

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

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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

1 Abstract

2

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

22 Introduction

23

24 The focal point of sustainable development is the rational use of resources, aimed not only at satisfying
25 current needs, but also at guaranteeing the fulfilment of the needs of future generations, who indeed occupy

26 a prominent place in this vision (Brundtland, 1987). Water resources are at the core of many of the main
27 global and regional challenges our planet is facing. Freshwater is mentioned as one of the Planetary
28 Boundaries (Gerten et al., 2013; Gleeson et al., 2020; Rockström et al., 2009), it constitutes the main object
29 in one of the United Nations (UN) Sustainable Development Goals (SDGs), SDG6, while appearing in other
30 four (SDGs 3,11,12,15) and being indirectly involved in at least other two (SDGs 2,7) (UN, 2020). In fact, it is
31 well known that freshwater is an essential ecosystem service flow(Gerten et al., 2013), a fundamental
32 resource for the production of food and energy (D’Odorico et al., 2018; FAO & Food and Agriculture
33 Organization of the United Nations, 2014), and the constitutor of many basic human services (UNDP, 2016).
34 Among other sectors, agriculture plays a key role in meeting the food, fibre, and energy demand, but it is also
35 the largest natural resources consumer, in particular concerning freshwater use. In fact, 70% of the world
36 water use is linked to agriculture (Siebert & Döll, 2010), and this amount is expected to increase even more
37 in order to meet the future rise in demand driven by population growth, energy policies and changing dietary
38 habits (Godfray et al., 2010).

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

44 Recent studies have quantified the sustainably attainable additional food production (Rosa et al., 2018, 2020)
45 and evaluated possible crop production optimization strategies based on local water availability (K. F. Davis
46 et al., 2017, 2019). Other studies analysed the downstream effects of such mechanisms (Chiarelli, Passera,
47 Rulli, et al., 2020; Galli et al., 2022). However, there still is the need to establish a method which enables to
48 identify and evaluate, globally and locally, under what conditions certain land use and crop use choices and
49 changes may be sustainable. From a hydrological point of view, land use and crop use change impact the
50 water balance in more than one way. The most direct impact is likely the localized increase in water scarcity
51 because of an increase in blue water demand associated to irrigation, with the same water availability. In a
52 more indirect way, land use and crop use change produce variations in water scarcity because the higher

53 evapotranspiration rates of the new agricultural areas reduce the formation of blue water (Ricciardi et al.,
54 2022). Also, water scarcity can propagate downstream. Assuming, for the sake of simplicity, to divide a
55 watershed in an upstream region and a downstream region, increased demand, or decreased formation, of
56 blue water upstream can produce water scarcity downstream, if upstream blue water was originally used
57 downstream. These upstream-downstream effects of water scarcity can arise also in absence of upstream
58 water scarcity: even limiting new upstream irrigation water uses to the amount that does not generate water
59 scarcity where it is used, this new water use produces downstream water scarcity if that volume originally
60 flowed downstream and was used to satisfy the downstream blue water demand (Chiarelli et al., 2022). How
61 can the knowledge of these mechanisms be leveraged to design sustainable agricultural expansion and
62 intensification? While water scarcity assessments can provide the quantitative base for a more hydrologically
63 conscious formulation of sustainable development policies, strategies, and solutions (Z. Hussain et al., 2022),
64 the challenge is to go beyond providing ready-to-use assessments of baseline water scarcity indicators and
65 basing policy recommendations on their interpretation. Can water scarcity assessments be used to further
66 bridge this science-policy gap, directly basing sustainability policies on water scarcity related targets? The
67 answer to this question, besides being of value within science, can play an essential role in economic and
68 political decision making. Economic development strategies must be considered according to, among other
69 criteria, sustainability and resource-based feasibility. In this context, the matter of cash crops is highly
70 debated, as their water requirements have often proved to be higher than those of the main food crops
71 (Chiarelli, Passera, Rulli, et al., 2020). Therefore, a thorough sustainability assessment of such policies is
72 needed to avoid transitory benefits which may otherwise worsen the water scarce conditions in the country
73 on the long terms. Investigations on the potential increase of cash crop production require attention to the
74 natural resources (i.e. suitable land and water) demand and availability as well as to the direct and indirect
75 effects of natural resources use.

76 Here we propose a methodology to assess hydrological sustainability of land use and crop use changes,
77 evaluating both in situ and downstream effects of water use. We apply this framework on the expansion of
78 coffee cultivations an example of a water intensive cash crop whose expansion in subtropical countries has
79 seen a rapid and ongoing boom (FAO, 2019a). We select Kenya as a case study, where coffee also has a

80 recognized potential in promoting agricultural, economic, and social development (International Coffee
81 Organization, 2019). Coffee is also the most water-intensive crop in Kenya (in terms of water volume per
82 produced tonne), the third crop by total volumetric water consumption, and the most important component
83 of the Kenyan virtual water export (Mekonnen & Hoekstra, 2011). The coffee production and export sector
84 in Kenya, among the biggest in Africa, currently employs around 5 million people (L. A. S. Hussain et al., 2020).
85 In contrast to many other coffee exporting countries, in Kenya smallholders account for most of the
86 production. Some 700,000 small scale farmers, organized in hundreds of cooperatives to which they sell their
87 cherries, account for 80% of the country's coffee production (Mugo et al., 2019). The rest are around 3,000
88 large coffee estates, selling their own coffee directly (L. A. S. Hussain et al., 2020). The Kenyan government
89 recently approved a plan for the development and expansion of agriculture, including coffee plantations, in
90 order to promote agricultural and economic development (Agriculture and Food Authority (AFA), 2018b).
91 Growth rates for the coffee sector in Kenya are increasing, moving from a less than 10% growth in 2017/18
92 with respect to the previous season(Agriculture and Food Authority (AFA), 2018a) to an almost 30% increase
93 in 2020/21 with respect to the previous season (Agriculture and Food Authority (AFA), 2021). Part of this
94 increase in production is associated to agricultural expansion(Agriculture and Food Authority (AFA), 2021).
95 However, policy plans like this often miss an in-depth hydrological analysis of the impacts connected to the
96 expansion of such water-demanding crops, especially in light of the well-known environmental impacts of
97 agricultural expansion, often deemed higher than those, for instance, of yield gap closure by agricultural
98 intensification (D'Odorico et al., 2018). Water scarcity- and food insecurity-related consequences of poorly
99 planned agricultural policies may derail the very same plan they arose from. Evidences of such backfiring can
100 be observed, for instance, in the United Arab Emirates, where agricultural development and production saw
101 a rapid boom in the early 2000s only to come to a quick stop shortly after, caused by the progressive fossil
102 ground water depletion (Sherif et al., 2021). A similar situation has been observed in India since the late 60s
103 (K. F. Davis et al., 2018). The then adopted self-sufficiency policy in cereal production, has led, in the following
104 decades, to a steady lowering of the groundwater table (Rodell et al., 2009). Kenya is facing a situation of
105 acute water and food insecurity, which will be worsened by hydroclimatic change (Ngaira, 2009). Therefore,

106 boosting coffee production in Kenya would will improve the livelihoods of local people and generate export
107 revenue only if it is planned within resource boundaries.

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

119 Methods

120

121 Kenya is an African country extending over 580370km² in the Eastern part of the continent, on the Indian
122 Ocean coast. The population of Kenya was estimated as 51 million in 2018 and it is expected to have a sharp
123 growth in the next decades since it will more than double (UN, 2019). 37.5 million people live in rural areas,
124 and almost 70% of the economically active population worked in the agricultural sector in 2014 (FAO, 2016a).
125 The high diversity of the Kenyan morphology, the presence of the ocean and of major inland water bodies,
126 and the low latitudes create a climate that ranges from arid to equatorial through humid subtropical in the
127 uplands (Kottek et al., 2006). The rain pattern is bimodal, with a first rainy season from March to May and a
128 second one from October to December. The concentration of water towers in the central-western area of
129 the country generates inhomogeneity in the catchments' water availability, and most of the catchments are
130 shared with neighbouring countries (FAO, 2015, 2016b). The total actual renewable water resources (TRWR)

131 correspond to a per capita value of 617 m³/year, which is just above the 500m³/year absolute water scarcity
132 threshold (Falkenmark, M, 1989; FAO, 2016b).

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

135 We base our analysis of the sustainable coffee extensification on spatially distributed agro-hydrological
136 simulations for different land use scenarios in Kenya. To guarantee effectivity while countering the risk of
137 resource depletion, the extensification of coffee cultivation is designed considering the plant characteristics
138 and optimal growing conditions. The elevation is needed to guarantee the ideal temperature range that
139 delays the bean ripening increasing coffee quality and prevent pests (A. P. Davis et al., 2012; Jaramillo et al.,
140 2011). A higher temperature would affect the plant's photosynthesis, resulting in stress, whereas lower
141 temperatures increase the risk of frosting. The slope is required to improve air drainage and reduce frost
142 damage (Valipour & Eslamian, 2014), but it has to be gentle to prevent soil erosion. The correct aspect assures
143 a good sun exposure. The application of lime can be effective to overcome the limitations concerning soil
144 type and characteristics. The pH is important for the plant yield: a too acid soil can undermine the presence
145 of phosphorus and other fundamental nutrients. Coffee land suitability data based on these factors are
146 retrieved from the GAEZ project (FAO, 2021; IIASA & FAO, 2012), which provides crop-specific global
147 suitability maps. These maps are calculated from the crop yield. Among all, we consider three significant
148 levels of suitability: very high, high and moderate, corresponding respectively to a yield higher than 80%, 60%
149 and 40% of the maximum attainable yield. These three levels of suitability (moderate, high, very high) are
150 combined with the remaining available shrub areas obtained from the Copernicus Land Service Land Cover
151 data (Buchhorn et al., 2019). We consider for expansion only areas that have at least a given suitability and
152 are not used for equally important activities, e.g., as pasturelands or protected areas. In this way, we define
153 two initial extensification alternatives: current areas (used as baseline), additional areas with at least
154 moderate suitability and no competing uses.

155 First, we expand coffee cultivation under current climate on suitable areas and evaluate the effect of such
156 expansion on water availability. Crop specific cultivated areas (including coffee) are retrieved from the MIRCA
157 dataset, updated to around year 2000 (Portmann et al., 2010). The land classification for uncultivated areas

158 is obtained from the GlobCover 2009 project (Bontemps et al., 2009). Whenever the cultivated areas from
159 GlobCover do not match the MIRCA croplands, GlobCover data are proportionally rescaled. Crop calendars
160 and crop vegetative phases are taken from (Siebert & Döll, 2010). Soil data come from FAO's Harmonized
161 World Soil Database (FAO et al., 2012).

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

171

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

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173 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
174 day. P_{eff} is the effective precipitation, calculated starting from CHIRPS data (Climate Hazards Group, 2015)
175 and assuming that 5% of the precipitation is immediately partitioned to runoff (Hoogeveen et al., 2015).
176 $ET_{a,i,t}$ is the actual evapotranspiration, calculated starting from the potential evapotranspiration, i.e. the
177 product of reference evapotranspiration and crop coefficient (Allen et al., 1998). Reference
178 evapotranspiration is retrieved from the CRU TS3.10 Dataset (Harris et al., 2014), which uses the Penman-
179 Monteith equation. For rainfed crops, when the crop water requirement exceeds the readily available water,
180 i.e. the water the plant can uptake from the root zone without entering crop water stress, the crop coefficient
181 is opportunely reduced by a stress factor. For irrigated crops, this excess demand with respect to the available
182 water is supplied by irrigation. $D_{i,t}$ is the deep percolation below the root area, occurring when soil moisture
183 exceeds field capacity, i.e. the maximum volume of water that can be retained by the soil. $R_{i,t}$ is the sub-

184 surface runoff, occurring when the excess in soil moisture cannot be uptaken exclusively by deep percolation
185 because it would require an infiltration rate higher than the maximum.

186 The results are then monthly aggregated.

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

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

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193 Where *Dom*, *Ind* and *Agr* are domestic, industrial, and agricultural blue water demands, respectively.
194 Agricultural blue water is given as an output by the soil water balance, whereas industrial and domestic water
195 footprints are retrieved from (Hoekstra & Mekonnen, 2012). Local blue water availability is calculated from
196 runoff *R*, also an output of the hydrological model, constrained by environmental flow requirements through
197 the 0.2 factor in Equation 2, representing a fixed unconstrained runoff fraction of 20% (Rosa et al., 2018). To
198 model the impact of upstream users on downstream areas, the local blue water availability in a grid cell is
199 summed to the net blue water availability from the upstream grid cells. Net blue water availability is
200 calculated as the cumulated surplus of upstream cells with respect to their water demand. The pointy
201 brackets in Equation 2 represent a conditional statement by which, if in a cell the sum of water availability in
202 the cell and surplus water coming from upstream areas exceeds human demand, this excess is passed onto
203 downstream cells, whereas if the demand is higher than the availability all the water is consumed in the cell
204 and no surplus is passed onto downstream cells. By calculating blue water scarcity in the current scenario
205 and in the coffee expansion scenario, and comparing the two sets of results, we can evaluate the impact of
206 this agricultural expansion on water scarcity. In particular, we measure the impact as variation in yearly blue
207 water scarcity months, i.e. months during which the blue water scarcity index has a value greater than 1. This
208 means the demand of water is higher than the availability, and thus that this demand cannot be satisfied, or

209 at least not without depleting environmental flows. Starting from this impact assessment we build up an
210 iterative procedure to design agricultural expansion with no tangible water scarcity effects. A simplified
211 example of this procedure is represented in Figure 1. The two sets of water scarcity data are therefore used
212 as boundary conditions: the modified blue water scarcity, accounting for agricultural expansion, is the initial
213 condition for the iterative procedure, and the baseline situation, before the expansion, is considered as the
214 target. The steps of the procedure are the following:

215 1. **Identification of new water scarce areas.** We compare the initial (new) and target (baseline) blue
216 water scarcity months data. Areas having a number of months higher in the new situation than in
217 the baseline (red areas in Figure 1, map b) are areas where the coffee expansion produced the onset
218 of water scarcity for at least one month in the average year.

219 2. **Identification of upstream areas responsible for the onset of blue water scarcity** (Figure 1, map c).
220 Each pixel experiencing changes in blue water scarcity months is snapped to the closest subbasin
221 outlet. The watershed is reconstructed for each of these outlets, and the coffee expansion areas
222 within these watersheds are identified.

223 3. **Reduction of the irrigated crop expansion** (Figure 1, map d). In each irrigated crop expansion pixel
224 that generates water scarcity, the blue water allocated to coffee in expansion areas is reduced by a
225 fraction of the currently allocated value. This means that, along iterations, blue water allocation
226 decreases following an exponential decay to reach asymptotically zero. To limit iterations, pixels are
227 shut off once they reach a cut-off value of blue water allocation, meaning that no expansion is
228 allowed to take place (Figure 1, map f), and in the following iteration the soil water balance values
229 for those pixels are taken from the baseline scenario and not from the expansion scenario.

230 4. **Decision.** After step 3 we return to step 1, comparing target (baseline) blue water scarcity to blue
231 water scarcity calculated from the redesigned expansion resulting from step 3. The possible cases
232 are the following:

233 a. **Variations in water scarcity, some expansion areas still active** (Figure 1, map d). This means
234 that there are still some areas generating downstream water scarcity effects, for which the

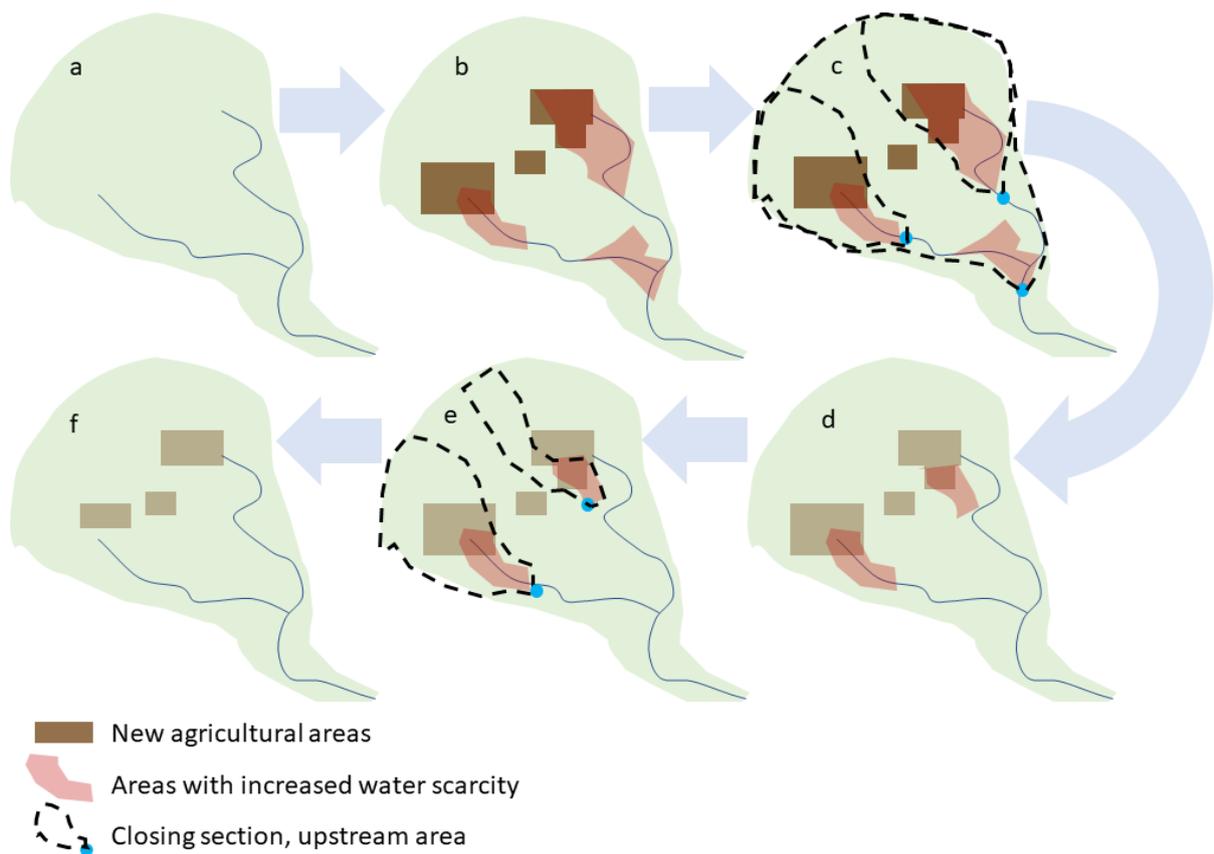
235 blue water contribution has to be reduced, so we go through steps 2 and 3 again (Figure 1,
236 maps e and f).

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

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

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

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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.

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Results

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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 (approximately 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).

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

Crop	Area [ha]	Green Water [Mm³]	Blue Water [Mm³]
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

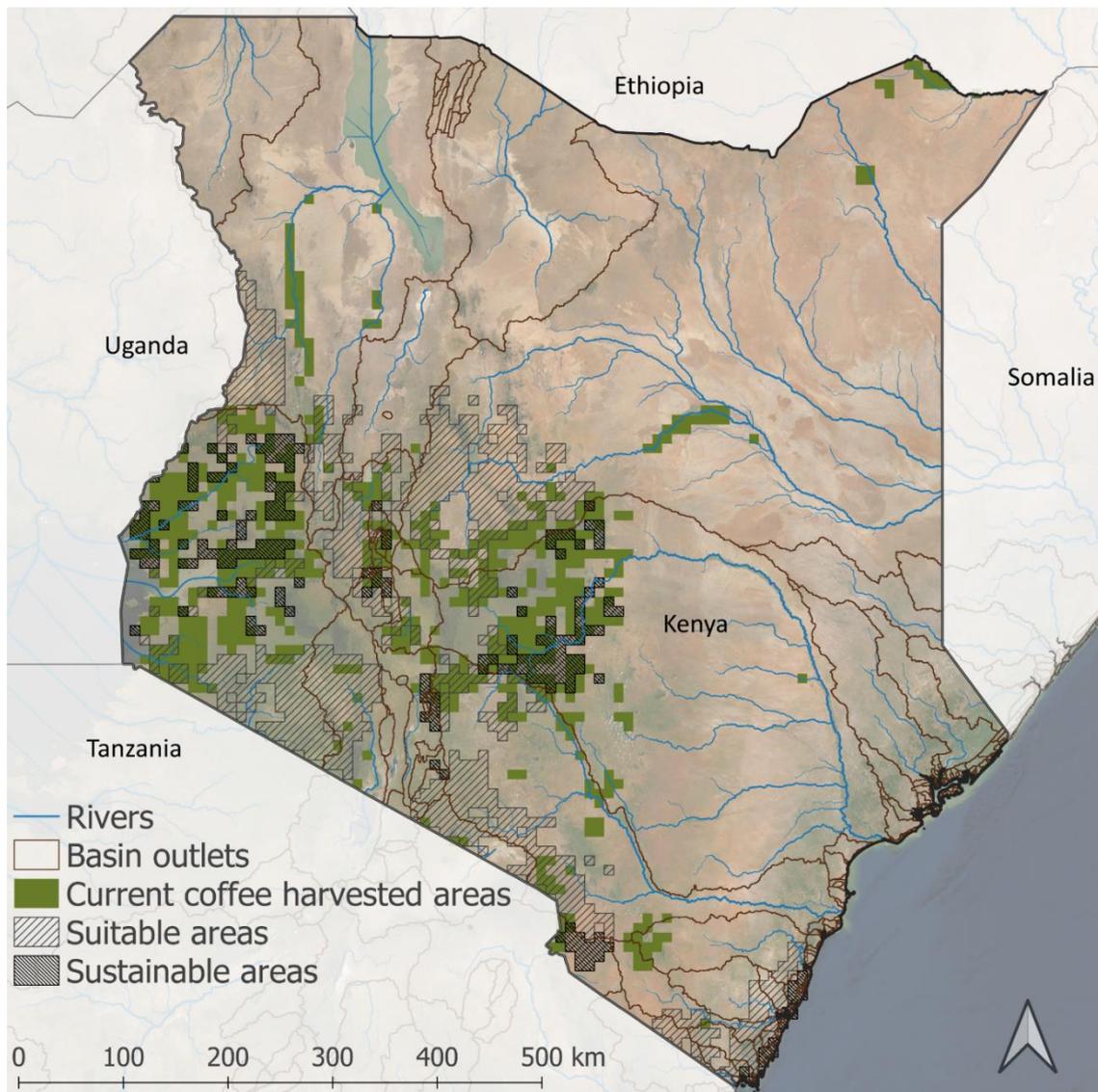
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268 We choose to consider all expansion areas as irrigated areas, under the hypothesis of maximizing the
 269 productivity of the new areas by closing the crop yield gap through irrigation (Rosa et al., 2018a). Therefore,
 270 when comparing water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

272

273 The blue water scarcity-based design of coffee harvest expansion in Kenya renders a positive outcome,
 274 meaning that areas are identified where the expansion of coffee cultivation does not generate additional
 275 water scarcity. The total areas available for expansion extend over 3.38Mha, of which 2.27Mha are at least
 276 moderately suitable to the cultivation of coffee. The iterative procedure narrows this pool down to 0.24Mha
 277 that can be harvested in conditions of hydrological sustainability. The spatial distribution of these areas,
 278 visible in Figure 2, helps better understand how these areas are identified. The map in Figure 2 shows where

279 the areas are located avoiding to show, for the sake of completeness in the visualization, the 'intensity' of
280 the expansion, i.e. how many hectares are used for expansion in each of the mapped pixels. However, the
281 general trend in this sense can be inferred qualitatively by comparing the extent with the totals. Areas
282 currently harvested with coffee amount to 0.15Mha, of which only one tenth are irrigated. They appear in
283 Figure 2 to be mostly located in the Southwest of Kenya. These are the hilly areas where Kenya's water towers
284 are located (FAO, 2015), having many of the characteristics that make an area suitable for the cultivation of
285 coffee. In fact, coffee thrives best in elevated areas, that ensure mild temperatures even in tropical climates,
286 so to avoid at the same time frosting and heat stress. Also the mild slope of these mountainous areas helps
287 preventing frosting, while ensuring sufficient drainage without setting on erosion (FAO, 2021; Valipour &
288 Eslamian, 2014). The areas available for expansion with at least moderate suitability, labelled 'Suitable areas'
289 in Figure 2, extend from these mountainous regions onto the neighbouring ones, especially southwards, i.e.
290 towards areas where the humid climate is preserved, while northwards the climate becomes progressively
291 arid (Kottek et al., 2006). While, visually, current and suitable areas extend over similar regions, suitable areas
292 are more than 20 times higher than current areas. This means that suitable areas represent shares of
293 expansion pixels that are much higher than the common coffee harvested pixel share. It is rather unrealistic
294 to consider these areas available for expansion as a whole, i.e. to project agricultural expansion on the total
295 of these areas. This is why they are used here only for the sake of hydrological characterization, and as an
296 initial pool from which to choose expansion areas, i.e. as a set of areas that are equally (un)sustainable *a*
297 *priori*, from the land use and crop suitability point of view, from which to select only those that are also
298 hydrologically sustainable. These hydrologically sustainable areas, i.e. areas using water without conflicting
299 with pre-existing water uses, labelled 'Sustainable areas' in Figure 2, are more strictly located in the region
300 currently harvested with coffee than the suitable superset. In many cases, they overlap with currently
301 harvested pixels. In these cases, shares of available areas are converted to coffee cultivation in pixels where
302 coffee cultivations where already pre-existing. This is probably the less impacting type of expansion from the
303 environmental, social and landscape point of view, as we project new coffee plantations where they are
304 already present in the mix, rather than introducing them as a new species, agricultural system, and landscape
305 element.



306

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

309 The sustainable expansion areas amount, as already mentioned, to 0.24Mha, which is more than the current
 310 coffee harvested areas in Kenya. The fact that they extend over a smaller region than current coffee
 311 harvested areas means that, as for the suitable areas, sustainable areas occupy larger shares of the pixels
 312 they are in than current coffee harvested areas. In terms of how the iterative procedure works, this means
 313 that the areas in many of the pixels in the initial pool of available areas are either used almost completely or
 314 completely shut off. In essence, in areas where water is available, it is also sufficient for relatively larger
 315 expansion schemes, while in many other regions water scarcity is very sensitive to land use change. The fact
 316 that sustainable areas are mostly located in co-presence with existing areas also shows that, to some degree,

317 the existing agricultural system has adapted to the local water availability spatiotemporal gradients. Indeed,
318 the only sustainable expansion areas located far from existing ones are on the southern coast of Kenya. In
319 this case, being close to river outlets of small coastal basins (Figure 2), excess water has no downstream
320 users, therefore the model identifies them as areas not producing any downstream water scarcity effects.

321 Table 2 and Figure 3 show how increasing the areas for coffee production results in significantly higher water
322 requirements. First of all, even though coffee cultivation in Kenya is primarily rainfed, blue water
323 requirements occupy a significant share of the crop water requirement. Interestingly, green water use in
324 rainfed areas is lower than in irrigated areas, more likely due to a lack in availability than to a lower demand
325 of the plant. This is probably one of the main factors underlying the low yield of coffee in Kenya. The cascading
326 effects of expanding coffee plantations by cultivating suitable areas without hydrological constraints can be
327 evaluated both from the partition of water requirements in Figure 3 and from the water scarcity map in
328 Figure 4. Coffee in suitable expansion areas would have a higher crop water requirement than currently
329 irrigated coffee. The green water contribution to this requirement is slightly higher, in absolute terms, in
330 suitable expansion areas, but the higher total water requirement counters this effect, leading to an overall
331 higher blue water consumption. This, combined with the high extent of these new agricultural areas,
332 produces strong variations in blue water scarcity. Figure 4 shows maps of yearly months of water scarcity,
333 i.e. months during which the demand for blue water exceeds the availability. The left map shows water
334 scarcity months when coffee cultivation expands onto suitable areas, while the right map shows water
335 scarcity months when coffee cultivation expands onto sustainable areas, i.e., the areas that are obtained at
336 the end of the iterative procedure. Because the iterative procedure is designed to find expansion areas that
337 produce negligible variations in blue water scarcity, the blue water scarcity map for sustainable areas is
338 visually equivalent to current actual blue water scarcity, before expansion, and thus can be used for
339 comparatively analysing both the performance of sustainable areas with respect to suitable areas, and of
340 suitable areas with respect to the baseline condition. On average, suitable areas suffer from water scarcity
341 almost three times longer than areas where coffee is currently cultivated. While there are some areas where
342 this effect is lower than average, some clusters emerge in Figure 4, where blue water scarcity increases

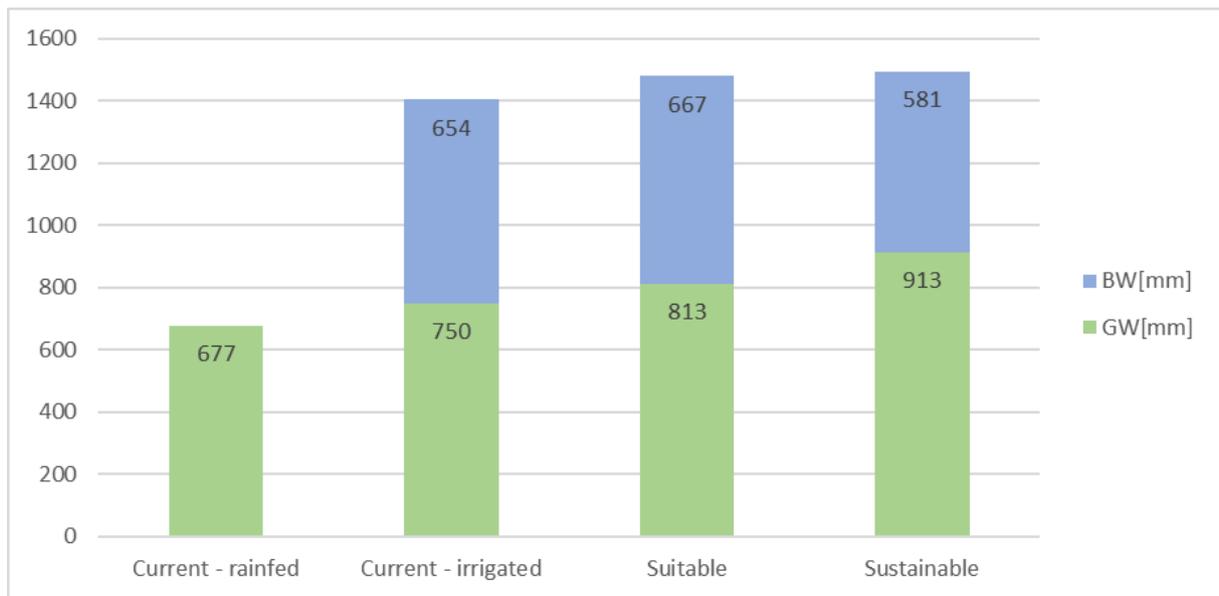
343 dramatically, moving for instance from 0-1 months/year to 10-11months/year. These extensive and intense
344 increases in blue water scarcity, mostly localized within the expansion areas, expand also downstream, which
345 can also be inferred from the visual comparison of the two maps in Figure 4. By comparing the two maps, is
346 becomes evident how, for instance, coffee expansion on suitable areas without hydrological constraints
347 would produce a far-reaching depletion effect on the Ewaso-Ngiro river, flowing from West to East in the
348 centre of the country. Indeed, while in the right map the trace of the river is evident, as a stream of pixels
349 with lower water scarcity months values than the surrounding pixels, this stream disappears in the left map,
350 showing how the pixels where the Ewaso-Ngiro flows do not benefit anymore, in terms of water availability,
351 from the presence of the river. The Ewaso-Ngiro then flows into Somalia. This means that, in a scenario where
352 coffee expansion significantly depletes the river's resources, transnational issues may arise if the depletion
353 reaches the border, thus impacting Somalia's water scarcity situation. The blue water scarcity-based crop
354 expansion design, instead, allows to accurately target areas preventing this water resource depletion. What
355 is interesting to observe, in this regard, from Figure 3, is that, even though coffee has a slightly higher crop
356 water requirement in sustainable areas than in both current irrigated and suitable expansion areas, the
357 relative contribution of green water to this requirement is much higher. If we compute green water scarcity
358 as the ratio of blue water consumption with respect to the total water requirement, we obtain values of 0.47,
359 0.45 and 0.39 for current, suitable and sustainable areas respectively. This means that, while suitable areas
360 are very similar to current ones in terms of green water scarcity, harvesting on sustainable areas implies
361 having a 15% lower green water scarcity in these areas than in current areas. Moreover, the fact that
362 sustainable areas use much more green water (100mm more than sustainable areas, 163mm more than
363 current irrigated areas) does not mean that sustainable areas are more green water intensive, but rather that
364 more green water is available in these areas. As mentioned before, agricultural expansion can increase water
365 scarcity both through the increase in blue water demand given by irrigation and through the decrease in blue
366 water availability caused by lower generation of runoff. In the case of sustainable expansion areas, the lower
367 blue water demand and the higher green water availability create a synergy that reduced both this effect,
368 allowing to harvest and irrigate new areas without generating water scarcity not only in the areas themselves,
369 but also downstream. An important addition to this is that, even though substantially reduced with respect

370 to the total suitable areas, sustainable areas for expansion exceed expansion policy forecasts for coffee in
 371 Kenya. Therefore, there is space of action that remains available to further limit the expansion according to
 372 other important criteria to be accounted for when designing the implementation of such policies. On the
 373 other hand, as already mentioned, these areas are in proximity of existing coffee plantations, and existing
 374 plantations are to the largest share not irrigated, despite the high water intensity of coffee. Therefore, being
 375 the procedure based on water before being based on land, the results also show that, alternatively to pure
 376 expansion, there is also room for increasing production by combining, in a well calibrated manner,
 377 intensification of existing plantations through irrigation and expansion on new areas.

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

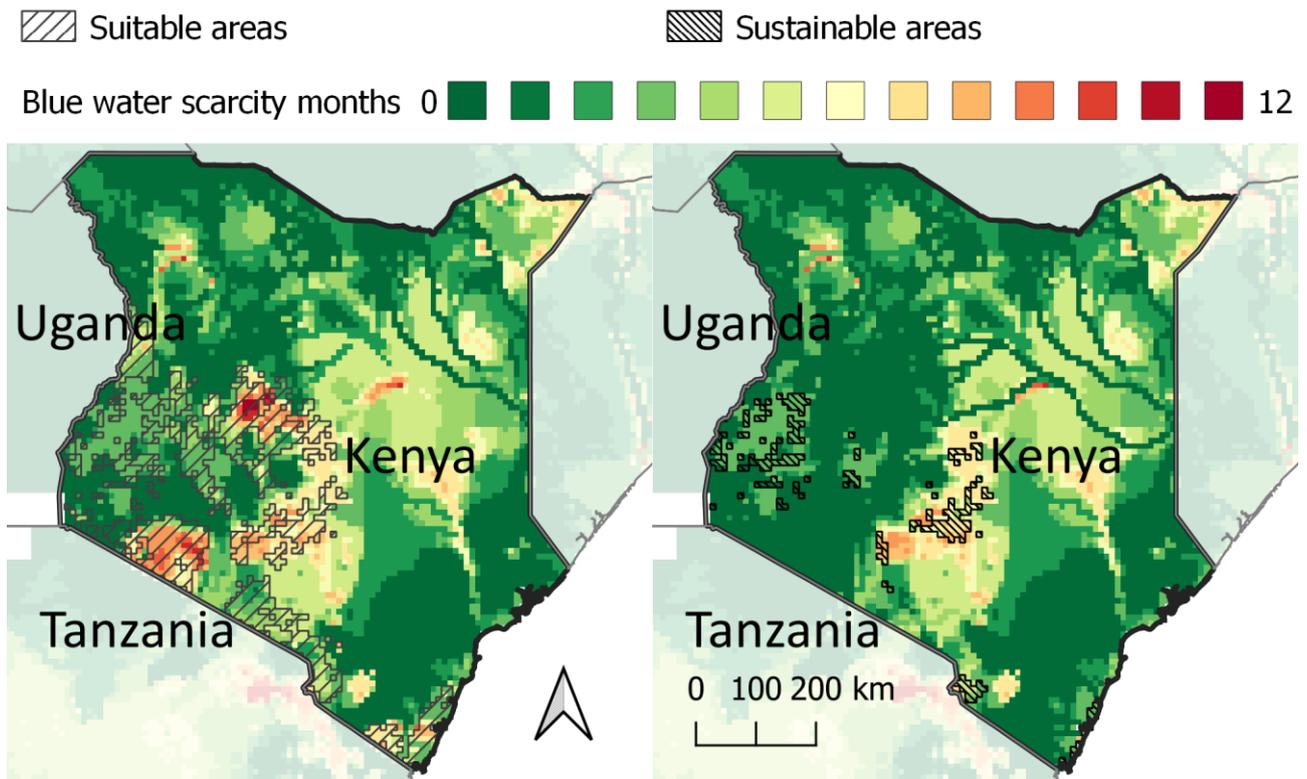
	Areas [ha]	Blue Water [Mm3]	Green Water [Mm3]
Current - rainfed	134790	-	912
Current - irrigated	14526	95	109
Suitable	2727849	18187	22179
Sustainable	243147	1414	2219

381



382

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



386

387 *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*
 388 *expansion, or expansion on hydrologically sustainable areas.*

389 Discussion

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

398 As this work aimed at flexibility and generalizability of the methodology, some limitations arise from the
399 simplifications introduced to reach these aims. For what concerns the hydrological implementation of coffee
400 expansion, our results reflect an ideal situation in which irrigation always provides the whole amount of crop
401 water needs that is not supplied by rainfall. In practice, different irrigation techniques can be adopted, e.g.
402 supplemental irrigation and deficit irrigation. However, at the initial planning stage in which the scope of this
403 paper is located, the best practice is to design strategies considering the whole resource demand. It is also
404 important to take into account the whole water demand when evaluating water scarcity, which is by
405 definition a demand-supply based index. Analogously, we accounted only for the consumptive use of water,
406 thus avoiding the losses associated to irrigation application (i.e. transport of water, leakages) for two reasons.
407 First, it is common practice in water footprint assessments to consider only consumptive water use because
408 other losses are supposed to re-enter the hydrological cycle (Hoekstra & Mekonnen, 2012). Second, irrigation
409 application losses depend strongly on the type of irrigation and of water source, and these can be very
410 different in a sector in which the farming method ranges from small subsistence farming to large estates
411 (Allen et al., 1998; FAO, 2015; Jägermeyr et al., 2015). The iterative procedure progressively reduces the blue
412 water allocated to expansion areas. When it reaches a low threshold and blue water scarcity effects are still
413 detected, it means that the expansion areas are causing water scarcity not by putting additional demand
414 onto blue water resources, but by reducing, through the additional transpiration due to change in land use,

415 the formation of (available) blue water. In these cases, following the proposed methodology, the pixel is 'shut
416 off', meaning no expansion is allowed in the pixel at all. A conceptually refined alternative to this approach
417 could be to directly reduce the expansion area instead of reducing the blue water contribution to this area.
418 While this approach may seem more straightforward from a theoretical point of view, its application might
419 be more complex. In fact, it would require either to iteratively run a water balance model, with high
420 computational costs, or to reconstruct the cell-specific land and crop use matrix after the hydrological
421 simulation, instead of simulating the water balance of the given (current or modified) land use matrix.

422 Agricultural expansion plans and policies tend to be connected to the risk of Large-Scale Land Acquisition,
423 especially for commercial agriculture in institutionally fragile states (Lanz et al., 2018; Rulli et al., 2013; Rulli
424 & D'Odorico, 2014). This risk also applies to coffee expansion in Kenya. While our results show that
425 sustainable expansion of coffee areas is possible mostly in proximity of already existing coffee areas, thus
426 suggesting the risk of monocultures, it does so only in limited extents, in certain regions of the country. This
427 is still a rightful constraint to the scale of possible agricultural development policies, but it can also serve as
428 a bulwark against LSLA risk, in the sense that it intrinsically excludes the possibilities of very large
429 monocultural plantations. In fact, such an analysis can fit well into a wider context of agricultural
430 development, one that includes the conservation of biodiversity and landscape diversity among its
431 objectives. The projection of several small to medium scale patches for the expansion of coffee harvesting in
432 regions that are already familiar with this sector is also coherent with the socio-economic structure of the
433 coffee production chain in Kenya, based mostly on networks of small producers. The creation of structured
434 policies in that sense may help safeguard this business structure, preventing the risk of abandonment of
435 agricultural land, an emerging trend following the increasing average age of the farmers (Ngeywo et al.,
436 2015). This aspect increases in relevance in the light of the fact that a large share of the population is involved
437 in the coffee production system, and women play a central role. In fact, even though women provide roughly
438 two thirds of the workforce employed in coffee farms, they occupy only 5% of the managing positions in
439 coffee cooperatives, with most of them being widows inheriting the farm (International Coffee Organization,
440 2019; Onyalo, 2019). Therefore, if the already existing coffee production boosting policies are backed up by
441 actions towards the involvement of women in coffee management activities, this may also help to achieve

442 gender equality and reduce injustice, in line with the 5th and 10th Sustainable Development Goals, respectively
443 (United Nations General Assembly, 2015).

444 While the scope of our study is to assess and size potential areas for agricultural expansion, intensification is
445 often seen by the research and policy agendas as a more sustainable way to increase agricultural production
446 (Tilman et al., 2011). However, a hydrological impacts analysis is a rather natural outgrowth of intensification
447 scenarios (Rosa et al., 2018), while it tends to be neglected in expansion plans. In the case of coffee in Kenya,
448 there is a wide scope of action for closing the yield gap through intensification, such that different
449 irrigation/fertigation systems could be proposed, depending on external and context specific factors as the
450 energy availability for withdrawing water, the availability of pre-existent infrastructures or the financial
451 capability to install new ones, the skills of the farmers and the possible cultural barriers to the adoption of
452 new agricultural technologies (Piemontese et al., 2021). Indeed, the identified sustainable areas target
453 precise regions within the country, and this could furtherly be refined when considering other factors, such
454 as proximity to markets, to workforce or to infrastructure, as well as more local knowledge-based insights on
455 the ecosystem and heritage values of the pre-existing landscape. In the case of commercial agriculture
456 expansion in developing countries, as here, giving policy relevance to this type of biophysical assessments,
457 especially when combined with bottom-up co-creation approaches, can serve as a significant dissuasion also
458 against LSLA, which otherwise often take advantage of less specific agricultural expansion policies (Lanz et
459 al., 2018). In any case, the proposed methodology for the assessment of hydrological impacts of agricultural
460 expansion and subsequent sizing of expansion scenarios can be adapted to agricultural intensification in a
461 relatively straightforward way. As already stated in the results section, the procedure is water-based,
462 meaning that areas identified as sustainable for coffee expansion are areas where water is sufficient to
463 ensure a hydrologically sustainable implementation of that scenario. But if we decouple the scenario from
464 the water availability, it means that in these areas there is water available to support, to different extents,
465 different development scenarios, without impacting on pre-existing water uses. Simple instances of this
466 include the aforementioned possibility of mixing intensification of existing plantations and the creation of
467 new ones, or the use of deficit or emergency irrigation. More in general, the advantages of the proposed
468 methodology, related to the low amount of necessary input data and the high flexibility, make it viable for

469 replication for different crops in different contexts. In fact, the procedure can be adopted for other situations
470 similar to the one analysed here, identifying areas for hydrologically sustainable agricultural production. It
471 may potentially be a prominent and useful tool for country-level planning of agricultural development. This
472 analysis clearly shows how referring only to partial information with respect to the complexity of the issue of
473 agricultural development may lead to partial, when not misleading, results with respect to a correct framing
474 of sustainability in agriculture. Thus, it can be seen as a research contribution towards the integration of the
475 blue water scarcity indicator into quantitative analyses aimed at the design and/or impact assessment of
476 nexus solutions employing irrigated agriculture within the water planetary boundary.

477 Acknowledgements – conflict of interest statement

478 The authors declare no conflict of interest.

479 Data availability statement

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

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

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

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

495

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

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

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526 [specific_Green_and_Blue_Water_Requirements/4893084](https://springernature.figshare.com/collections/Global_Gridded_Dataset_of_Crop-specific_Green_and_Blue_Water_Requirements/4893084)
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