A blue water scarcity-based method for hydrologically sustainable agricultural expansion design

Nikolas Galli*[1], Davide Danilo Chiarelli[1], Livia Ricciardi[1], Maria Cristina Rulli[1]

*nikolas.galli@polimi.it

1 Department of Civil and Environmental Engineering, Politecnico di Milano, Milano, Italy

Key points

A new methodology for designing sustainable agricultural expansion while preventing water scarcity is developed

The method selects, among areas with high water availability, those not onsetting water scarcity either locally nor downstream

An application on coffee expansion in Kenya identifies more areas than foreseen by policy, leaving action space for further selection criteria

Abstract

At the heart of the vision of sustainable development and intergenerational responsibility lies the prudent use of natural resources. Agriculture is a key sector both in terms of resources consumed and of goods and services provided. Recently Its intensification and expansion have been studied and their sustainability evaluated, often with a particular focus on water management. While, in literature, possible agricultural strategies have been based on local water availability and, in some cases, downstream effects of such strategies have been evaluated, a method to identify and quantify hydrologically sustainable land use and crop use changes directly accounting for downstream effects is yet to be defined. Here we propose a framework to assess hydrological sustainability of land use and crop use changes, preventing both in situ and downstream effects. We apply this framework on the case study of coffee plantations expansion in Kenya, a sector that is seeing, and is planned to see, a rapid growth, given its potential in promoting agricultural, economic, and social development, not without risks associated to hydroclimatic change. We simulate the hydrological alterations caused by coffee plantation expansion onto available suitable areas, and use these simulations to identify areas where the expansion does not generate water scarcity either in situ or downstream. The assessment of hydrological suitability proves effective in preventing water availability reduction. Areas selected for expansion present similar total water footprints as currently used areas, but with higher precipitation-generated water availability. The proposed methodology identifies and quantifies areas in a physically robust, and thus transparent, way, also maintaining flexibility to the selected expansion scenario and low data intensity. This makes this framework a potentially easily replicable methodology for planning sustainable agricultural development within planetary boundaries.

Introduction

The focal point of sustainable development is the rational use of resources, aimed not only at satisfying current needs, but also at guaranteeing the fulfilment of the needs of future generations, who indeed occupy a prominent place in this vision (Brundtland, 1987). Water resources are at the core of many of the main global and regional challenges our planet is facing. Freshwater is mentioned as one of the Planetary Boundaries (Gerten et al., 2013; Gleeson et al., 2020; Rockström et al., 2009), it constitutes the main object in one of the United Nations (UN) Sustainable Development Goals (SDGs), SDG6, while appearing in other four (SDGs 3,11,12,15) and being indirectly involved in at least other two (SDGs 2,7) (UN, 2020). In fact, it is well known that freshwater is an essential ecosystem service flow(Gerten et al., 2013), a fundamental resource for the production of food and energy (D'Odorico et al., 2018; FAO & Food and Agriculture Organization of the United Nations, 2014), and the constitutor of many basic human services (UNDP, 2016). Among other sectors, agriculture plays a key role in meeting the food, fibre, and energy demand, but it is also the largest natural resources consumer, in particular concerning freshwater use. In fact, 70% of the world water use is linked to agriculture (Siebert & Döll, 2010), and this amount is expected to increase even more in order to meet the future rise in demand driven by population growth, energy policies and changing dietary habits (Godfray et al., 2010).

Accurately assessing demand for freshwater resources – both in terms of timing and magnitude – is critical for understanding the water sustainability of agriculture. A better understanding of agricultural water needs could be used to identify those places where water demand and its variability could potentially increase or compromise the reliability of crop production, and for formulating solutions to promote sustainable water management.

Recent studies have quantified the sustainably attainable additional food production (Rosa et al., 2018, 2020) and evaluated possible crop production optimization strategies based on local water availability (K. F. Davis et al., 2017, 2019). Other studies analysed the downstream effects of such mechanisms (Chiarelli, Passera, Rulli, et al., 2020; Galli et al., 2022). However, there still is the need to establish a method which enables to identify and evaluate, globally and locally, under what conditions certain land use and crop use choices and changes may be sustainable. From a hydrological point of view, land use and crop use change impact the water balance in more than one way. The most direct impact is likely the localized increase in water scarcity because of an increase in blue water demand associated to irrigation, with the same water availability. In a more indirect way, land use and crop use change produce variations in water scarcity because the higher evapotranspiration rates of the new agricultural areas reduce the formation of blue water (Ricciardi et al., 2022). Also, water scarcity can propagate downstream. Assuming, for the sake of simplicity, to divide a watershed in an upstream region and a downstream region, increased demand, or decreased formation, of blue water upstream can produce water scarcity downstream, if upstream blue water was originally used downstream. These upstream-downstream effects of water scarcity can arise also in absence of upstream water scarcity: even limiting new upstream irrigation water uses to the amount that does not generate water scarcity where it is used, this new water use produces downstream water scarcity if that volume originally flowed downstream and was used to satisfy the downstream blue water demand(Chiarelli et al., 2022). How can the knowledge of these mechanisms be leveraged to design sustainable agricultural expansion and intensification? While water scarcity assessments can provide the quantitative base for a more hydrologically conscious formulation of sustainable development policies, strategies, and solutions (Z. Hussain et al., 2022), the challenge is to go beyond providing ready-to-use assessments of baseline water scarcity indicators and basing policy recommendations on their interpretation. Can water scarcity assessments be used to further bridge this science-policy gap, directly basing sustainability policies on water scarcity related targets? The answer to this question, besides being of value within science, can play an essential role in economic and political decision making. Economic development strategies must be considered according to, among other criteria, sustainability and resource-based feasibility. In this context, the matter of cash crops is highly debated, as their water requirements have often proved to be higher than those of the main food crops (Chiarelli, Passera, Rulli, et al., 2020). Therefore, a thorough sustainability assessment of such policies is needed to avoid transitory benefits which may otherwise worsen the water scarce conditions in the country on the long terms. Investigations on the potential increase of cash crop production require attention to the natural resources (i.e. suitable land and water) demand and availability as well as to the direct and indirect effects of natural resources use.

Here we propose a methodology to assess hydrological sustainability of land use and crop use changes, evaluating both in situ and downstream effects of water use. We apply this framework on the expansion of coffee cultivations an example of a water intensive cash crop whose expansion in subtropical countries has seen a rapid and ongoing boom (FAO, 2019a). We select Kenya as a case study, where coffee also has a recognized potential in promoting agricultural, economic, and social development (International Coffee Organization, 2019). Coffee is also the most water-intensive crop in Kenya (in terms of water volume per produced tonne), the third crop by total volumetric water consumption, and the most important component of the Kenyan virtual water export (Mekonnen & Hoekstra, 2011). The coffee production and export sector in Kenya, among the biggest in Africa, currently employs around 5 million people (L. A. S. Hussain et al., 2020). In contrast to many other coffee exporting countries, in Kenya smallholders account for most of the production. Some 700,000 small scale farmers, organized in hundreds of cooperatives to which they sell their cherries, account for 80% of the country's coffee production (Mugo et al., 2019). The rest are around 3,000 large coffee estates, selling their own coffee directly (L. A. S. Hussain et al., 2020). The Kenyan government recently approved a plan for the development and expansion of agriculture, including coffee plantations, in order to promote agricultural and economic development (Agriculture and Food Authority (AFA), 2018b). Growth rates for the coffee sector in Kenya are increasing, moving from a less than 10% growth in 2017/18 with respect to the previous season(Agriculture and Food Authority (AFA), 2018a) to an almost 30% increase in 2020/21 with respect to the previous season (Agriculture and Food Authority (AFA), 2021). Part of this increase in production is associated to agricultural expansion(Agriculture and Food Authority (AFA), 2021). However, policy plans like this often miss an in-depth hydrological analysis of the impacts connected to the expansion of such water-demanding crops, especially in light of the well-known environmental impacts of agricultural expansion, often deemed higher than those, for instance, of yield gap closure by agricultural intensification (D'Odorico et al., 2018). Water scarcity- and food insecurity-related consequences of poorly planned agricultural policies may derail the very same plan they arose from. Evidences of such backfiring can be observed, for instance, in the United Arab Emirates, where agricultural development and production saw a rapid boom in the early 2000s only to come to a quick stop shortly after, caused by the progressive fossil ground water depletion (Sherif et al., 2021). A similar situation has been observed in India since the late 60s (K. F. Davis et al., 2018). The then adopted self-sufficiency policy in cereal production, has led, in the following decades, to a steady lowering of the groundwater table (Rodell et al., 2009). Kenya is facing a situation of acute water and food insecurity, which will be worsened by hydroclimatic change (Ngaira, 2009). Therefore, boosting coffee production in Kenya would will improve the livelihoods of local people and generate export revenue only if it is planned within resource boundaries.

On one hand, coffee is a plant with well-defined optimal growing conditions, regarding a broad spectrum of climatic, morphological, chemical and pedologic parameters (Allen et al., 1998; IIASA & FAO, 2012). All these parameters have to be taken into account to maximize the yield. On the other hand, increased coffee production is associated to increased natural resource consumption, expecially water (Mekonnen & Hoekstra, 2011). To guarantee the environmental sustainability of the additional coffee production, it must not induce resource scarcity as much as it must not conflict with demands for the same resources coming from crucial activities. To assess whether it is possible to expand coffee plantation in a sustainable way, we start the crop expansion from the suitable areas for coffee cultivation as reported by the Global Agroecological Zones Data Portal (GAEZ) (FAO, 2021). Then, we use hydrological modeling of water scarcity to narrow down the selection of these areas to those not generating water scarcity, not only locally (i.e. where coffee is or may be actually cultivated), but also in the downslope and downstream areas.

Methods

Kenya is an African country extending over 580370km^2 in the Eastern part of the continent, on the Indian Ocean coast. The population of Kenya was estimated as 51 million in 2018 and it is expected to have a sharp growth in the next decades since it will more than double (UN, 2019). 37.5 million people live in rural areas, and almost 70% of the economically active population worked in the agricultural sector in 2014 (FAO, 2016a). The high diversity of the Kenyan morphology, the presence of the ocean and of major inland water bodies, and the low latitudes create a climate that ranges from arid to equatorial through humid subtropical in the uplands (Kottek et al., 2006). The rain pattern is bimodal, with a first rainy season from March to May and a second one from October to December. The concentration of water towers in the central-western area of the country generates inhomogeneity in the catchments' water availability, and most of the catchments are shared with neighbouring countries (FAO, 2015, 2016b). The total actual renewable water resources (TRWR) correspond to a per capita value of 617 m3/year, which is just above the 500m3/year absolute water scarcity threshold (Falkenmark, M, 1989; FAO, 2016b).

According to (FAO, 2019b), it is estimated that in Kenya the area harvested with coffee in 2018 was 115570 ha, having agricultural yield of 0.358 ton/ha and crop production of 41375 tonnes.

We base our analysis of the sustainable coffee extensification on spatially distributed agro-hydrological simulations for different land use scenarios in Kenya. To guarantee effectivity while countering the risk of resource depletion, the extensification of coffee cultivation is designed considering the plant characteristics and optimal growing conditions. The elevation is needed to guarantee the ideal temperature range that delays the bean ripening increasing coffee quality and prevent pests (A. P. Davis et al., 2012; Jaramillo et al., 2011). A higher temperature would affect the plant’s photosynthesis, resulting in stress, whereas lower temperatures increase the risk of frosting. The slope is required to improve air drainage and reduce frost damage (Valipour & Eslamian, 2014), but it has to be gentle to prevent soil erosion. The correct aspect assures a good sun exposure. The application of lime can be effective to overcome the limitations concerning soil type and characteristics. The pH is important for the plant yield: a too acid soil can undermine the presence of phosphorus and other fundamental nutrients. Coffee land suitability data based on these factors are retrieved from the GAEZ project (FAO, 2021; IIASA & FAO, 2012), which provides crop-specific global suitability maps. These maps are calculated from the crop yield. Among all, we consider three significant levels of suitability: very high, high and moderate, corresponding respectively to a yield higher than 80%, 60% and 40% of the maximum attainable yield. These three levels of suitability (moderate, high, very high) are combined with the remaining available shrub areas obtained from the Copernicus Land Service Land Cover data (Buchhorn et al., 2019). We consider for expansion only areas that have at least a given suitability and are not used for equally important activities, e.g., as pasturelands or protected areas. In this way, we define two initial extensification alternatives: current areas (used as baseline), additional areas with at least moderate suitability and no competing uses.

First, we expand coffee cultivation under current climate on suitable areas and evaluate the effect of such expansion on water availability. Crop specific cultivated areas (including coffee) are retrieved from the MIRCA dataset, updated to around year 2000 (Portmann et al., 2010). The land classification for uncultivated areas is obtained from the GlobCover 2009 project (Bontemps et al., 2009). Whenever the cultivated areas from GlobCover do not match the MIRCA croplands, GlobCover data are proportionally rescaled. Crop calendars and crop vegetative phases are taken from (Siebert & Döll, 2010). Soil data come from FAO's Harmonized World Soil Database (FAO et al., 2012).

Crop water use (including coffee) is calculated using the physically based and spatially distributed agro-hydrological model WATNEEDS (Chiarelli, Passera, Rosa, et al., 2020). The water footprint approach of this model partitions crop water requirements in green water and blue water: the crop water requirement is the volume of water needed to support a crop's evapotranspiration, green water is the fraction provided through precipitation and blue water is the remainder, provided through groundwater resources and/or irrigation. The model is centred on a vertical water balance equation, solved at a daily time scale and at 5 arc-minutes (around 10 km) resolution in order to obtain the crop water requirements (CWR) through the estimation of crop evapotranspiration. The vertical water balance is reported in Equation 1 by means of soil moisture accounting. In a single cell, the soil moisture is calculated for each crop and land use i at each day t as:

$$S_{i,t} = S_{i,t-1} + \Delta t \cdot (P_{eff} + I_{i,t} - ET_{a,i,t} - D_{i,t} - R_{i,t}) \qquad (1)$$

where $S_{i,t-1}$ is the soil moisture in the previous time step, Δt is the duration of the time step, equal to one day. P_{eff} is the effective precipitation, calculated starting from CHIRPS data (Climate Hazards Group, 2015) and assuming that 5% of the precipitation is immediately partitioned to runoff (Hoogeveen et al., 2015). $ET_{a,i,t}$ is the actual evapotranspiration, calculated starting from the potential evapotranspiration, i.e. the product of reference evapotranspiration and crop coefficient (Allen et al., 1998). Reference evapotranspiration is retrieved from the CRU TS3.10 Dataset (Harris et al., 2014), which uses the Penman-Monteith equation. For rainfed crops, when the crop water requirement exceeds the readily available water, i.e. the water the plant can uptake from the root zone without entering crop water stress, the crop coefficient is opportunely reduced by a stress factor. For irrigated crops, this excess demand with respect to the available water is supplied by irrigation. $D_{i,t}$ is the deep percolation below the root area, occurring when soil moisture exceeds field capacity, i.e. the maximum volume of water that can be retained by the soil. $R_{i,t}$ is the subsurface runoff, occurring when the excess in soil moisture cannot be uptaken exclusively by deep percolation because it would require an infiltration rate higher than the maximum.

The results are then monthly aggregated.

The model is run in current (baseline conditions) and considering the replacement of coffee in all areas where suitability of coffee is at least moderate and no competing uses where identified. Basing on the results of these two scenarios, blue water scarcity (Equation 2) is computed as the ratio between demand and availability of freshwater:

$$BWS = \frac{Dom + Ind + Agr}{0.2R + \langle 0.2R_{up} - (Dom + Ind + Agr)_{up} \rangle} \tag{2}$$

Where Dom, Ind and Agr are domestic, industrial, and agricultural blue water demands, respectively. Agricultural blue water is given as an output by the soil water balance, whereas industrial and domestic water footprints are retrieved from (Hoekstra & Mekonnen, 2012). Local blue water availability is calculated from runoff R, also an output of the hydrological model, constrained by environmental flow requirements through the 0.2 factor in Equation 2, representing a fixed unconstrained runoff fraction of 20% (Rosa et al., 2018). To model the impact of upstream users on downstream areas, the local blue water availability in a grid cell is summed to the net blue water availability from the upstream grid cells. Net blue water availability is calculated as the cumulated surplus of upstream cells with respect to their water demand. The pointy brackets in Equation 2 represent a conditional statement by which, if in a cell the sum of water availability in the cell and surplus water coming from upstream areas exceeds human demand, this excess is passed onto downstream cells, whereas if the demand is higher than the availability all the water is consumed in the cell and no surplus is passed onto downstream cells. By calculating blue water scarcity in the current scenario and in the coffee expansion scenario, and comparing the two sets of results, we can evaluate the impact of this agricultural expansion on water scarcity. In particular, we measure the impact as variation in yearly blue water scarcity months, i.e. months during which the blue water scarcity index has a value greater than 1. This means the demand of water is higher than the availability, and thus that this demand cannot be satisfied, or at least not without depleting environmental flows. Starting from this impact assessment we build up an iterative procedure to design agricultural expansion with no tangible water scarcity effects. A simplified example of this procedure is represented in Figure 1. The two sets of water scarcity data are therefore used as boundary conditions: the modified blue water scarcity, accounting for agricultural expansion, is the initial condition for the iterative procedure, and the baseline situation, before the expansion, is considered as the target. The steps of the procedure are the following:

1. **Identification of new water scarce areas.** We compare the initial (new) and target (baseline) blue water scarcity months data. Areas having a number of months higher in the new situation than in the baseline (red areas in Figure 1, map b) are areas where the coffee expansion produced the onset of water scarcity for at least one month in the average year.
2. **Identification of upstream areas responsible for the onset of blue water scarcity** (Figure 1, map c). Each pixel experiencing changes in blue water scarcity months is snapped to the closest subbasin outlet. The watershed is reconstructed for each of these outlets, and the coffee expansion areas within these watersheds are identified.
3. **Reduction of the irrigated crop expansion** (Figure 1, map d). In each irrigated crop expansion pixel that generates water scarcity, the blue water allocated to coffee in expansion areas is reduced by a fraction of the currently allocated value. This means that, along iterations, blue water allocation decreases following an exponential decay to reach asymptotically zero. To limit iterations, pixels are shut off once they reach a cut-off value of blue water allocation, meaning that no expansion is allowed to take place (Figure 1, map f), and in the following iteration the soil water balance values for those pixels are taken from the baseline scenario and not from the expansion scenario.
4. **Decision.** After step 3 we return to step 1, comparing target (baseline) blue water scarcity to blue water scarcity calculated from the redesigned expansion resulting from step 3. The possible cases are the following:
    a. **Variations in water scarcity, some expansion areas still active** (Figure 1, map d). This means that there are still some areas generating downstream water scarcity effects, for which the

blue water contribution has to be reduced, so we go through steps 2 and 3 again (Figure 1, maps e and f).

b. **No variations in water scarcity, no expansion areas active.** This means that any expansion intervention in the area will lead to the onset of water scarcity somewhere, so the expansion is completely unfeasible, and we exit the process.

c. **No variations in water scarcity, some expansion areas still active** (Figure 1, map f). This means that the remaining expansion areas can satisfy their blue water demand without generating blue water scarcity, so, to this extent, the expansion is hydrologically sustainable, and we exit the process.

For the specific application of coffee in Kenya, the procedure has been run using a 0.1 cut-off fraction, meaning pixels are shut off if less than 10% of the blue water required can be provided. Concerning the reduction factor, we ran the procedure with different factors ranging from 0.5 to 0.75, obtaining substantially equivalent results, but, clearly, with longer computational times for higher factors, as more iterations are needed in that case to reach the target values.

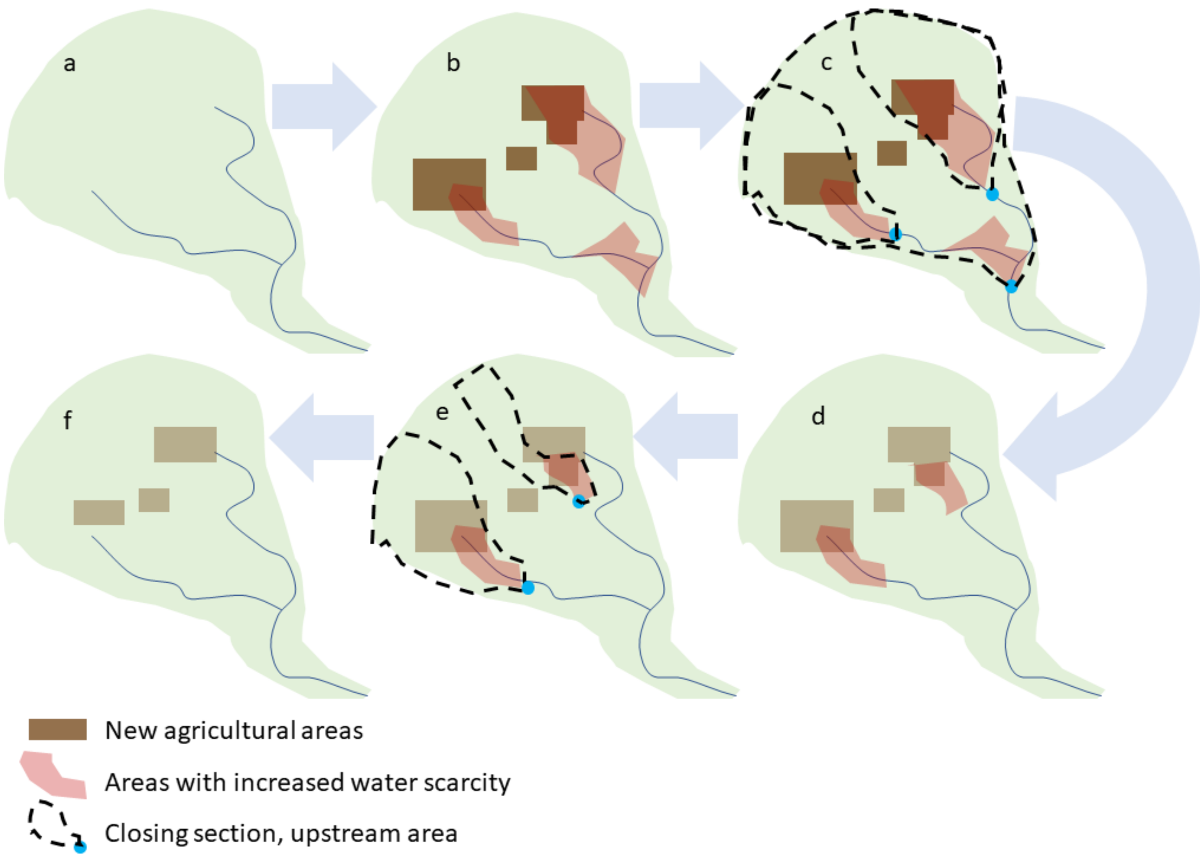

Figure 1. Graphic schematization of the followed methodology for a single catchment. In this simplified representation, agricultural areas are shut off after one reduction of water contribution (paler brown areas), and a solution is found after two iterations.

Results

Land use and water requirements for the main crops (cultivated areas greater than 50000ha) are reported in Table 1. Land use data are computed from the maps by GlobCover (Bontemps et al., 2009), while water volumes are calculated from the results of the soil water balance. Maize, pulses, and coffee are the most widespread crops harvested in Kenya. Crop production in Kenya is mainly rainfed, with only less than 5% of crop being irrigated (approximatively 77000 ha, 20% of which for coffee). Almost 150 thousand hectares are harvested with coffee in Kenya, 10% of which are irrigated. Coffee is a relatively water intense crop in Kenya, being the fifth crop by harvested area, but the third by green water requirement and the first by blue water requirement. The high volumes of blue water are also related to the value of coffee as a crop, as irrigation is associated to a cost that must be compensated by the revenues. However, crop yield of coffee in Kenya amounts to 0.34t/ha, which is a very low value if compared to top producer countries' values (e.g. it is 1/10 of Malaysia crop yield) (FAO, 2019a).

Table 1. Harvested area and yearly crop water requirements for Scenario 1

Crop	Area [ha]	Green Water [Mm^3]	Blue Water [Mm^3]
Maize	1574203	4444	7
Pulses	1202510	3050	0
Others annual	368562	853	54
Others perennial	261613	1722	51
Coffee	149316	1021	95
Wheat	141242	426	0
Sorghum	134094	382	0
Potatoes	113930	252	0
Millet	96552	265	0
Cassava	93443	414	0
Sugar cane	53227	343	11

We choose to consider all expansion areas as irrigated areas, under the hypothesis of maximizing the productivity of the new areas by closing the crop yield gap trough irrigation (Rosa et al., 2018a). Therefore, when comparing water requirements in expansion scenarios with current water requirements, we consider those of irrigated coffee areas.

The blue water scarcity-based design of coffee harvest expansion in Kenya renders a positive outcome, meaning that areas are identified where the expansion of coffee cultivation does not generate additional water scarcity. The total areas available for expansion extend over 3.38Mha, of which 2.27Mha are at least moderately suitable to the cultivation of coffee. The iterative procedure narrows this pool down to 0.24Mha that can be harvested in conditions of hydrological sustainability. The spatial distribution of these areas, visible in Figure 2, helps better understand how these areas are identified. The map in Figure 2 shows where the areas are located avoiding to show, for the sake of completeness in the visualization, the ‘intensity’ of the expansion, i.e. how many hectares are used for expansion in each of the mapped pixels. However, the general trend in this sense can be inferred qualitatively by comparing the extent with the totals. Areas currently harvested with coffee amount to 0.15Mha, of which only one tenth are irrigated. They appear in Figure 2 to be mostly located in the Southwest of Kenya. These are the hilly areas where Kenya’s water towers are located(FAO, 2015), having many of the characteristics that make an area suitable for the cultivation of coffee. In fact, coffee thrives best in elevated areas, that ensure mild temperatures even in tropical climates, so to avoid at the same time frosting and heat stress. Also the mild slope of these mountainous areas helps preventing frosting, while ensuring sufficient drainage without setting on erosion (FAO, 2021; Valipour & Eslamian, 2014). The areas available for expansion with at least moderate suitability, labelled ‘Suitable areas’ in Figure 2, extend from these mountainous regions onto the neighbouring ones, especially southwards, i.e. towards areas where the humid climate is preserved, while northwards the climate becomes progressively arid (Kottek et al., 2006). While, visually, current and suitable areas extend over similar regions, suitable areas are more than 20 times higher than current areas. This means that suitable areas represent shares of expansion pixels that are much higher than the common coffee harvested pixel share. It is rather unrealistic to consider these areas available for expansion as a whole, i.e. to project agricultural expansion on the total of these areas. This is why they are used here only for the sake of hydrological characterization, and as an initial pool from which to choose expansion areas, i.e. as a set of areas that are equally (un)sustainable *a priori*, from the land use and crop suitability point of view, from which to select only those that are also hydrologically sustainable. These hydrologically sustainable areas, i.e. areas using water without conflicting with pre-existing water uses, labelled ‘Sustainable areas’ in Figure 2, are more strictly located in the region currently harvested with coffee than the suitable superset. In many cases, they overlap with currently harvested pixels. In these cases, shares of available areas are converted to coffee cultivation in pixels where coffee cultivations where already pre-existing. This is probably the less impacting type of expansion from the environmental, social and landscape point of view, as we project new coffee plantations where they are already present in the mix, rather than introducing them as a new species, agricultural system, and landscape element.

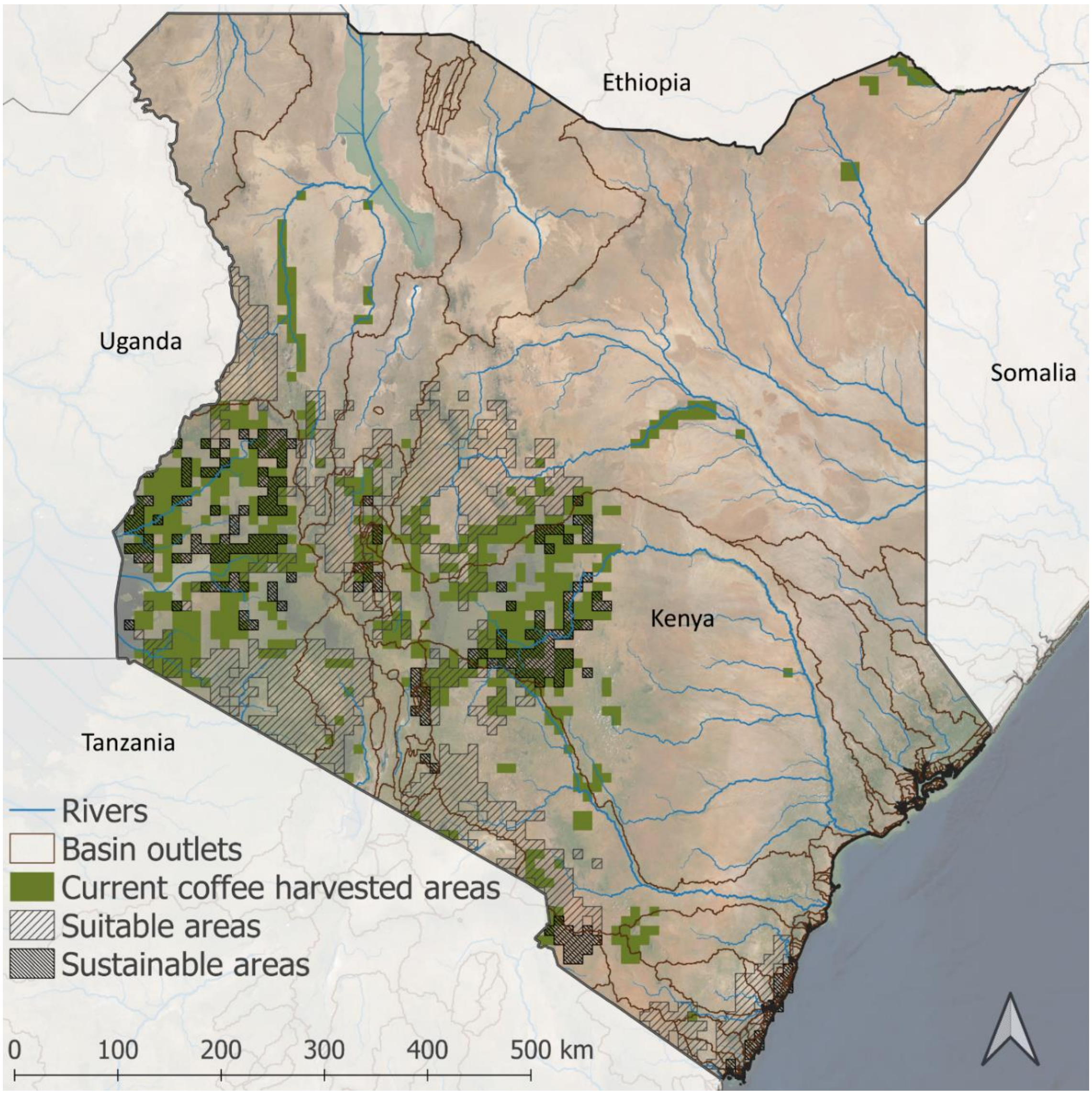

Figure 2. Current coffee harvested areas in Kenya, and suitable and hydrologically sustainable areas for the agricultural expansion of coffee cultivation.

The sustainable expansion areas amount, as already mentioned, to 0.24Mha, which is more than the current coffee harvested areas in Kenya. The fact that they extend over a smaller region than current coffee harvested areas means that, as for the suitable areas, sustainable areas occupy larger shares of the pixels they are in than current coffee harvested areas. In terms of how the iterative procedure works, this means that the areas in many of the pixels in the initial pool of available areas are either used almost completely or completely shut off. In essence, in areas where water is available, it is also sufficient for relatively larger expansion schemes, while in many other regions water scarcity is very sensitive to land use change. The fact that sustainable areas are mostly located in co-presence with existing areas also shows that, to some degree, the existing agricultural system has adapted to the local water availability spatiotemporal gradients. Indeed, the only sustainable expansion areas located far from existing ones are on the southern coast of Kenya. In this case, being close to river outlets of small coastal basins (Figure 2), excess water has no downstream users, therefore the model identifies them as areas not producing any downstream water scarcity effects.

Table 2 and Figure 3 show how increasing the areas for coffee production results in significantly higher water requirements. First of all, even though coffee cultivation in Kenya is primarily rainfed, blue water requirements occupy a significant share of the crop water requirement. Interestingly, green water use in rainfed areas is lower than in irrigated areas, more likely due to a lack in availability than to a lower demand of the plant. This is probably one of the main factors underlying the low yield of coffee in Kenya. The cascading effects of expanding coffee plantations by cultivating suitable areas without hydrological constraints can be evaluated both from the partition of water requirements in Figure 3 and from the water scarcity map in Figure 4. Coffee in suitable expansion areas would have a higher crop water requirement than currently irrigated coffee. The green water contribution to this requirement is slightly higher, in absolute terms, in suitable expansion areas, but the higher total water requirement counters this effect, leading to an overall higher blue water consumption. This, combined with the high extent of these new agricultural areas, produces strong variations in blue water scarcity. Figure 4 shows maps of yearly months of water scarcity, i.e. months during which the demand for blue water exceeds the availability. The left map shows water scarcity months when coffee cultivation expands onto suitable areas, while the right map shows water scarcity months when coffee cultivation expands onto sustainable areas, i.e., the areas that are obtained at the end of the iterative procedure. Because the iterative procedure is designed to find expansion areas that produce negligible variations in blue water scarcity, the blue water scarcity map for sustainable areas is visually equivalent to current actual blue water scarcity, before expansion, and thus can be used for comparatively analysing both the performance of sustainable areas with respect to suitable areas, and of suitable areas with respect to the baseline condition. On average, suitable areas suffer from water scarcity almost three times longer than areas where coffee is currently cultivated. While there are some areas where this effect is lower than average, some clusters emerge in Figure 4, where blue water scarcity increases dramatically, moving for instance from 0-1 months/year to 10-11months/year. These extensive and intense increases in blue water scarcity, mostly localized within the expansion areas, expand also downstream, which can also be inferred from the visual comparison of the two maps in Figure 4. By comparing the two maps, is becomes evident how, for instance, coffee expansion on suitable areas without hydrological constraints would produce a far-reaching depletion effect on the Ewaso-Ngiro river, flowing from West to East in the centre of the country. Indeed, while in the right map the trace of the river is evident, as a stream of pixels with lower water scarcity months values than the surrounding pixels, this stream disappears in the left map, showing how the pixels where the Ewaso-Ngiro flows do not benefit anymore, in terms of water availability, from the presence of the river. The Ewaso-Nigro then flows into Somalia. This means that, in a scenario where coffee expansion significantly depletes the river's resources, transnational issues may arise if the depletion reaches the border, thus impacting Somalia's water scarcity situation. The blue water scarcity-based crop expansion design, instead, allows to accurately target areas preventing this water resource depletion. What is interesting to observe, in this regard, from Figure 3, is that, even though coffee has a slightly higher crop water requirement in sustainable areas than in both current irrigated and suitable expansion areas, the relative contribution of green water to this requirement is much higher. If we compute green water scarcity as the ratio of blue water consumption with respect to the total water requirement, we obtain values of 0.47, 0.45 and 0.39 for current, suitable and sustainable areas respectively. This means that, while suitable areas are very similar to current ones in terms of green water scarcity, harvesting on sustainable areas implies having a 15% lower green water scarcity in these areas than in current areas. Moreover, the fact that sustainable areas use much more green water (100mm more than sustainable areas, 163mm more than current irrigated areas) does not mean that sustainable areas are more green water intensive, but rather that more green water is available in these areas. As mentioned before, agricultural expansion can increase water scarcity both through the increase in blue water demand given by irrigation and through the decrease in blue water availability caused by lower generation of runoff. In the case of sustainable expansion areas, the lower blue water demand and the higher green water availability create a synergy that reduced both this effect, allowing to harvest and irrigate new areas without generating water scarcity not only in the areas themselves, but also downstream. An important addition to this is that, even though substantially reduced with respect to the total suitable areas, sustainable areas for expansion exceed expansion policy forecasts for coffee in Kenya. Therefore, there is space of action that remains available to further limit the expansion according to other important criteria to be accounted for when designing the implementation of such policies. On the other hand, as already mentioned, these areas are in proximity of existing coffee plantations, and existing plantations are to the largest share not irrigated, despite the high water intensity of coffee. Therefore, being the procedure based on water before being based on land, the results also show that, alternatively to pure expansion, there is also room for increasing production by combining, in a well calibrated manner, intensification of existing plantations through irrigation and expansion on new areas.

Table 2. ***Harvested areas and relative blue and green water consumptions for current conditions and in irrigated expansion areas.*** *Areas and volumes in the extensification scenarios are reported as additional to the current data, displayed in the first line of the table for currently rainfed areas and in in the second line for currently irrigated areas.*

	Areas [ha]	Blue Water [Mm3]	Green Water [Mm3]
Current - rainfed	134790	-	912
Current - irrigated	14526	95	109
Suitable	2727849	18187	22179
Sustainable	243147	1414	2219

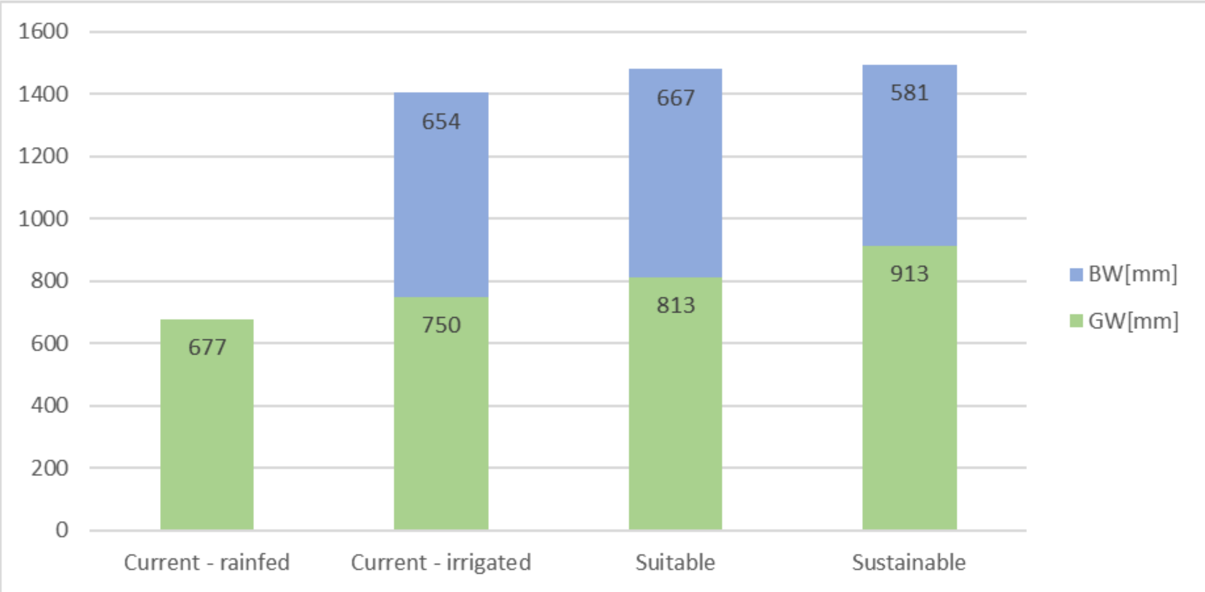

Figure 3. ***Hydrological behaviour of current and potential expansion coffee harvested areas****. Average millimetric green and blue water demands for coffee in currently rainfed and irrigated coffee harvested areas and in irrigated expansion areas. Water heights in the extensification areas are specific to those areas.*

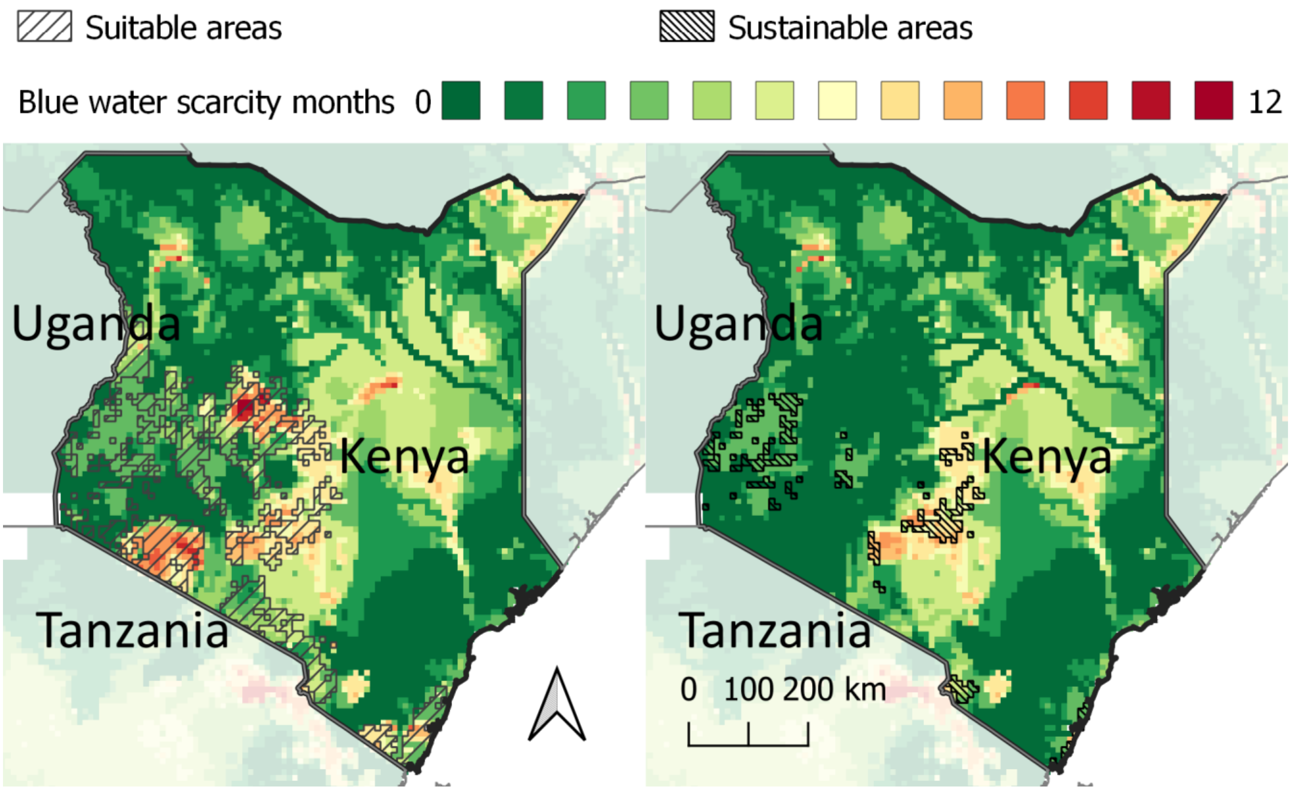

Figure 4. Blue water scarcity months in Kenya, in the case of expanding coffee cultivation on all suitable areas, and in the case of no expansion, or expansion on hydrologically sustainable areas.

Discussion

In this study, we propose a replicable and scalable methodology to evaluate the hydrological sustainability of agricultural expansions, in an integrated way with respect to both the ecological and socio-economic value of water, and accounting for both local and downstream effects of water withdrawals. We use this methodology to directly design agricultural expansion interventions in a hydrologically sustainable way. We find that selecting areas not only based on the optimal suitability criteria of the target crop, but also on local water availability and its timing, helps preventing water scarcity in areas that include, but also go beyond those directly interested by the expansion. Our research highlights the potential water competition rising for coffee intensification and expansion, as we evaluate the cumulative effects on water withdrawal.

As this work aimed at flexibility and generalizability of the methodology, some limitations arise from the simplifications introduced to reach these aims. For what concerns the hydrological implementation of coffee expansion, our results reflect an ideal situation in which irrigation always provides the whole amount of crop water needs that is not supplied by rainfall. In practice, different irrigation techniques can be adopted, e.g. supplemental irrigation and deficit irrigation. However, at the initial planning stage in which the scope of this paper is located, the best practice is to design strategies considering the whole resource demand. It is also important to take into account the whole water demand when evaluating water scarcity, which is by definition a demand-supply based index. Analogously, we accounted only for the consumptive use of water, thus avoiding the losses associated to irrigation application (i.e. transport of water, leakages) for two reasons. First, it is common practice in water footprint assessments to consider only consumptive water use because other losses are supposed to re-enter the hydrological cycle (Hoekstra & Mekonnen, 2012). Second, irrigation application losses depend strongly on the type of irrigation and of water source, and these can be very different in a sector in which the farming method ranges from small subsistence farming to large estates (Allen et al., 1998; FAO, 2015; Jägermeyr et al., 2015). The iterative procedure progressively reduces the blue water allocated to expansion areas. When it reaches a low threshold and blue water scarcity effects are still detected, it means that the expansion areas are causing water scarcity not by putting additional demand onto blue water resources, but by reducing, through the additional transpiration due to change in land use, the formation of (available) blue water. In these cases, following the proposed methodology, the pixel is 'shut off', meaning no expansion is allowed in the pixel at all. A conceptually refined alternative to this approach could be to directly reduce the expansion area instead of reducing the blue water contribution to this area. While this approach may seem more straightforward from a theoretical point of view, its application might be more complex. In fact, it would require either to iteratively run a water balance model, with high computational costs, or to reconstruct the cell-specific land and crop use matrix after the hydrological simulation, instead of simulating the water balance of the given (current or modified) land use matrix.

Agricultural expansion plans and policies tend to be connected to the risk of Large-Scale Land Acquisition, especially for commercial agriculture in institutionally fragile states (Lanz et al., 2018; Rulli et al., 2013; Rulli & D'Odorico, 2014). This risk also applies to coffee expansion in Kenya. While our results show that sustainable expansion of coffee areas is possible mostly in proximity of already existing coffee areas, thus suggesting the risk of monocultures, it does so only in limited extents, in certain regions of the country. This is still a rightful constraint to the scale of possible agricultural development policies, but it can also serve as a bulwark against LSLA risk, in the sense that it intrinsically excludes the possibilities of very large monocultural plantations. In fact, such an analysis can fit well into a wider context of agricultural development, one that includes the conservation of biodiversity and landscape diversity among its objectives. The projection of several small to medium scale patches for the expansion of coffee harvesting in regions that are already familiar with this sector is also coherent with the socio-economic structure of the coffee production chain in Kenya, based mostly on networks of small producers. The creation of structured policies in that sense may help safeguard this business structure, preventing the risk of abandonment of agricultural land, an emerging trend following the increasing average age of the farmers (Ngeywo et al., 2015). This aspect increases in relevance in the light of the fact that a large share of the population is involved in the coffee production system, and women play a central role. In fact, even though women provide roughly two thirds of the workforce employed in coffee farms, they occupy only 5% of the managing positions in coffee cooperatives, with most of them being widows inheriting the farm (International Coffee Organization, 2019; Onyalo, 2019). Therefore, if the already existing coffee production boosting policies are backed up by actions towards the involvement of women in coffee management activities, this may also help to achieve gender equality and reduce injustice, in line with the 5th and 10th Sustainable Development Goals, respectively (United Nations General Assembly, 2015).

While the scope of our study is to assess and size potential areas for agricultural expansion, intensification is often seen by the research and policy agendas as a more sustainable way to increase agricultural production (Tilman et al., 2011). However, a hydrological impacts analysis is a rather natural outgrowth of intensification scenarios (Rosa et al., 2018), while it tends to be neglected in expansion plans. In the case of coffee in Kenya, there is a wide scope of action for closing the yield gap through intensification, such that different irrigation/fertigation systems could be proposed, depending on external and context specific factors as the energy availability for withdrawing water, the availability of pre-existent infrastructures or the financial capability to install new ones, the skills of the farmers and the possible cultural barriers to the adoption of new agricultural technologies (Piemontese et al., 2021). Indeed, the identified sustainable areas target precise regions within the country, and this could furtherly be refined when considering other factors, such as proximity to markets, to workforce or to infrastructure, as well as more local knowledge-based insights on the ecosystem and heritage values of the pre-existing landscape. In the case of commercial agriculture expansion in developing countries, as here, giving policy relevance to this type of biophysical assessments, especially when combined with bottom-up co-creation approaches, can serve as a significant dissuasion also against LSLA, which otherwise often take advantage of less specific agricultural expansion policies (Lanz et al., 2018). In any case, the proposed methodology for the assessment of hydrological impacts of agricultural expansion and subsequent sizing of expansion scenarios can be adapted to agricultural intensification in a relatively straightforward way. As already stated in the results section, the procedure is water-based, meaning that areas identified as sustainable for coffee expansion are areas where water is sufficient to ensure a hydrologically sustainable implementation of that scenario. But if we decouple the scenario from the water availability, it means that in these areas there is water available to support, to different extents, different development scenarios, without impacting on pre-existing water uses. Simple instances of this include the aforementioned possibility of mixing intensification of existing plantations and the creation of new ones, or the use of deficit or emergency irrigation. More in general, the advantages of the proposed methodology, related to the low amount of necessary input data and the high flexibility, make it viable for replication for different crops in different contexts. In fact, the procedure can be adopted for other situations similar to the one analysed here, identifying areas for hydrologically sustainable agricultural production. It may potentially be a prominent and useful tool for country-level planning of agricultural development. This analysis clearly shows how referring only to partial information with respect to the complexity of the issue of agricultural development may lead to partial, when not misleading, results with respect to a correct framing of sustainability in agriculture. Thus, it can be seen as a research contribution towards the integration of the blue water scarcity indicator into quantitative analyses aimed at the design and/or impact assessment of nexus solutions employing irrigated agriculture within the water planetary boundary.

Acknowledgements – conflict of interest statement

The authors declare no conflict of interest.

Data availability statement

Suitability maps are retrieved from the GAEZ project (FAO, 2021; IIASA & FAO, 2012) available from https://gaez.fao.org/

Land cover data are obtained from the Copernicus Land Service Land Cover data (Buchhorn et al., 2019) (https://doi.org/10.5281/ZENODO.3243509)

Crop specific cultivated areas (including coffee) are retrieved from the MIRCA dataset (Portmann et al., 2010) (https://www.uni-frankfurt.de/45218031/Data_download_center_for_MIRCA2000), while other land uses are retrieved from the GlobCover 2009 project (Bontemps et al., 2009) (http://due.esrin.esa.int/page_globcover.php).

Crop calendars and crop vegetative phases are taken from (Siebert & Döll, 2010), available from https://www.uni-frankfurt.de/45218023/MIRCA. Crop parameters are taken from the FAO Paper 56 (Allen et al., 1998) (https://doi.org/10.1016/j.eja.2010.12.001). Soil data come from FAO's Harmonized World Soil Database (FAO et al., 2012), available from https://www.fao.org/land-water/databases-and-software/hwsd/en/. Precipitation data are taken from CHIRPS (Climate Hazards Group, 2015) (https://www.chc.ucsb.edu/data/chirps) and evapotranspiration data are taken from the CRU TS Dataset (Harris et al., 2014) (https://crudata.uea.ac.uk/cru/data/hrg/).

The WATNEEDS model (Chiarelli, Passera, Rosa, et al., 2020) runs on MATLAB. Agricultural blue water computed by the model is available at https://springernature.figshare.com/collections/Global_Gridded_Dataset_of_Crop-specific_Green_and_Blue_Water_Requirements/4893084

Industrial and domestic water footprints are retrieved from (Hoekstra & Mekonnen, 2012) (https://waterfootprint.org/en/resources/waterstat/product-water-footprint-statistics/).

References

Agriculture and Food Authority (AFA). (2018a). *Coffee Year Book 2017/18*.

Agriculture and Food Authority (AFA). (2018b). *Strategic Plan 2017/18-2021/22*.

Agriculture and Food Authority (AFA). (2021). *Coffee Year Book 2020/21*.

Allen, R. G., Pereira, L. S., Raes, D., et al. (1998). FAO Irrigation and Drainage No. 56. Crop Evapotranspiration (guidelines for computing crop water requirements). [Dataset] https://doi.org/10.1016/j.eja.2010.12.001

Bontemps, S., Defourny, P., van Bogaert, E., et al. (2009). GlobCorine - A joint EEA-ESA project for operational land dynamics monitoring at pan-European scale. *Proceedings, 33rd International Symposium on Remote Sensing of Environment, ISRSE 2009*, (June 2006), 289–292. [Dataset] retrieved from http://due.esrin.esa.int/page_globcover.php

Brundtland, G. H. (1987). *Report of the World Commission on Environment and Development: Our Common Future. United Nations General Assembly document A/42/427.* https://doi.org/10.1017/s0376892900016805

Buchhorn, M., Smets, B., Bertels, L., et al. (2019). Copernicus Global Land Service: Land Cover 100m: epoch 2015: Globe. [Dataset] retrieved from https://doi.org/10.5281/ZENODO.3243509

Chiarelli, D. D., Passera, C., Rulli, M. C., et al. (2020). Hydrological consequences of natural rubber plantations in Southeast Asia. *Land Degradation & Development*, *31*(15), 2060–2073. https://doi.org/10.1002/ldr.3591

Chiarelli, D. D., Passera, C., Rosa, L., et al. (2020). The green and blue crop water requirement WATNEEDS model and its global gridded outputs. *Scientific Data*, *7*(1), 1–9. https://doi.org/10.1038/s41597-020-00612-0. [Dataset] retrieved from https://springernature.figshare.com/collections/Global_Gridded_Dataset_of_Crop-specific_Green_and_Blue_Water_Requirements/4893084

Chiarelli, D. D., D'Odorico, P., Müller, M. F., et al. (2022). Competition for water induced by transnational land acquisitions for agriculture. *Nature Communications*, *13*(1), 1–9. https://doi.org/10.1038/s41467-022-28077-2

Climate Hazards Group. (2015). CHIRPSv2.0. Climate Hazards Group. https://doi.org/10.15780/G2RP4Q [Dataset] retrieved from https://www.chc.ucsb.edu/data/chirps

Davis, A. P., Gole, T. W., Baena, S., et al. (2012). The Impact of Climate Change on Indigenous Arabica Coffee (Coffea arabica): Predicting Future Trends and Identifying Priorities. *PLoS ONE*, *7*(11), e47981. https://doi.org/10.1371/journal.pone.0047981

Davis, K. F., Rulli, M. C., Garrassino, F., et al. (2017). Water limits to closing yield gaps. *Advances in Water Resources*, *99*, 67–75. https://doi.org/10.1016/j.advwatres.2016.11.015

Davis, K. F., Chiarelli, D. D., Rulli, M. C., et al. (2018). Alternative cereals can improve water use and nutrient supply in India. *Science Advances*, *4*(7), 1–12. https://doi.org/10.1126/sciadv.aao1108

Davis, K. F., Chhatre, A., Rao, N. D., et al. (2019). Assessing the sustainability of post-Green Revolution cereals in India. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(50), 25034–25041. https://doi.org/10.1073/pnas.1910935116

D'Odorico, P., Davis, K. F., Rosa, L., et al. (2018). The Global Food-Energy-Water Nexus. *Reviews of Geophysics*, *56*(3), 456–531. https://doi.org/10.1029/2017RG000591

Falkenmark, M, J. L. and C. W. (1989). Macro-scale water scarcity requires micro-scale approaches: Aspects of vulnerability in semi-arid development. Natural Resources Forum 13(4):258267, (December).

FAO. (2015). *Country profile-Kenya*. Rome. Retrieved from www.fao.org/

FAO. (2016a). AQUASTAT Main Database, Food and Agriculture Organization of the United Nations (FAO).

FAO. (2016b). AQUASTAT Main Database, Food and Agriculture Organization of the United Nations (FAO).

FAO. (2019a). FAOSTAT Main Database, Food and Agriculture Organization of the United Nations (FAO).

FAO. (2019b). FAOSTAT Main Database, Food and Agriculture Organization of the United Nations (FAO).

FAO. (2021). GAEZ Data Portal. [Dataset] Retrieved May 13, 2021, from https://gaez.fao.org/

FAO, & Food and Agriculture Organization of the United Nations. (2014). The Water-Energy-Food Nexus - A new approach in support of food security and sustainable agriculture. *Food and Agriculture Organization of the United Nations*, 1–11.

FAO, IIASA, ISRIC, ISSCAS, & JRC. (2012). Harmonized world soil database v1.2 | FAO SOILS PORTAL | Food and Agriculture Organization of the United Nations. Retrieved from https://www.fao.org/land-water/databases-and-software/hwsd/en/

Galli, N., Chiarelli, D. D., D'Angelo, M., et al. (2022). Socio-environmental impacts of diamond mining areas in the Democratic Republic of Congo. *Science of the Total Environment*, *810*, 152037. https://doi.org/10.1016/j.scitotenv.2021.152037

Gerten, D., Hoff, H., Rockström, J., et al. (2013). Towards a revised planetary boundary for consumptive freshwater use: Role of environmental flow requirements. *Current Opinion in Environmental Sustainability*, *5*(6), 551–558. https://doi.org/10.1016/j.cosust.2013.11.001

Gleeson, T., Wang-Erlandsson, L., Zipper, S. C., et al. (2020). The Water Planetary Boundary: Interrogation and Revision. *One Earth*, *2*(3), 223–234. https://doi.org/10.1016/j.oneear.2020.02.009

Godfray, H. C. J., Beddington, J. R., Crute, I. R., et al. (2010). Food security: The challenge of feeding 9 billion people. *Science*, *327*(5967), 812–818. https://doi.org/10.1126/SCIENCE.1185383

Harris, I., Jones, P. D., Osborn, T. J., et al. (2014). Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *International Journal of Climatology*, *34*(3), 623–642. https://doi.org/10.1002/joc.3711

Hoekstra, A. Y., & Mekonnen, M. M. (2012). The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(9), 3232–3237. https://doi.org/10.1073/pnas.1109936109 [Dataset] retrieved from https://waterfootprint.org/en/resources/waterstat/product-water-footprint-statistics/

Hoogeveen, J., Faurès, J. M., Peiser, L., et al. (2015). GlobWat - A global water balance model to assess water use in irrigated agriculture. *Hydrology and Earth System Sciences*, *19*(9), 3829–3844. https://doi.org/10.5194/hess-19-3829-2015

Hussain, L. A. S., Inzoli, F., Golinucci, N., et al. (2020). FEEM Approach to Supply Chain Analysis The coffee Sector in Kenya. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3733699

Hussain, Z., Wang, Z., Wang, J., et al. (2022). A comparative Appraisal of Classical and Holistic Water Scarcity Indicators. *Water Resources Management*, *36*(3), 931–950. https://doi.org/10.1007/S11269-022-03061-Z/TABLES/2

IIASA, & FAO. (2012). *Global Agro-ecological Zones Model Documentation*.

International Coffee Organization. (2019). Country Coffee Profile: Kenya. *International Coffee Council*, (124th Session), 1–29.

Jägermeyr, J., Gerten, D., Heinke, J., et al. (2015). Water savings potentials of irrigation systems: Global simulation of processes and linkages. *Hydrology and Earth System Sciences*, *19*(7), 3073–3091. https://doi.org/10.5194/hess-19-3073-2015

Jaramillo, J., Muchugu, E., Vega, F. E., et al. (2011). Some Like It Hot: The Influence and Implications of Climate Change on Coffee Berry Borer (Hypothenemus hampei) and Coffee Production in East Africa. *PLoS ONE*, *6*(9), e24528. https://doi.org/10.1371/journal.pone.0024528

Kottek, M., Grieser, J., Beck, C., et al. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Lanz, K., Gerber, J. D., & Haller, T. (2018). Land Grabbing, the State and Chiefs: The Politics of Extending Commercial Agriculture in Ghana. *Development and Change*, *49*(6), 1526–1552. https://doi.org/10.1111/dech.12429

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The relation between national water management and international trade: A case study for Kenya. *Value of Water Research Report Series No*, *15*(5), 1577–1600.

Mugo, H., Lubabali, H., & Salasya, B. (2019). The impact of public private partnership in the role of coffee farmers' cooperative societies in Kenya. *Journal of Agricultural and Crop Research*, *7*(12), 224–231. https://doi.org/10.33495/jacr_v7i12.19.130

Ngaira, J. K. W. (2009). Challenges of water resource management and food production in a changing climate in Kenya. *Journal of Geography and Regional Planning*, *2*(4), 97–103.

Ngeywo, J., Basweti, E., & Shitandi, A. (2015). Influence of Gender, Age, Marital Status and Farm Size on Coffee Production: A Case of Kisii County, Kenya. *Asian Journal of Agricultural Extension, Economics & Sociology*, *5*(3), 117–125. https://doi.org/10.9734/AJAEES/2015/15702

Onyalo, P. O. (2019). Women and Agriculture in Rural Kenya: Role in Agricultural Production. *International Journal of Humanities, Art and Social Studies (IJHAS)*, *4*(4).

Piemontese, L., Kamugisha, R. N., Tukahirwa, J. M. B., et al. (2021). Barriers to scaling sustainable land and water management in Uganda: a cross-scale archetype approach. *Ecology and Society, Published Online: Jul 26, 2021 | Doi:10.5751/ES-12531-260306*, *26*(3). https://doi.org/10.5751/ES-12531-260306

Portmann, F. T., Siebert, S., & Döll, P. (2010). MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, *24*(1), n/a-n/a. https://doi.org/10.1029/2008gb003435. [Dataset] retrieved from https://www.uni-frankfurt.de/45218031/Data_download_center_for_MIRCA2000

Ricciardi, L., D'Odorico, P., Galli, N., et al. (2022). Hydrological implications of large-scale afforestation in tropical biomes for climate change mitigation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *377*(1857), 1–9. https://doi.org/10.1098/rstb.2021.0391

Rockström, J., Steffen, W., Noone, K., et al. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, *14*(2). https://doi.org/10.5751/ES-03180-140232

Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, *460*(7258), 999–1002. https://doi.org/10.1038/nature08238

Rosa, L., Rulli, M. C., Davis, K. F., et al. (2018). Closing the yield gap while ensuring water sustainability. *Environmental Research Letters*, *13*(10), 104002. https://doi.org/10.1088/1748-9326/aadeef

Rosa, L., Chiarelli, D. D., Rulli, M. C., et al. (2020). Global agricultural economic water scarcity. *Science Advances*, *6*(18), eaaz6031. https://doi.org/10.1126/sciadv.aaz6031

Rulli, M. C., & D'Odorico, P. (2014). Food appropriation through large scale land acquisitions. *Environmental Research Letters*, *9*(6), 064030. https://doi.org/10.1088/1748-9326/9/6/064030

Rulli, M. C., Saviori, A., & D'Odorico, P. (2013). Global land and water grabbing. *Proceedings of the National Academy of Sciences*, *110*(3), 892–897. https://doi.org/10.1073/pnas.1213163110

Sherif, M., Sefelnasr, A., Ebraheem, A. A., et al. (2021). Spatial and temporal changes of groundwater storage in the quaternary aquifer, uae. *Water (Switzerland)*, *13*(6), 1–24. https://doi.org/10.3390/w13060864

Siebert, S., & Döll, P. (2010). Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology*, *384*(3–4), 198–217. https://doi.org/10.1016/j.jhydrol.2009.07.031. [Dataset] retrieved from https://www.uni-frankfurt.de/45218031/Data_download_center_for_MIRCA2000

Tilman, D., Balzer, C., Hill, J., et al. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(50), 20260–20264. https://doi.org/10.1073/PNAS.1116437108/-/DCSUPPLEMENTAL

UN. (2019). *World Population Prospects 2019 Data Booklet*.

UN. (2020). THE 17 GOALS | Sustainable Development. *Department of Economic and Social Affairs*.

UNDP. (2016). Goal 6 | Department of Economic and Social Affairs. Retrieved from https://sdgs.un.org/goals/goal6

United Nations General Assembly. (2015). Transforming our world: the 2030 Agenda for Sustainable Development. United Nations.

Valipour, M., & Eslamian, S. (2014). Analysis of potential evapotranspiration using 11 modified temperature-based models. *International Journal of Hydrology Science and Technology*, *4*(3), 192. https://doi.org/10.1504/IJHST.2014.067733