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A characterisation model to address the environmental impact of green water flows for water scarcity footprints

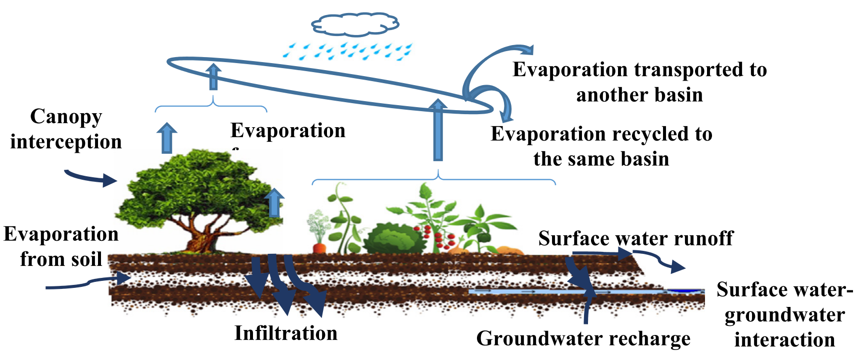
Paula Quinteiro [a,*], Sandra Rafael [a], Pedro Villanueva-Rey [a,b], Bradley Ridoutt [c,d], Myriam Lopes [a], Luís Arroja [a], Ana Cláudia Dias [a]

[a] Centre for Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
[b] Department of Chemical Engineering, Institute of Technology, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain
[c] University of the Free State, Department of Agricultural Economics, Bloemfontein 9300, South Africa
[d] Commonwealth Scientific and Industrial Research Organisation (CSIRO), Private Bag 10, Clayton South, Victoria 3169, Australia

HIGHLIGHTS

- Development of global spatially differentiated green water scarcity CFs for LCA.
- Potential impact of ET on blue water production and green water recycled into the basin.
- CF_{WS} and CF_{WA} show high variability mostly in the northern hemisphere.
- Uncertainty of CF_{WS} and CF_{WA} is high due to changes on green water availability to ET purposes.

GRAPHICAL ABSTRACT



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ABSTRACT

The development of methods to assess the potential environmental impact of green water consumption in life cycle assessment has lagged behind those for blue water use, which are now routinely applied in industrial and policy-related studies. This represents a critical gap in the assessment of land-based production systems and the ability to inform policy related to the bio-economy. Combining satellite remote sensing and meteorological data sets, this study develops two new sets of spatially-differentiated and globally applicable characterisation factors (CFs) to assess the environmental impact of green water flows in LCA.

One set of CFs addresses the impact of shifts in water vapour flow by evapotranspiration on blue water availability (CFWS) and the other set of CFs addresses moisture recycling within a basin (CFWA). Furthermore, as an

Abbreviations: 1 − a, Fraction of ET_t that is estimated as being the green water ET from soil and vegetation (dimensionless); $AWARE_y$, Available water remaining blue water scarcity CFs (in m^3/m^3); BIER, Basin internal evaporation recycling ratio (dimensionless); CF_{green}, Global weighted-average green water scarcity CFs (in mm/mm_{eq} or m^3/m^3_{eq}); CFs, Characterisation factors; CF_{WA}, CFs at green water and atmosphere interface (in mm/mm_{eq} or m^3/m^3_{eq}); $CF_{WA,\ max}$, Maximum value of the CF_{WA} (in mm/mm_{eq} or m^3/m^3_{eq}); CF_{WS}, CFs at green water and soil interface (in mm/mm_{eq} or m^3/m^3_{eq}); $CF_{WS,\ max}$, Maximum value of the CF_{WS}(in mm/mm_{eq} or m^3/m^3_{eq}); ET, Water evaporated and transpired (in mm/yr or m^3/ha/yr); ET_{eff}, Total effective ET (in mm/yr or m^3/ha/yr); ET_g, Green ET from soil and vegetation growth (in mm/yr or m^3/ha/yr); $ET_{g,\ eff}$, Regional annual effective green ET (in mm/yr or m^3/ha/yr); $\overline{ET}_{g,eff}$, World average annual effective green ET (in mm_{eq}/yr or m^3_{eq}/ha/yr); ET_{pot}, Potential ET (in mm_{eq}/yr or m^3_{eq}/ha/yr); ET_{PNV}, Green ET of the reference land use (in mm/yr or m^3/ha/yr); $ET_{PNV,\ eff}$, Effective blue and green ET of the reference land use (PNV) (in mm/yr or m^3/ha/yr); ET_t, Global blue and green ET (in mm/yr or m^3/ha/yr); LCA, Life cycle assessment; LUCC, Land-use and land-cover change; MODIS, Moderate resolution imaging spectroradiometer; P, Average annual precipitation (in mm/yr or m^3/ha/yr); PNV, Potential natural vegetation; T, Air temperature (in °C); WA, Green water and atmosphere interface; WS, Green water and soil interface; w_{max}, Maximum value of w_T (dimensionless); w_T, Capability of plants to store water in the root zone for transpiration purposes (dimensionless).

* Corresponding author.
E-mail addresses: p.sofia@ua.pt (P. Quinteiro), sandra.rafel@ua.pt (S. Rafael), pedro.villanueva@usc.es (P. Villanueva-Rey), Brad.Ridoutt@csiro.au (B. Ridoutt), myr@ua.pt (M. Lopes), arroja@ua.pt (L. Arroja), acdias@ua.pt (A.C. Dias).

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additional and optional step, these two indicators are combined into an aggregated green water scarcity indicator, representing the global variability of green water scarcity. The values obtained for CFWA show that there are significant changes in green water flows that were returned to the atmosphere in Alaska (covered by open shrublands) and in some central regions of China (covered by grasslands and barren or sparsely vegetated land), where precipitation levels are lower than 10 mm/yr. The results obtained for CFWS indicate that severe perturbations in surface blue water production occur, particularly in central regions of China (covered by grasslands), the southeast of Australia (covered by evergreen broadleaf forest) and in some central regions of the USA (covered by grassland and evergreen needleleaf forest).
The application of the green water scarcity CFs enables the evaluation of the potential environmental impact due to green water consumption by agricultural and forestry products, informing both technical and non-technical audiences and decision-makers for the purpose of strategic planning of land use and to identify green water protection measures.

1. Introduction

Green water use associated with land-use and land-cover change (LUCC) leads to shifts in water vapour flows, which are relevant in supporting ecosystem resilience and the global food supply (Ran et al., 2016; Rockström and Gordon, 2001). Water vapour flows consist of the water evaporated and transpired (ET), and more specifically, water vapour from soil evaporation, wet canopy evaporation and plant transpiration at the dry canopy surface that returns to the atmosphere. Shifts in water vapour flows arising from LUCC can lead to abrupt and irreversible spatial and temporal precipitation patterns, resulting in increased green water scarcity and surface blue water availability (Jung et al., 2010), which can hamper the insurance of both human and environmental flow requirements to fulfil the overall resilience of aquatic and terrestrial ecosystems. Precipitation gives rise to two components, namely: (1) green water, which refers to precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation, and also refers to the rainwater incorporated into harvested crops or wood (Hoekstra et al., 2011); (2) blue water, which refers to surface and groundwater, i.e., water in freshwater lakes, rivers and aquifers (Hoekstra et al., 2011).

Green water is crucial to support plant growth in rain-feed regions, while in semi-arid, arid and dry-humid regions, a complementary irrigation with blue water resources may be necessary to ensure plant productivity (Rockström and Falkenmark, 2006). A comparison of different models (hydrological, vegetation growth, water resources management and economic) showed that green water consumption for agricultural production is about 4 or 5 times greater than the blue water consumption in global crop production (Hoff et al., 2010). Therefore, green water is a critical natural resource that requires careful management and allocation for all users competing for it. Green water flows, which refer to the portions of green water used by soil and vegetation that is ET (Quinteiro et al., 2015), are affected predominantly by land management and land use change. For instance, when a forest is replaced with non-irrigated crop fields, the amount of ET from vegetation is most often reduced, which may have effects on the atmospheric vapour flow, and therefore, contribute to a decrease in precipitation levels (Deutsch et al., 2010; van Dijk and Keenan, 2007).

Life cycle assessment (LCA) is a methodology that quantifies the potential environmental impacts of a product or service over its entire life cycle on a wide range of environmental issues, such as climate change, eutrophication, acidification, toxicity and land use (ISO, 2006). The consideration of water use in LCA has been rapidly evolving in recent years (e.g., Berger et al., 2014; Hanafiah et al., 2011; Kounina et al., 2013; Motoshita et al., 2010; Quinteiro et al., 2015, 2017; Schyns et al., 2015; Tendall et al., 2014). Despite the relevance of green water flows for vegetation, studies have been mainly focusing on blue water. In this context, several impact LCA-based water footprint methods, considering blue water scarcity/stress, have been developed (Bayart et al., 2014; Boulay et al., 2017; Kounina et al., 2013; Milà i Canals et al., 2009; Motoshita et al., 2014; Pfister et al., 2009; Pfister and Bayer, 2014; Ridoutt et al., 2010).

The development of methods related to green water scarcity has progressed much more slowly, overlooking the opportunity cost of green water resources and its relevance to a bio-economy strategy. In fact, there are only a few studies that develop a framework for estimating green water flows or green water scarcity characterisation factors (CFs) (e.g., Lathuillière et al., 2016; Núñez et al., 2012, 2013; Quinteiro et al., 2015). Lathuillière et al. (2016) proposed a method to estimate precipitation reduction potential due to LUCC, and the resulting damage to terrestrial ecosystems due to LUCC in seasonally dry, semiarid and arid regions. Núñez et al. (2013) estimated the ET of the potential natural vegetation (PNV) (which is taken as a baseline to establish the green water inventory) on global dry lands. No green water scarcity CFs have been developed. Núñez et al. (2012) assessed the environmental impact of green water consumption by energy crops in Spain by developing green water scarcity CFs to the interface between green water and soil, i.e., how a change in green water availability affects the regional long-term availability of surface blue water. Quinteiro et al. (2015) proposed a method to assess the impacts on terrestrial green water flows that address reductions in surface blue water production caused by reductions in surface runoff due to land-use production systems. Based on this method, they derived CFs for Portugal. Despite the efforts to model the impact pathways linked to ET, precipitation and surface blue water production, none of the studies have so far considered blue water scarcity, which is closely linked with the changes in green water flows and LUCC. In addition, none of the studies derived green water scarcity CFs on a global scale.

As water consumption varies spatially depending on crop types, irrigation techniques, soil characteristics and water availability (Pfister and Bayer, 2014), the related blue water scarcity CFs also vary from place to place. Focusing only on blue water consumption does not give a very accurate picture of the potential environmental impact. Similarly, only observing net green water flows does not give an indication of how changes of green water flows due to LUCC affects the availability of green water to field crops and to surface runoff. The green water scarcity CFs make it possible to assess the relevance of net green water flows across a life cycle or between different alternative land-use production systems in different regions. Following the purpose of improving the management and the efficient use of water resources to the increasing constraints on water availability for food, fibre or bio-based products, blue water scarcity is now routinely included in industrial and policy-related LCA studies (Berger et al., 2012; Hess et al., 2015; Peña and Huijbregts, 2014; Tom et al., 2016). Green water CFs have the potential to be used in a similar way. Taking into account the complex interactions between plants/roots, soil and green water availability, the green water CFs allow us to characterise the potential impacts caused by perturbation in green water flows of land-use production systems. By excluding the green water in LCA studies, the land-based production