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Restoration of dryland ecosystem services is non-deferrable to sustain food security and mitigate climate change impacts

Global agricultural land available to support each human on Earth will decline ~32% by the year 2050 [1]. Rising population levels, the expansion of fuel crops and the loss of productive land due to unsustainable agricultural practises, urbanisation and climate change will have serious implications for food security. The year 2015 marked the tenth anniversary of the Millennium Ecosystem Assessment (MA) [2]. Many pressures reducing food security highlighted in the MA still require urgent action. These include sustainable use for food/energy production of the ~40% of the Earth's terrestrial surface considered to be 'drylands', and technological solutions to remediate degraded and damaged dryland ecosystems. At this important milestone for the MA, we address the challenges to the sustainability of drylands, and the frequent lack of consideration given to the role of water for "ecosystem services" such as climate regulation, carbon sequestration [3], maintenance of biodiversity [4] and water purification [5]. This review wishes to refocus on the importance of water in sustaining productivity in drylands, remediating degraded ecosystems and maintaining ecosystem services towards meeting the original aims of the MA and the Sustainable Development Goals of Rio 2020.

Drylands occur in regions with dry sub-humid, semi-arid and arid climates, where plant growth is limited by the availability of water. In drylands, it is the

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amount of water that determines ecosystem function. It may seem incongruous to contemplate that the role of water, the main element for life itself, has been largely neglected in the climate, agricultural and ecosystem analysis of drylands. This apparent oversight in the consideration of the function of water in drylands is perhaps due to the predominance of climate models concerning tropical, sub-tropical and temperate regions, where water is more abundant, and the link between water and carbon cycles is less evident [6].

The degradation of drylands is often associated with disruption to the hydrological cycle; without water, the provision of dryland ecosystem services progressively declines and desertification begins. In drylands, water acts as a 'climate regulation valve' through its effects on ecosystem processes; therefore any assessment of the role of drylands in the global climate system should reflect the fundamental importance of water [7]. The role of water in the climate system is complex, unlike carbon, it is comparatively difficult to characterise how water will interact with climate over different temporal and spatial scales [8]. For example, a warmer Earth may result in regional increases in aridity and accelerated land degradation, but the expansion of deserts also causes higher global albedo and cooling [9-12]. Conversely, as global temperatures rise, enhanced evaporation may induce a more active hydrological cycle, causing increased storminess and terrestrial run-off; yet a cloudier planet would also have greater albedo [13]. Recent models have attempted to incorporate metrics quantifying the role of transpiration and water in the climate system [8, 14, 15]. However, further work is required to fully integrate the ecological impact of water on carbon dynamics in drylands.

The importance of the hydrological cycle in the regulation of ecosystem services and climate is evident in the 'biotic pump' [16]. Like any other physical bodies, plant canopies intercept solar radiation and then release long-wave radiation that heats the surrounding air (known as the greenhouse effect). Moreover, as the vegetation transpires water through the soil-plant-atmosphere continuum, the air above canopies becomes moist and warm. As warm air then rises reaching higher elevations, driven by expansive motion of its molecules, it eventually cools and water vapour condenses. The release of latent heat forms an area of low pressure, and results in a pressure gradient that drives the movement of air, and in particular, the input of more humid air from adjacent regions. This «biotic pump» facilitates the transport of water over continents [17]. In areas where deforestation has occurred, the subsequent disruption to the biotic pump has led to reductions in precipitation many thousands of kilometres away [18, 19]. For example, the conversion of forest to agricultural land in western Kenya has led to droughts and land degradation in the East of the country [20]. While the underlying cause of this land degradation is disruption to the biotic pump, its effect on the climate system will not only be apparent in the hydrological cycle but also through the release of carbon and lower biotic uptake and storage of carbon dioxide. It is the interconnectivity of the hydrological cycle, through the action of processes such as the biotic pump, that makes water a fundamental driver in the Earth's climate system and central to efforts to mitigate climate change and restrict the expansion of deserts.

The regulation of ecosystem services by water is evident during desertification; particularly in fragile environments where the balance between water sources and sinks is less robust. The causes and processes involved in land degradation are interwoven; disturbance of an ecosystem through loss of vegetation cover, climate change and alteration in precipitation patterns or local hydrology can shift the balance between potential and actual evapotranspiration (Fig 1). Any increase or prolonged persistence in the divergence between actual evapotranspiration and the level that the ecosystem is capable of sustaining will result in denudation of the land and degradation of ecosystem services. The resultant loss of vegetation cover increases land surface temperatures and further enhances potential evapotranspiration [21]. In conjunction with soil erosion, the reduction of soil water holding capacity, increases susceptibility to fire and the loss of nutrients and carbon. This is a 'vicious circle', where land degradation progresses to desertification and the consequent formation of barren 'dust bowls', where all ecosystem services are lost. Nevertheless, such scenarios are not irretrievable. There are ways to remediate damaged drylands through technological and ecological solutions that manipulate water on an ecosystem level, inducing a 'virtuous circle' to restart the biotic pump.

A number of large-scale projects have attempted to restore the vegetation of degraded and desert lands [22]. Modification of the hydrology of the Negev desert, Israel, to increase ground-water stored in aquifers and reduce run-off has permitted the establishment of the Yatir Forest [12]. The extensive planting of drought tolerant trees has affected radiative forcing and altered regional climate, resulting in a cooler land surface but warmer air above the vegetation, and transpiration releasing water-vapour into the atmosphere [23]. The conifers that compose the Yatir forest have adjusted their photosynthesis to exploit favourable growth conditions earlier in the year (i.e. during less hot months) in comparison to plants growing in more northerly forests. Similar large-scale re-vegetation of desert/degraded dryland has been undertaken in China [24] and planned for Sahara and Sahel [25]. These projects require extensive technological, environmental and social co-operation of stakeholders at local to national scales. For example, a lack of local consultation, education or economic development may result in over-exploitation of trees as a source of fuel [2]; while inappropriate selection of plant species or insufficient irrigation during seedling establishment may lead to a significant loss of vegetation cover [26]. Nevertheless, if successful, these projects could have significant benefits in terms of reduced dust, increased precipitation, provision of food/fuel, carbon sequestration, soil stability, enhanced biodiversity, and overall mitigation of climate change.

The remediation and re-vegetation of drylands requires increased input of water and large-scale tree planting to modify the ecosystem towards the point of stability where actual and potential evapotranspiration become balanced (Fig 1). This may necessitate novel irrigation technologies, utilisation of irrigated 'nurse' trees to facil-

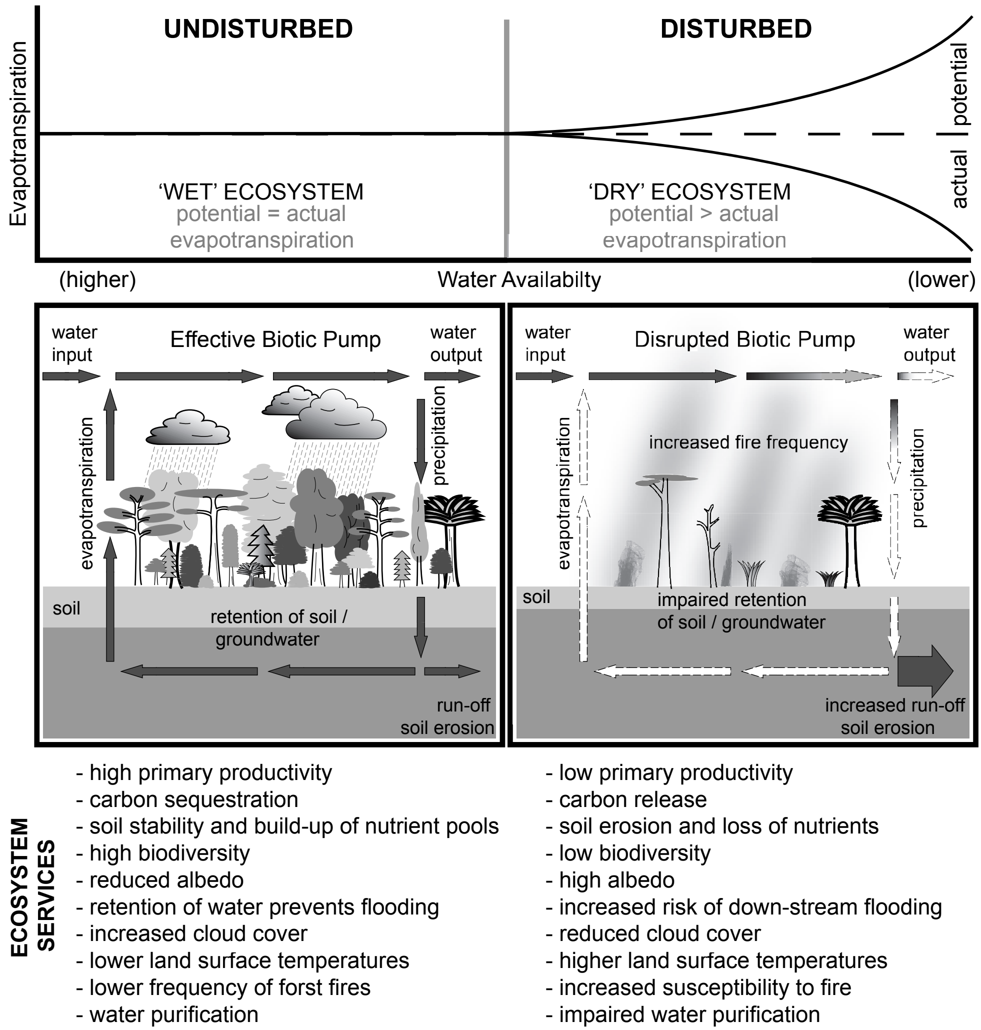

Fig. 1. Illustration of the role of water in the maintenance of climate stability and ecosystem function via the role of the biotic pump in disturbed and undisturbed ecosystems. As an ecosystem becomes degraded via reduced water availability and/or loss of vegetation cover, then potential evapotranspiration exceeds actual evapotranspiration leading to desertification: this disrupts the biotic pump leading to a vicious circle of land degradation. An increase in water availability over an ecosystem level will reduce the disparity between potential and actual evapotranspiration, possibly allowing re-vegetation of previously degraded land. Re-drawn from Hobbins *et al.* [28], Aragão [18], Maestre *et al.* [4].

itate the establishment of surrounding vegetation [27], the re-use of waste-water or the modification of local hydrology to increase aquafers and reduce run-off speed and intensity. Given the challenges posed by population growth and climate change, as the world's largest terrestrial biome, drylands will play a central role in climate regulation and the production of food/fuel crops. To fully utilise the potential of drylands, an understanding of the role of water in the regulation of ecosystem services and the coupling of the hydrological and carbon cycles will be required. This will necessitate improved empirical data and modelling, to effectively characterise how water underpins dryland ecosystem processes. The current lack of acknowledgement of water in the regulation of dryland ecosystem services jeopardizes the sustainability of these delicate ecosystems and negates their importance to global climate. The impact of climate change and over-exploitation is already evident in the 20% of drylands that are degraded [28]. Predictions of increased drought frequency and duration, so-called 'mega-droughts', will escalate desertification processes and the formation of ecologically barren dust-bowls [29, 30]. The fragility of these ecosystems, and the nature of the pressures they experience, leaves little time for action to prevent further climate and ecological damage.

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