Moreover, since flood moderation represents a benefit to the local basin, this example importantly highlights the fact that not all forest landscape restoration strategies involve tradeoffs but rather represent important and positive synergies based on real win-win situations.

   Better understanding ways in which land-atmosphere interactions likewise influence climate and patterns of precipitation recycling is important. Local precipitation recycling (i.e. precipitation-recycling generated on the basis of the catchment-specific contribution to the water cycle), in particular, appears to be impacted by the land-atmosphere interaction generated by forest cover. Thus, larger total amounts of forest cover and increased forest density appear to positively impact the likelihood of local precipitation recycling by reinforcing mechanisms that both slow windspeed, help facilitate soil moisture storage and trigger rainfall (Ellison and Ellis, 2019).
2) **Infiltration, Soil Moisture Storage and Groundwater Recharge** (Bargués Tobella et al., 2014; Bargués-Tobella et al., 2020 Ilstedt et al., 2016; Lal, 1996; Neumann and Cardon, 2012; Bogie et al., 2018; Bayala et al., 2008; Bruijnzeel, 2004; Peña-Arancibia et al., 2019; Prieto et al., 2012; Nyberg et al., 2012): Tree and potentially forest cover is essential for the infiltration of water and rainfall into the soil, soil moisture storage and the recharge of groundwater resources. Vegetation promotes both the infiltration of water into soil surfaces, soil water storage, as well as the recharge of soil and groundwater resources. Moreover, water purification is primarily a function of the processes that filter rainfall through these various levels of high quality (non-degraded) plant, tree litter and soil surfaces.

   The concept of "optimal tree cover" (Ilstedt et al., 2016) highlights the role of the relative share of tree cover in the landscape and its impact on infiltration, soil moisture storage and groundwater recharge. This optimal density is defined as the point at which infiltration and groundwater recharge rates are at their maximum, while evapotranspiration is at its minmum, with minimal impacts on the downward supply of moisture. Alternatively, for the purposes of restoration, we might think of this 'optimum density' as a 'minimum tree cover requirement'.Tree cover facilitates these processes by providing shade, which reduces tempeartures and thereby soil evaporation, thus enhancing downward water seepage. Trees further shed litter beneath, which helps to absorb water and provide carbon resources for the soil, thus enhancing soil organic matter. This further improves the soil's ability to store water.

   Tree roots and faunal activity further enhance macroporosity, thereby promoting infiltration, soil water storage and groundwater recharge. Tree root architecture can thereby facilitate sub-surface, upward and downward hydraulic flows. Thus, even or perhaps especially in semi-arid regions, some degree of tree cover is required in order to promote infiltration and groundwater recharge. While denser tree and forest cover can lead to excessive evapotranspiration, thus reducing infiltration and groundwater recharge, the removal of all tree cover may have opposing and even more direct consequences for local water availability and the loss of moisture through increased surface runoff.
3) **Agroforestry and Hydraulic Liift** (Reij and Garrity, 2016; van Noordwijk, 2019; van Noordwijk, 2018; Reij et al., 2009; Neumann and Cardon, 2012; Bogie et al., 2018; Bayala et al., 2008; Sinare and Gordon, 2015): Due in particular to the effects of infiltration, soil moisture storage, and soil and groundwater recharge, trees in the landscape are increasingly seen as beneficial for cropland management. For these reasons and more, agroforestry is increasingly seen as a strategy for improving overall agricultural productivity. It does this, in particular, by bringing more moisture to the immediate landscape and improving both soil carbon (Bayala et al., 2019) and soil water content. Further, the property of hydraulic lift, which trees exert by moving water from the sub-soil to locations where shorter-rooted agricultural plants can access it, may significantly assist crops in gaining access to both water and nutrients. With more tree cover, lowered air temperatures and wind speed reduce evapotranspiration and improve the climate over smaller fields, improving soil moisture and ultimately also tree growth (Sendzimir et al., 2011). Thus, multiple benefits arise from the singular impact of tree-promoted surface cooling.
4) **Terrestrial Surface Cooling – Sensible vs. Latent Heat** (Ban-Weiss et al., 2011; Bonan, 2016; Bright et al., 2017; Duveiller et al., 2018; Hesslerová et al., 2013; Pokorny et al., 2010; Zeng et al., 2017): In locations with adequate water supply, trees and forests have a net cooling impact on surface temperature and dissipate incoming energy from the sun (surface radiation or sensible heat) through the process of photosynthesis. Plants use water for the purposes of binding carbon and expelling water in the form of transpiration. Passive evaporation of moisture from leaf and soil surfaces further contributes to cooling. Evapotranspiration (ET), the principal form of latent heat and the combination of evaporation and transpiration, further produces clouds, which can reflect additional radiation away from the planet's surface (but may also trap some radiation below cloud surfaces).

   The surface albedo of trees has the opposite effect. The darker color of tree and forest surfaces (relative to things like snow cover, open fields and grasslands) naturally attract sunlight and absorb warmth. Considered on their own, trees absorb higher amounts of sunlight due to lower albedo, thereby contributing to regional (and global) warming. Measured, however, in combination with the processes described above (trees disperse surface radiation through the production of ET), for most places around the globe, trees and forests are increasingly recognized as having a net cooling effect.

In what follows, we apply each element of this forest-water lens in turn to current analyses of the factors driving water availability in the Sahel. We will arrive at a complex picture of the many ways in which the strategic implementation of forest-water interactions can potentially facilitate improved landscape resilience in the Sahel.

4. Forest-water and land-atmosphere interactions – linking forest-water interactions to rainfall and climate in the Sahel

Broadly stated, forest-water and land-atmosphere interactions are important for arriving at a potential model of resilience in the Sahel. In what follows, we apply the above defined forest-water lens to land-atmosphere and forest-water interactions in the Sahel, with a specific focus on rainfall generation, agroforestry potential and surface cooling.

4.1. Precipitation-recycling, wind and weather patterns

According to existing estimates, the principal ET contributions to rainfall almost never originate from the location where re-deposition finally occurs (Ellison et al., 2012; van der Ent et al., 2010; Eltahir and Bras, 1994). In fact, the relative share of local precipitation recycling in local rainfall is quite small (on average around 8–12%) (Ellison et al., 2012). The principal ET contribution to rainfall derives from upwind locations. Much current research on the Sahel, however, neglects this fact. Lee et al., for example, associate increasing amounts of local vegetation cover with increasing amounts of rainfall (Lee et al., 2015). But while they provide a potentially logical explanation (increasing amounts of local vegetation produce increasing amounts of atmospheric moisture that can return as rainfall), they provide no analysis or validation to confirm that locally produced moisture does in fact return as local rainfall. Moreover, the more common phenomenon in other parts of the world is that locally produced ET will simply move on to fall as rain in other locations (van der Ent et al., 2010; Eltahir and Bras, 1994). Thus, the mechanism and links between ET and rainfall are at best under-developed.

Wind and weather patterns in the Sahel are complex and have been the subject of intensive study. On a particularly propitious day (March 7th, 2019), the wind patterns in this region are those pictured in Fig. 3. On this day, wind patterns illustrate moderate flows coming down from both the NW and NE parts of the African continent, as well as moderate winds coming up across the southern Atlantic coast. The outcome for some of the more central parts (e.g. in this particular case, almost the entire state of Burkina Faso), leads to significant wind speed reductions. While wind speeds typically decline over land surfaces (and are much greater over oceans), they decline even more over areas with forest (and vegetation) cover (Ellison and Ellis, 2019). Likewise, wind speeds over the Sahara are significantly higher than over other regions of West Africa (see e.g. Windy.com). For rainfall in the Sahel, southerly winds across the coast from the Atlantic must be strong enough to dominate the warm winds coming down across the Sahara. Including the day indicated above, over an estimated 10-day period significant rainfall was projected along the coastal region. However,

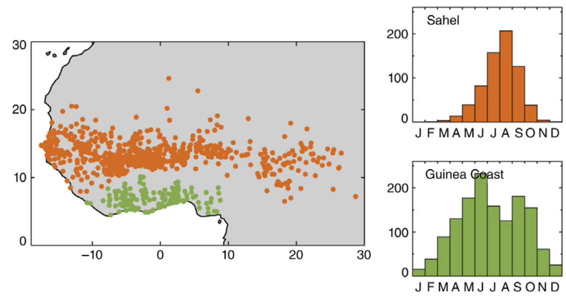


Fig. 4. Wet season in the Sahel compared to the Guinea Coast.
Source: Nicholson et al. (2018).

winds were reportedly not strong enough to carry moisture further inland than an imaginary line drawn around the northern parts of Korhogo, Tamale, Parakou and Abuja. Thus, for the most part, rainfall did not even reach the Sahel.

Such wind patterns are common across the Guinea coast and on into the Sahel. Moreover, the extent of wet season rainfall across the coast and in the Sahel differs significantly (Fig. 4). Favorable rainfall events in the Sahel generally occur within a small window, primarily June through September. Strong seasonality in Sahel rainfall, is driven by the positioning of the Inter-Tropical Convergence Zone (ITCZ), the space that forms between the tropical continental air mass (north-easterly winds) and the tropical maritime air mass moving from the Atlantic and across the southern, West African coast (south-westerly winds). The ITCZ shifts in response to temperature changes occurring both over land and changing SSTs (Vischel et al., 2019; Biasutti, 2019; Charney, 1975; Wilcox et al., 2010), moving further north during the rainy season (with a high point around 22° and its low point around 7°N) and enabling south-westerly winds to carry atmospheric moisture deeper into the interior.

When rainfall occurs in the Sahel, it comes primarily as a result of storms moving from East to West across the West African region. This finding is supported by remote-sensing data from the IMERG Global Precipitation Measurement project, which provides remotely-sensed, combined rainfall imagery based on combined data input from 12

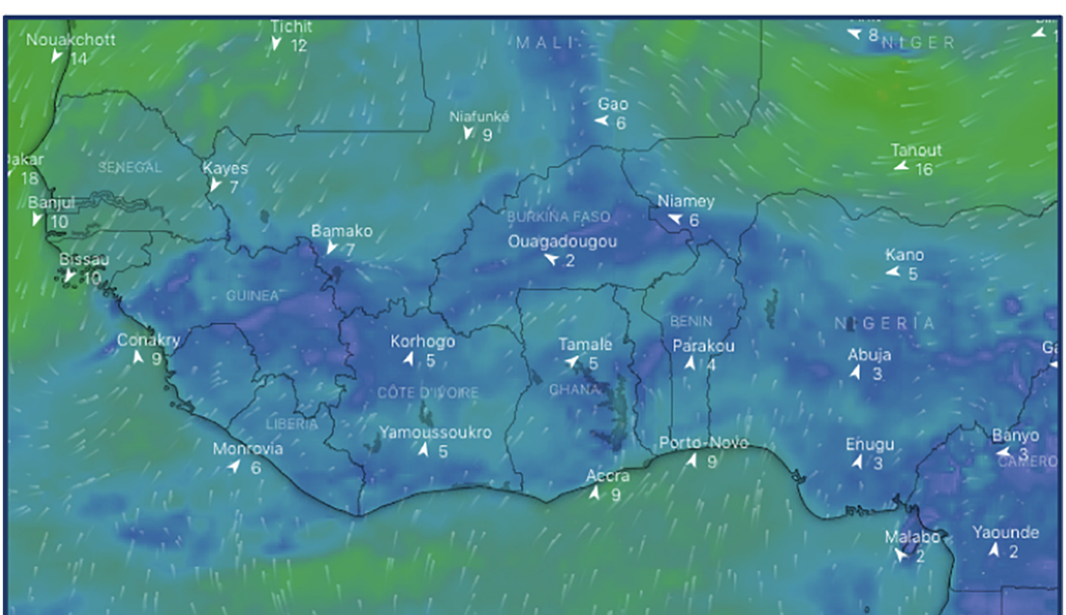


Fig. 3. Wind Patterns on March 7th, 2019. *Note*: slower windspeeds are highlighted by smaller arrows and blue to lighter purple colors, while faster windspeeds are indicated by bigger arrows and range from light green to darker green and turquoise.
Source: Image generated at Windy.com (© OpenStreetMap contributors) on March 7th, 2019.

satellites (Huffman et al., 2019). This strategy provides the most up-to-date method for visualizing rainfall in real-time, making it possible for researchers both to observe the movement of storm systems across land, as well as to see what happens beneath the cloud systems (for a 10-day, close to real-time window that also encompasses West Africa, see: https://svs.gsfc.nasa.gov/4285).

Several authors further note that the storm systems that break over the Sahel are favored by the African Easterly Jet (AEJ) which carries moisture into the Sahel region from the coast and provides wind shear against the wind systems moving from East to West across the African continent (Vischel et al., 2019; Abiodun et al., 2008; Cook, 1999). When the northward shifting ITCZ permits, these two dominant systems collide, pushing winds and rainfall further north into the Sahel. The westward moving storm system provides rainfall within a fairly precise band, with smaller amounts below 10° latitude and higher amounts between 10°-20° North. This band is clearly discernable in IMERG imagery that covers the wet season.

Many highlight that moisture supply to the region is very important for the occurrence of rainfall (Vischel et al., 2019; Abiodun et al., 2008; Keys et al., 2014; Cook, 1999). The predominant wind and weather patterns suggest rainfall events in the region likely incorporate moisture from both nearby sources, as well as from locations both further to the south as well as to the east. Data from Keys et al., for example, suggests some 10% to 40% of the rainfall in the Sahel region is promoted by tree, forest and vegetation-based ET production (Fig. 5) (Keys et al., 2016). Much of the tree, forest and vegetation cover producing ET-based atmospheric moisture that potentially falls over the Sahel lies closer to the southern coast of West Africa. Moreover, more local precipitation recycling may further enhance these wind and weather patterns. Thus, although most of the source moisture for rainfall in the Sahel likely originates from other locations, re-greening in the Sahel may also contribute to the rise in total annual amounts of precipitation.

While distinguishing adequately between oceanic and terrestrial sources of moisture production and their potential impact on rainfall is complicated, there are many reasons, in addition to the contribution of atmospheric moisture, why the land contribution is likely to matter. Spracklen et al., for example, note that winds passing through heavily forested regions more likely to lead to rainfall (Spracklen et al., 2012). And several authors suggest cloud formation itself is often promoted by forest cover (Morris et al., 2017; Teuling et al., 2017; Bosman et al., 2019). Finally, attention should also be paid to the potential role of forest-based aerosols as potential rainfall triggers (Morris et al., 2017) and carried from the South.

The wind rose data (Fig. 5) suggests prevailing winds tend to flow from the Southern Atlantic, across the more heavily forested areas and up into the Sahel and Sahara. However, the shape of the wind rose is highly sensitive to location. As one moves further north, deeper into the Sahel, the wind rose tips and is dominated by strong easterly and westerly winds. Though winds in the Sahel come from many different directions, those coming from the Sahara are not likely to bring moisture, while those originating either from the Atlantic and moving north-eastward over and through the forest and vegetation covered regions from the coast on up, as well as those moving into the Sahel from the East, are likely to provide the largest contributions of atmospheric moisture to rainfall in the Sahel.

4.2. Infiltration, soil moisture storage and groundwater recharge

More locally based land-atmosphere interactions are also important for the production of rainfall over the Sahel. However, what these land-atmosphere interactions actually consist of remains contested. Nowhere in the Sahel literature do we encounter a singular, clear picture of the mechanisms capable of driving local land-atmosphere interactions, since each set of authors predicts a different set of outcomes based on competing land-atmosphere interaction models (Charney, 1975; Mathon et al., 2002; Taylor and Lebel, 1998; Nicholson, 2015; Koster et al., 2011). Charney, for example, suggests albedo effects associated with the loss of vegetation cover in the Sahel drive surface warming through radiative fluxes, which in turn can bring about a shift in wind patterns, causing winds to sink across the southern margins of the Sahara, leading to more arid weather patterns (Charney, 1975). Charney et al. suggest a 14–35% rise in albedo results in a several degree southward shift in the ITCZ. These authors estimate this shift caused as much as a 40% decline in wet season rainfall in the Sahel during the early drought years in the 70's.

Analyses that look at the role of land-atmosphere interactions in triggering convection and rainfall, however, frequently either ignore

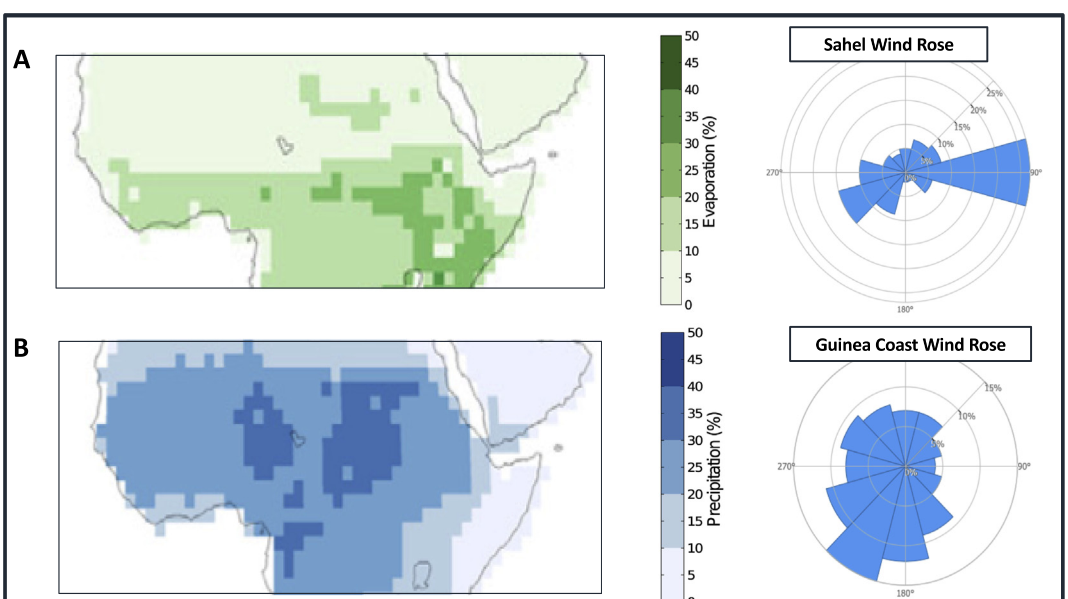


Fig. 5. Vegetation regulated evapotranspiration and precipitation, and wind roses for the Sahel and Southern West Africa Regions. *Notes and Sources:* Vegetation-based ET (A) and Rainfall from Vegetation Sources (B), adapted from Keys, Wang-Erlandsson and Gordon (2016). These modeled simulations capture immediate interactions with the atmospheric water cycle but do not consider changes in circulation, soil quality, runoff and water availability. We produced the wind roses for the southern West African and the Sahel using the Global Wind Atlas (globalwindatlas.info). The wind roses highlight the directional origins and quantities of annual winds along the Guinean coastal region and just inside the southern border of the Sahel.

the potential role and importance of vegetation cover (Biasutti, 2013; Giannini, 2010; Mathon et al., 2002), or suggest the explanatory factors are not so much vegetation cover itself, but rather other features of the landscape. The focus on mesoscale convective system rainfall, for example, looks primarily at interaction and feedback effects across soil moisture and the atmosphere (Mathon et al., 2002; Taylor and Lebel, 1998; Taylor et al., 2011). In Nicholson's review and analysis of the role of land-atmosphere interactions, the role of vegetation is primarily addressed in the context of the potential for abrupt change (Nicholson, 2015). Though Nicholson places some emphasis on these desert landscape vegetation dynamics, their explicit connection to rainfall remains largely unexplained.

The strongest suggestion that vegetation cover, or change in vegetation, may not be the key factor driving change in land-atmosphere interactions arises out of a focus on the role of soil moisture in predicting rainfall “memory”, by which authors typically mean that rain frequently falls in approximately the same locations as previously (Nicholson, 2015; Koster et al., 2011; Dirmeyer, 2006; Guo et al., 2006). However, why these land-atmosphere interactions might occur in the first place is not adequately explained. In this sense, the memory literature provides no real theory about the factors driving land-atmosphere interactions in the Sahel.

There are a number of reasons, however, why vegetation might positively impact land-atmosphere interactions. Several authors highlight the fact that this type of land-atmosphere interaction, which occurs primarily in very arid, almost desert-like environments, is primarily a function of the relative wetness of dryland soils (Dirmeyer, 2006; Guo et al., 2006). Moreover, only a few regions in the world represent hotspots for this type of land-atmosphere interaction – the Sahel and the US Great Plains. Thus, as we move across drylands to ever drier locations, convection events resulting from strong land-atmosphere coupling become less likely.

The principal driver of these land-atmosphere interactions may however most easily be explained by the role of soil moisture in producing evaporation and providing a source for additional transpiration that can then act as a trigger for convection and rainfall. Tree cover promotes litter fall and the decomposition of litter promotes higher soil carbon content, both of which support greater soil water retention. Together these factors positively influence and promote greater ET production potential. Finally, in the arid Sahel region, vegetation tends to be sparse and patchy. While moderate ET amounts are produced by the existing vegetation cover and evaporation from soil surfaces in patchy systems, denser tree cover and heavier foliage produce higher ET amounts, potentially surpassing the local ecosystem's potential to support vegetation and thereby depleting available water resources (Bargués-Tobella et al., 2020; Ilstedt et al., 2007).

Abiodun et al. remarks that by the time monsoon flows reach 9°N, they are already approximately 80% saturated with atmospheric moisture, requiring little additional lift and moisture in order for convection to occur (Abiodun et al., 2008). These findings are further supported by an extended literature suggesting the atmospheric moisture flows from further South play an important role in rainfall in the Sahel (Keys et al., 2014; Monteny, 1986; Monteny and Casenave, 1989; Savenije, 1995). The work on land-atmosphere coupling strongly suggests the additional element from local ET provides the additional moisture fluxes required to trigger lifting and convection. Moreover, where adequate amounts of tree and vegetation cover can successfully trigger infiltration, soil moisture storage and groundwater recharge, soil moisture retention is likely to be higher, and thus able to provide the required local ET.

On the other hand, areas without adequate vegetation are likely to dry out, with more rainfall lost to surface flows and rapid runoff. Thus, the small amounts of rainfall that do manage to infiltrate the subsurface are less likely to resurface as ET, especially without the help of root systems to bring it back and send it into the atmosphere where it can contribute to potential weather and storm systems. The only exception is when runoff lands in endorheic systems and builds ponds where the water can stagnate and evaporate (Leblanc et al., 2008). Overall, increased amounts of surface and river runoff mean that groundwater resources will be further depleted.

Descroix et al., who look at measures of the water balance from the perspective of individual river basins, highlight what they call the *Sahel Paradox*, the phenomenon that river runoff data has shown an increase in discharge, both during the severe drought period (70's–80's), as well as throughout the re-greening and increased rainfall period (90's and beyond). This phenomenon is ‘paradoxical’, because both periods should have witnessed reduced river runoff (via loss of rainfall during the drought period and increased tree and vegetation cover during the re-greening period). Moreover, during the re-greening period, runoff is approximately four times amounts measured during the previous wet period (1951–1967), despite comparatively smaller amounts of rainfall (Descroix et al., 2018).

The phenomena of severely declining rainfall (70–90's) and increased re-greening and vegetation cover (90's-present) should have had the opposite effect, reducing basin-level runoff. For the latter period, the authors appear to suggest the re-greening that has occurred has not adequately improved water infiltration potential, nor has it adequately affected the water retention capacity of the soil. The authors further note that in places where erosion has been particularly strong and gullying has occurred, plant growth has frequently regenerated only near the tops of gullies. Their explanation for increased runoff during the earlier drought period (70's–80's) is similar. Despite dramatic changes in precipitation, extreme drought, plant die-off and the impact of increasing population growth on vegetation use (e.g. fuelwood), tend to explain the rise in runoff.

The implicit suggestion, in particular for the current period, is that re-greening still has a long way to go before it can adequately regenerate the infiltration and groundwater recharge properties of the soil, and thus before re-greening would lead to larger amounts of water being retained and eventually evapotranspired. If we place this discussion of rainfall and river runoff in the context of the discussion on soil memory and its impact on land-atmosphere coupling and feedback effects, it suggests the existing landscape makes inadequate use of the available rainfall. Increasing amounts of rainfall should provide adequate moisture for ET, making it possible for that moisture to act as an additional rainfall trigger. Without adequate infiltration and soil moisture retention, however, too much water is lost to surface and river runoff and further results in negative downstream impacts (flooding, etc.). Moreover, since the ET-rainfall trigger has presumably not been adequately reactivated, current rainfall amounts may remain below their potential.

This perspective on tree and forest-based landscape regeneration potential in the Sahel contrasts sharply with experience in some other parts of the world. Thus, for example, as noted above, reforestation in the Loess plateau region in China exhibits the opposite dynamic, where potentially excessive reforestation has resulted in a substantial drop in the available runoff due to increased evapotranspiration (Feng et al., 2016). In the case of the Sahel, however, the opposite is true and based on current findings (Descroix et al., 2018), we are far from encroaching upon the limits to the available local water balance. Moreover, if the strategy proposed herein can be put in place, increasing rainfall, as well as a share of the problems associated with increasing rainfall intensity (Panthou et al., 2018), may potentially be directed away from runoff and toward improving the locally available water supply, land-atmosphere interactions and rainfall triggering. And even if predictions regarding future increases in rainfall due to global warming should turn out to be correct, more tree, shrub and forest cover will be beneficial, not less.

4.3. Agroforestry

As a goal, agroforestry has become increasingly popular (Reij and Garrity, 2016; van Noordwijk, 2019; Rosenstock et al., 2019). Sendzimir et al. note many benefits of trees in the landscape in the Sahel. Most importantly, these authors ascribe improvements in local resilience and agricultural productivity almost exclusively to the reemergence of woodland tree cover (Sendzimir et al., 2011). For many reasons, these authors associate increased tree cover with improved soil moisture and rising soil fertility, leading to greater overall agricultural productivity in the Sahel. Tree cover, in particular, is noted for attracting birds and other animals that leave behind manure, which, along with decomposing leaves and the infiltration of water into the soil, improves overall soil fertility.

Accessibility to water is generally favored by the impact of tree cover on hydraulic lift (Neumann and Cardon, 2012; Zimmermann and Elsenbeer, 2008; Bonell et al., 2010). Bogie et al. provide one of the more compelling studies on the potential in the Sahel region for using shrubs as a tool for raising water from the subsoil to crop root systems (Bogie et al., 2018) With a significant increase in the share of shrubs (*G. senegalensis*) planted alongside millet, these authors were able to raise millet productivity by a factor of 10. The relative increase in shrub growth was substantial, from a density of approximately 240 shrubs to an average of approximately 1666 shrubs per ha^{-1}. Though the shrub used typically grows in the range from 500 to 800 mm isohyets, this example remains instructive. Moreover, Sendzimir et al. note increased productivity for a broader range of crops (millet, sorghum, cowpeas, peanuts, hibiscus, sesame and cassava) (Sendzimir et al., 2011).

The infiltration, soil water storage and groundwater recharge elements of the agroforestry impact should be of great interest to the GGW community. The goals of the GGW, in particular, are focused not only on the goals of landscape restoration, but also on the goal of ensuring a resilient environment and ecosystem framework within which communities are able to ensure the future production of adequate agricultural output to ensure livelihoods. In this sense, the dual linkage between landscape resilience and agricultural productivity provides a further meaningful link to the goals of landscape restoration and the role of the social-ecological systems underlying it (Ifejika Speranza et al., 2014).

4.4. Terrestrial surface cooling

In the Sahel, where temperatures can reach almost 50 °C, added tree cover is recognized as a meaningful strategy for reducing temperatures to tolerable levels and providing respite from the sun. Thus, despite very high temperatures in direct sunlight, under trees and in the shade, temperatures can be as low as 35+ °C (Reij and Garrity, 2016; Reij and Winterbottom, 2015). Sendzimir et al., further provide circumstantial evidence pointing to the idyllic and harmonious synergy of systems that shade trees provide in the Sahel (Sendzimir et al., 2011). Temperatures are significantly cooler under trees and they provide much significant relief to people. These authors further note that livestock congregate under trees due to the shade, where tree litter biomass and dung from animals and birds combine to increase soil fertility and enhance seed dispersal.

5. Refining approaches to forest-water and land-atmosphere interactions in the Sahel

One might thus expect landscape restoration in the region to have a positive impact on the rainfall regime. Long-term historical deforestation and landscape degradation across the Sahel and on into the Guinean coast has presumably had a profound impact on the social and ecological resilience of the region. A large part of the Upper Guinean forest had disappeared already before 1900. As of 2013, as much as 90% of forest cover had been lost across this previously heavily forested region (Tappan et al., 2016). Fairhead and Leach provide corroborating forest loss data for individual countries from 1990 to approximately 1998 (Fairhead and Leach, 1998).

Deforestation continues in many places along the Guinea coast. Based on online Global Forest Watch data, a rough and ready analysis of change in regional forest cover with canopy of at least 30% density between 2001 and 2017 suggests the West African region may have lost an additional 14–15% of the remaining local forest cover. Though croplands produce considerable amounts of ET, on average they produce significantly less ET than forest (Ellison et al., 2019; Ellison, 2018; Oliveira et al., 2019). Moreover, crops typically have shorter roots unable to draw from moisture deep in the sub-soil. With reduced infiltration and groundwater recharge, there is likewise less water to access. The nature and timing of ET will also differ, being significantly reduced when crops are small and much greater when crops have grown to full height. Harvesting croplands, on the other hand, can break the ET chain across successive fields and basins. And fields that lie fallow for longer periods or become degraded may produce little or no ET. Thus, much of the ET production from this region has been substantially curtailed, with presumably negative effects on Sahel rainfall.

In the larger Sahel region, the most dramatic and rapid impact on forest cover loss arises with the emergence of colonial empires. Sendzimir et al. argue colonial regimes strongly favored the expansion of agricultural exports in order to service the homeland at the expense of tree and forest cover (Sendzimir et al., 2011). In the Maradi and Zinder regions in Niger, tree density dropped by more than 40% from about 70% in 1930 to approximately 24% in 1940. This decline in tree cover continued on through the century until about the early 80's, when it reached approximately 7%. In other regions, relative tree density may have bottomed out as early as 1975 and at significantly lower tree density levels (Reij et al., 2009).

Sendzimir et al. thus highlight the negative effects of social-ecological systems based on models of export-led economic growth geared, in particular, to providing adequate resource flows to France and other countries. Only once this system began to break down were traditional groups in the region able to re-establish social and political control over their lands and to plant more trees in the landscape. Recognition of the benefits creates feedback effects that further propel public support for trees in the landscape. And this creates favorable circumstances for the rise of a more resilient social-ecological system based on a revised model of pastoral sustainability (Reij and Garrity, 2016; Reij and Winterbottom, 2015).

Regreening of some of the region that comprises the Sahel proper has thus taken root and several studies provide evidence of increasing tree cover (Brandt et al., 2018; Dardel et al., 2014). The two southernmost regions of Niger, Maradi and Zinder, exhibit both increasing tree cover and improved rainfall (Sendzimir et al., 2011), though the links between them remain tenuous and have not been adequately validated. Brandt et al., in addition to noting the differences in tree density across the Niger and Nigerian borders, note that, in the Sahel, trees are more plentiful on farmland and in areas that are more arid (i.e. further north), but are less plentiful in more residential areas (Brandt et al., 2018). Hanan explains this seeming contradiction, noting that farmers in the more arid regions actively promote tree growth for potential livestock grazing and may also actively irrigate seedlings in order to encourage growth (Hanan, 2018). This vision of farmer managed natural regeneration (FMNR) has been documented and further promoted by Reij and others (Reij and Garrity, 2016; Reij et al., 2009; Reij and Winterbottom, 2015).

The precise extent of landscape restoration in the Sahel, however, is more complex. While multiple sources illustrate there has been some success in some regions (e.g. Burkina Faso, Mali and Niger) (Sendzimir et al., 2011; Reij and Garrity, 2016; Tappan et al., 2016; Brandt et al., 2018), in others, the evidence is often more sketchy. Certainly, one limitation has been the use of remote sensing as a technique for assessing growing season change over time. While regreening is likely to occur as a result of increased rainfall in the region, this is not necessarily an indicator of improvements in the *quality* of formerly degraded landscapes. Moreover, since much of the improvement in tree and forest cover has come about due to farmers actively regenerating trees in agricultural landscapes, this is not the same as the regeneration of more natural woodland landscapes that have been progressively degenerated due to population growth and excessive fuelwood use. Herrmann and Tappan, for example, find increasing loss of large trees and a surfeit of shrubs (Herrmann and Tappan, 2013), while Descroix et al. suggest considerably more landscape restoration would be needed in order to secure adequate soil moisture storage, infiltration and groundwater recharge (Descroix et al., 2018; Descroix et al., 2012).

5.1. Climatic boundaries

As illustrated in Fig. 6, the historical boundaries of the Sahel have shifted dramatically over time, highlighting the considerable difficulty in predicting future outcomes in a region with comparatively dramatic climate variability (Bossard, 2014). Previous analyses of the Sahelian rainfall zones (defined by *isohyets*) from 100 to 600 mm annual rainfall revealed a progressive southward migration by as much as 200 km due to the extended droughts of the 1970's–1990's (Bossard, 2009). But recent, gradual improvements in the rainfall regime have led to a gradual shift back toward the North (Bossard, 2014).

The pace and extent of climate change, both in the Sahel and other parts of the world, is significantly altering biome boundaries and challenging the capacity of trees and other forms of vegetation to keep pace (Keys et al., 2019; Aitken et al., 2008; Kremer et al., 2012). Both transformations (moderate re-greening and climate change) are presumably simultaneously influencing change in the Sahel. Even if the strategies proposed within the GGW framework can be effectively revised, questions remain regarding the viability of plant-based adaptation efforts under the primordial conditions of persistent climate change. Forest-water and land-atmosphere interactions in the Sahel thus appear challenged by the boundaries of the known world due to the uncertainty associated with climate change-related outcomes.

Ongoing desertification poses a significant threat in the Sahel. Staten et al. estimate the drier regions of the world have been expanding toward the poles at approximately 0.5° latitude per decade since around 1979 (Staten et al., 2018). Thomas and Nigam (2018) estimate the Sahara has grown some 10% since about 1920 (Thomas and Nigam, 2018). And Dai and others likewise predict many regions, including the Sahel, will witness increasing drought (Dai, 2013; Hill et al., 2018). Others have predicted additional potential shifts in climate and weather patterns resulting from changing land-atmosphere interactions (Abiodun et al., 2008; Charney, 1975). Schneider et al. project that cloud formation itself may be negatively impacted by progressive climate change and rising temperatures (Schneider et al., 2019). The fact that such transitions could forestall any plant-based strategy for improving the rainfall regime in regions like the Sahel cannot be emphasized enough.

Ongoing climate change thus potentially represents an upper bound to the goal of restoring landscape resilience. Even a more strategically focused, forest-water interaction-based landscape restoration strategy may be incapable of providing adequate guarantees of future survival should current rates of climate change and global warming proceed apace and should the Sahel experience another extended period of severe drought, as in the 1970's–1990's. By 2100, climate projections for the Sahel and the greater Middle East and North African (MENA) region

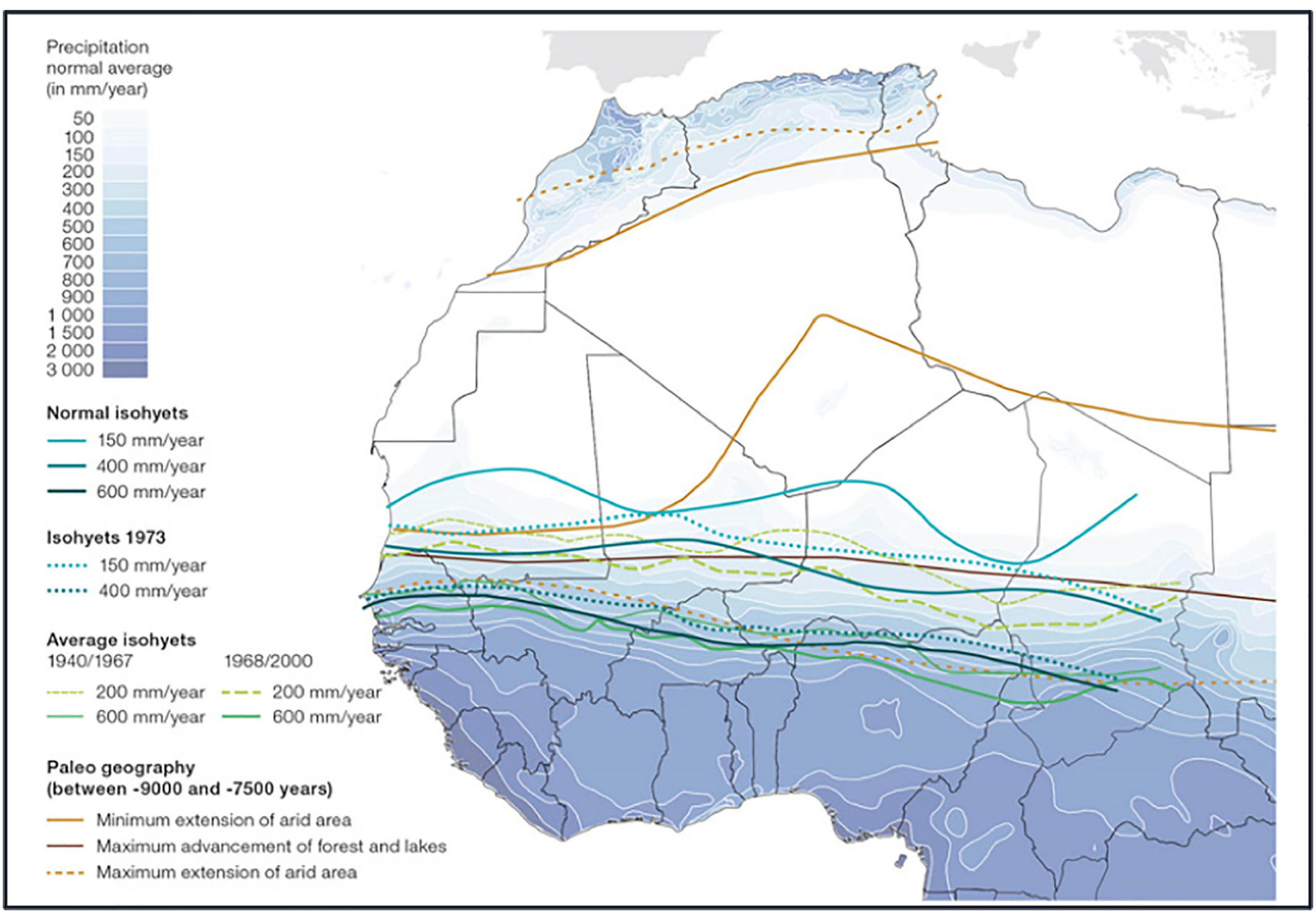


Fig. 6. The Shifting Boundaries of the Sahel.
Source: Bossard (2014).

suggest temperature increases of approximately +7 °C (Graves et al., 2019). This increase is reportedly enough to breach a humanly survivable threshold defined as a "wet bulb" temperature that rises above 35 °C (Sherwood and Huber, 2010). Even now, authors taking a more global perspective (Li et al., 2020; Mora et al., 2017), and those focusing specifically on the region around the Arabian Gulf (Pal and Eltahir, 2016), forecast increasing occurrences of extended heat wave events above humanly survivable thresholds.

No amount of regional adaptation can presumably hope to compensate for the core challenge of addressing climate change and its inescapable mitigation requirement. Persistent global warming and climate change impose an important upper threshold constraint on current efforts to improve landscape resilience in the greater Sahel region. Moreover, even with significant progress in reducing emissions and removing carbon from the atmosphere in other parts of the world, much of the Sahel region may still be significantly endangered by the current amount of built-in climate change that will occur as temperatures continue to rise, with unclear future impacts on total annual rainfall (Jones et al., 2009; Mauritsen and Pincus, 2017; Huntingford and Mercado, 2016). Though the outer Earth latitudes are typically seen as the regions experiencing the most dramatic temperature change, impacts in the Sahel are nonetheless highly problematic, in particular regarding their heat-related threats both to plant life and human welfare.

6. Conclusions

Given the long-term historical trend, it seems unlikely current improvements in tree and forest cover in the region have had any significant and positive impact on the Sahel rainfall regime. The historical record of ongoing deforestation and landscape degradation far outweighs the more recent, positive transition in the opposite direction. Continuous loss of atmospheric moisture supply from ever increasing shares of agricultural production, ongoing land use conversions and tree, shrub and forest loss may eventually spell the loss of the Sahel zone as we know it.

On the other hand, adaptation-related tree, shrub and forest restoration of agricultural and natural landscapes will likely have positive benefits for the regional and local hydrologic regimes. In this sense, the forest-water and land-atmosphere interaction lens provides a useful framework for better understanding the potential value of forest-water, land-atmosphere interactions in the Sahel and the greater West African region. Moreover, the role of forest water interactions and, in particular, the role of precipitation recycling, raise important questions about the most suitable strategy for improving green growth and resilience in the Sahel. Rather than propose a belt or wall of trees starting in the northern part of the Sahel region and butting up against the southern end of the Sahara, we should presumably be working on landscape restoration in the opposite direction, i.e. from the coast on into the interior.

This conceptualization of the advantages offered by increased tree and forest cover turns the GGW concept on its head and instead looks at forest-water interactions as a strategy for *bringing moisture back into the region* (rather than *keeping the desert out*). Forest-based atmospheric moisture production across the southern West African region matters for the reliability of rainfall in the Sahel. The production and transport of atmospheric moisture carried across this region by the African Easterly Jet (AEJ) presumably represents an important contribution. Tree and forest landscape restoration efforts should therefore focus both on the more humid, rapidly deforesting and degrading southern areas from the coast on up, as well as on into the northern most reaches of the Sahel. Moving from the coast to the Sahel, as the level of aridity increases, fewer and fewer trees should be planted per hectare of land. At the northern most reaches of the Sahel, tree and vegetation cover should remain comparatively sparse. On the other hand, unchecked deforestation and persistent landscape degradation represent a real threat to the future resilience, sustainability and human welfare of the entire region.

The application of the forest-water and land-atmosphere interaction lens highlights and further substantiates work on the advantages of farmer-managed natural regeneration (FMNR) efforts in the more arid regions of the Sahel. The role, in particular, of light tree and forest cover in supporting favorable infiltration, soil moisture storage and groundwater recharge, as well as the benefits of hydraulic lift and its contribution to agroforestry potential, appear both well-founded and relatively easy to conceptualize when placed in the context of the forest-water and land-atmosphere interaction lens. Moreover, if much of the monsoon-like convection that occurs over the Sahel is partly driven by more local land-atmosphere interactions, the best way to sustain it may be to promote continued FMNR-type landscape restoration across the broader Sahel.

Embedding this general discussion in the broader climatic envelope of which it is a part is key. We found no clear, dominant trend in rainfall recovery. Moreover, various regional and extra-regional climate systems influence rainfall patterns in the Sahel. In particular, strategies for aligning forest-water, land-atmosphere interactions with the African Easterly Jet and the West African Monsoon should be more firmly rooted in the context of restoration planning in the Sahel. Much room thus remains for future research to continue teasing out these intertwining, large scale, forest-water and land-atmosphere interaction relationships. Further validation of the potential for the forest-water, land-atmosphere interaction lens to enhance landscape resilience in the Sahel and in the West African region, as well as assistance in highlighting the social-ecological system parameters necessary for achieving such transformations represents the pivotal project of the 21st century.

Credit authorship contribution statement

David Ellison: Conceptualization, Investigation, Writing - review & editing. **Chinwe Ifejika Speranza:** Conceptualization, Writing - review & editing.

Declaration of competing interest

The authors declare no competing interests.

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