A methodology for quantifying global consumptive water use of coffee for sustainable production under conditions of climate change

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ABSTRACT

Coffee is the second most traded commodity in the world after oil. A sustainable coffee industry is crucial to maintaining global agriculture, trade, human and environmental well-being, and livelihoods. With increasing water scarcity and a changing climate, understanding and quantifying the risks associated with water, a primary input in coffee production, is vital. This methodological paper examines the means of quantifying: (a) ‘current’ consumptive water use (CWU) of green coffee (coffee beans at harvest time) globally; (b) coffee ‘hot spots’ and ‘bright spots’ with respect to levels of CWU, yields and water stress; and (c) possible impacts of climate change on the CWU of coffee. The methodology employs satellite-derived monthly evapotranspiration data and climate projections from two global circulation models for three future scenarios. Initial estimates suggest that currently (on average) 18.9 m³/kg of water is consumed in producing one unit of green coffee. The same estimate for irrigated coffee is 8.6 m³/kg, while that for rain fed coffee is 19.6 m³/kg. Climate scenarios show that effective mean annual rainfall in many major coffee areas may decrease by the 2050s. The generic methodology presented here may be applied to other crops, too, if crop data are available.

Key words | coffee, coffee yield, climate change, consumptive water use, irrigation, water stress

INTRODUCTION

Coffee is an extremely popular beverage worldwide with over 1,400 million cups being consumed every day. It is also one of the most traded commodities after oil (Nestlé 2011). The coffee trade generated approximately USD15 billion worth of exports in the 2009/2010 coffee year (defined as the period of 1 year, from October 1 to September 30, by the International Coffee Organization (ICO)), and coffee cultivation is the main livelihood for nearly 25 million farmers (ICO 2011). Coffee agro forests the world over provide important ecosystem services in the form of soil fertility improvement, biodiversity conservation and carbon capture and storage (e.g. Garcia et al. 2010; Ajayi et al. 2011; Davis & Méndez 2011; Cerdan et al. 2012; de Souza et al. 2012; Idol 2012; Reichhuber & Requate 2012; Toledo & Moguel 2012). Thus, sustainable coffee production is of paramount importance in maintaining global agriculture, trade, human and environmental well-being and livelihoods.

Coffee is an agricultural commodity with its own ‘sustainability labels’ (Fairtrade, Organic, Rainforest Alliance, UTZ) to account for the participation of growers (the supply chain) in various combinations of social, environmental and economic standards (Giovannuci & Koekoek 2003; Kolk 2011, 2012). Each label certifies the compliance of the supply chain to different aspects of sustainability, including conservation of soil and biodiversity in farms, and the assurance of sustainable livelihoods for farmers (Giovannuci & Koekoek 2003). The sustainability of coffee, as in the case of any other crop, depends on the sustainability of four over-arching dimensions of the production system (Pretty et al. 2010): (i) natural resource
inputs (water resources, soil nutrition, ecosystem services, energy, etc.); (ii) agronomic practices (production systems and technologies, crop genetic improvement, pest and disease management, etc.); (iii) agricultural development (social capital, extension, livelihoods, governance, etc.); and (iv) markets and consumption (prices, markets and trade, consumption patterns, etc.). Substantial research has been carried out on each of these four dimensions with regard to the coffee industry. They include (but are not limited to) studies by: Castro-Tanzi et al. (2012) on adverse consequences of intensive agrochemical use on the agro ecology of coffee; Ajayi et al. (2011), Cerdan et al. (2012), Davis & Méndez (2011), de Souza et al. (2012), Garcia et al. (2010), Idol (2012) and Reichhuber & Requate (2012) on the benefits from coffee agro ecosystems; Jensen & Dicks (2012) on the difference in profitability between organic and conventional coffee; López-Bravo et al. (2012) and Mendesil et al. (2012) on controlling coffee rust disease and coffee insect pests, respectively; and Kolk (2011, 2012) on market characteristics of products with ‘sustainable coffee’ labels. However, it is noted that studies focussed on the sustainability of the coffee industry with respect to consumptive water use (CWU), a primary input in coffee production, are few and far between.

The sustainability of the coffee crop itself depends on the availability of adequate water, while coffee production needs to ensure the sustainability of the water resources that it depends on by not overusing and over-polluting it. In the face of increasing water scarcity (CA 2007) and a changing climate, understanding and quantifying the risks to water, a primary input in coffee production, and coffee itself, is both timely and essential. This paper attempts to develop a methodology to: estimate the ‘current’ CWU of green coffee (coffee beans at harvest time) at the global scale; assess implications of the ‘current’ CWU on water-stressed locations of the world; and project the possible impacts of climate change (CC) on the CWU of coffee, with a view to understanding the influence of global water resources on the long-term sustainability of the coffee industry and vice versa.

The CWU, also referred to as the ‘water footprint’ or the ‘virtual water content’ (Chapagain & Hoekstra 2004; Siebert & Döll 2010), is represented by the total evapotranspiration (ET) requirement during a crop cycle, which is met from two sources, rainfall (green water) and irrigation (blue water). This study does not account for ‘grey water’ (the volume of water depleted in terms of quality deterioration during the crop production process and another component of the water footprint) because, generally, the ‘grey water’ component is much smaller than the ET component. In order to assess CWU, a novel approach (also discussed by Romaguera et al. 2010) is proposed, where actual monthly ET from coffee plantations across the globe is estimated using satellite-derived global land surface ET, compiled by Zhang et al. (2010), for the period 1983–2006. Traditionally, ET is estimated by multiplying the crop coefficient pertinent to a specific growth period (Kc) by reference ET (ET0) (Allen et al. 1998).

Earlier attempts to quantify the CWU of coffee include those studies carried out by Chapagain & Hoekstra (2004), Hoekstra & Chapagain (2007), Liu & Yang (2010), Mekonnen & Hoekstra (2011), Pfister et al. (2011) and Siebert & Döll (2010), where a global average CWU value for coffee is reported. However, these studies do not concentrate on coffee per se, but rather on global crop production as a whole (which includes cereals, vegetables, fruits, roots and tubers, etc.). Neither do they examine the CWU of coffee at the national or sub-national level. Chapagain & Hoekstra (2005) provide estimates of the CWU of coffee for the period 1995–1999 at the national level, but only for those countries that export coffee to the Netherlands. All of the above studies use the traditional method of estimating ET. Apart from the above, a few studies have attempted to establish ET rates and irrigation requirements of coffee plants, and also discuss the issue of over-irrigation (e.g. Carr 2001; D’haeze et al. 2003, 2005; Marin et al. 2005; Cessanelli & Gurracino 2011). However, they are location-specific experimental studies implemented in a few countries such as Brazil and Vietnam.

A handful of attempts have been made to visualize the impacts of rising temperature and changing patterns of precipitation (caused by CC) on coffee production quantities, areas suitable for coffee growth (loss of current areas and migration into new areas), and the coffee economy (e.g. Simonett 1989; Gay et al. 2006; Baker & Haggag 2007; Oxfam 2008; Zullo et al. 2008; Schroth et al. 2009; Läderach et al. 2009, 2010; Haggag & Shepp 2011). However, they remain focused on a few Central American and African
countries (Mexico, Nicaragua, Honduras, Brazil, Uganda, Kenya and Tanzania) and do not cover the entire globe. Therefore, there is a need for a comprehensive global assessment of the current and future CWU of coffee, to facilitate the identification of sustainable production practices, especially with respect to water use, as well as the risks to the sustainability of the coffee industry due to water stress and CC. The scope of this paper is limited to a methodological development of such a global study and a first reconnaissance application of it, due to uncertainties linked to the principal source of coffee information: the HarvestChoice database (http://harvestchoice.org/), the latest, best available, published, public global coffee dataset. The coffee grid data extracted from this database contain questionable information for several countries. For example, in Africa, substantial coffee-growing areas are shown for: central Madagascar, northern Cameroon, northern Ivory Coast, eastern Guinea and much of Zimbabwe, while coffee production is limited to the eastern highlands; and most of Tanzania, while production is concentrated in three specific regions (Figure 1(a)). Other questionable information includes average yields (e.g. Malawian coffee is not more productive than Brazilian) and the presence or absence of irrigation (e.g. Vietnam is shown as non-irrigated but uses substantial irrigation (D'haese et al. 2003, 2005; Figure 1(a)). Thus, this paper attempts to develop a methodology (using the latest, public, spatial data) to:

- quantify components (total, fractions from rainfall and irrigation) of current (represented by year 2000) CWU of coffee at grid, national, continent and global levels to ascertain differences (if any) in the CWUs of irrigated/rain fed coffee cultivation and Arabica/Robusta coffee varieties;
- identify countries operating at ‘optimum’ CWU levels, and assess different pathways and sustainable practices that other countries can follow to reach these optimum levels;
- identify current ‘hot spots’ and ‘bright spots’ considering CWU and yields, and assess implications of water scarcity and stress on these locations;
- assess the impacts of changing rainfall and temperature (caused by CC) on coffee yield and ET, and hence on CWU by 2050; and
- estimate potential changes in mean annual effective rainfall by the 2050s on current coffee areas and the implications of such changes on current ‘hot spots’ and ‘bright spots’.

DEVELOPMENT OF METHODOLOGY AND DATA USED

Estimating (current) CWU

Estimates of CWU are presented here as: (a) the quantity of water consumed in producing one unit of crop (CWU1 in cubic meters (m³)/kilogram (kg); Equation (1)); and (b) quantity of water consumed per year per unit of land (CWU2 in m³/hectare (ha).year; Equation (2)).

Considering that optimum production of a coffee tree occurs from years 5 to 15, the CWU of coffee in terms of total water consumed per unit of crop product (CWU1: m³/kg) is expressed as

\[
\text{CWU1} = \left( \frac{\text{ET}}{\text{Y}} \right) \times 10 \times 1.5
\] (1)

where \(\text{ET}\) = actual crop ET per year (mm/year); \(\text{Y}\) = coffee yield (kg/(ha.year)); 10 is a factor balancing units; and 1.5 is a factor reflecting the productive fraction of a coffee tree’s life span (10 out of 15 years approximately).

The CWU of coffee in terms of total water consumed per unit of land per year by coffee trees (CWU2: m³/(ha.year)) is expressed as

\[
\text{CWU2} = \text{ET} \times 10
\] (2)

The factor 1.5 is not applied in estimating CWU2 because it is only estimated for the cropped area in a certain year.

The \(\text{ET}\) in the above equations is sourced either from soil moisture (rainfall, green water) or from irrigation (blue water). In the case of irrigated coffee, the contribution from irrigation (\(\text{IR}\)) to \(\text{ET}\) in any given month is assessed as

\[
\text{IR} = \text{ET}_{\text{month}} - \text{EP}_{\text{month}} \text{ with } \text{IR} \geq 0
\] (3)

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where $ET_{month}$ = actual crop ET per month (mm/month) and $EP_{month}$ = effective precipitation per month (mm/month). $EP_{month}$ is calculated from the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) method implemented in CROPWAT software (Smith 1994) as $P_{month} \times (1 - 0.0016 \times P_{month})$ for $P_{month} \leq 250$ mm/month and $125 + 0.1 \times P_{month}$ for $P_{month} > 250$ mm/month, where $P_{month}$ is mean monthly rainfall. $IR$ may be summed up over a crop cycle to estimate irrigation requirement for a complete crop cycle.

As coffee is a perennial crop, the crop cycle runs from new leaf growth to the harvest of coffee beans and is approximately 1 year in duration (ICO 2011). The monthly ET estimates accumulated over the crop cycle of 12 months (consisting of different growth periods) make up the total water consumed by coffee per year. Although the crop cycles of coffee varieties Arabica and Robusta (Table 1) differ slightly from each other, they both consist of 12 months in total (Winston et al. 2005; FAO 2011). Arabica accounts for over 60% of the world’s coffee production and is grown throughout Latin America.
in Central and East Africa, in India and, to some extent, in Indonesia and China (Figure 2). *Arabica* beans mature in about 9 months (time from flowering to ripe bean) (ICO 2011). *Robusta* coffee is grown in West and Central Africa, throughout Southeast Asia and, to some extent, in Brazil (Figure 2). *Robusta* beans mature in 10–11 months (ICO 2011). The only way that this study distinguishes between the CWUs of the two coffee varieties is by attributing CWU estimates within a particular country to the major coffee variety grown in that country (since the HarvestChoice database does not specify the coffee variety present in each grid cell). The start and end of the crop year (crop cycle) in each country (Table 5) was obtained from ICO (2011). In the case of countries for which crop year information is not available from ICO, data of their nearest neighbours were adopted.

The current CWU1 and CWU2 of coffee are first estimated and mapped for the year 2000 across the globe at 5 × 5 min grid resolution (approximately 10 × 10 kilometres (km) at the equator) and are subsequently aggregated into national, continental and global levels (Tables 3–5 and Figures 1(b), 3 and 4). The relative position of each country with respect to CWU1, CWU2 and yield are mapped out (Figures 3 and 4) while an attempt is made to identify possible development pathways through which countries may reach ‘optimum’ CWU1, CWU2 and yield levels (Figure 5).

The reasons for considering the year 2000 as being representative of current conditions are: (a) it is the nearest year for which gridded coffee data are publicly available on a global scale; and (b) it is the base year (reference) for climate projections used in this study. Monthly ET estimates for 2000 were obtained from satellite-derived global land surface ET, compiled by Zhang et al. (2010), available at a nominal resolution of 8 × 8 km for the period 1983–2006. The ET estimates have been derived using a modified Penman-Monteith approach (Allen et al. 1998) and validated against *in situ*

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**Table 1 | Coffee crop cycle**

| Coffee variety | New leaf growth and development | Start of flowering | Fruit setting and maturing | Crop maturity | Harvest of berries |
|----------------|---------------------------------|-------------------|---------------------------|---------------|-------------------|
| *Arabica*      | Month 1–2                       | Month 3           | Month 4–9                 | Month 10      | Month 11–12       |
| *Robusta*      | Month 1–2                       | Month 3           | Month 4–mid-month 10      | Mid-month 10–mid-month 11 | Mid-month 11–month 12 |

**Figure 2 | Major coffee-growing countries and varieties. Source: mapped by IWMI based on data from the International Coffee Organization (ICO): www.ico.org/index.asp.**
measurements made at FLUXNET tower sites (a global monitoring network for measurement of land–atmosphere exchanges, including water vapour) (Baldocchi 2008). Monthly averaged ET from this dataset for 1991–2006 is used here as the actual monthly ET estimates for 2000. Other global gridded datasets employed in estimating current CWU1 and CWU2 are: (a) 2000 mean monthly precipitation (averaged over 1991–2010) from the Climate Change Agriculture and Food Security (CCAFS) General Circulation Models (GCM) Data Portal (www.ccafs-climate.org) described in Jones & Thornton (2012) and Jones et al. (2009); and (b) 2000 coffee crop area, yield and production data (at 5 × 5 min grid cell resolution) from the HarvestChoice database (http://harvestchoice.org/) maintained by the International Food Policy Research Institute (IFPRI) and the University of Minnesota, USA (You et al. 2006). All global datasets used in this assessment are summarized in Table 2.

Analysis of (current) ‘hot spots’ and ‘bright spots’

This paper attempts to gauge the ‘productivity’ of coffee with respect to water use at different locations of the world, and thereby identify current coffee hot spots (locations with low productivity) and bright spots (locations with high productivity). This is achieved by systematically classifying the 2000 values of CWU1, CWU2 and yield of individual grid cells into ‘favourable’ and ‘unfavourable’ categories by identifying certain favourable and unfavourable value ranges in all three parameters. This classification recognizes the importance of ensuring sufficient water delivery to the coffee tree as well as maximizing yields with less water...
input. All grid cells with a combination of three ‘unfavourable’ scores are considered to be coffee hot spots having very low productivity, while those with a combination of three ‘favourable’ scores are considered to be bright spots having very high productivity (Figure 6(a)). Two more classification levels are shown on Figure 6(a) provisionally named as ‘high productivity’ and ‘low productivity’ to account for the rest of the combinations of scores: two ‘favourable’, one ‘unfavourable’, and one ‘favourable’, two ‘unfavourable’, respectively. The identified ‘favourable’ and ‘unfavourable’ value ranges and the rationale behind their identification are further explained in the section ‘Current CWU, the role of irrigation and differences between Arabica/Robusta coffee varieties’.

The net annual irrigation requirement (sum of IR in Equation (3) over 12 months) is also estimated and mapped at grid cell level for 2000 (Figure 6(b)). Locations with a net positive irrigation requirement (IR > 0) are where annual ET is drawn from sources beyond effective rainfall (possibly through supplemental irrigation). Although it is widely believed that supplemental irrigation helps to improve coffee yields, the existence of water stress (physical water scarcity) may limit the irrigation potential at some locations (risking coffee production). Similarly, at other locations, over-allocation of water for coffee production may cause water stress during certain periods. The global distribution of net annual irrigation requirement is overlaid with spatial maps of freshwater availability (IWMI Global Water Scarcity Map; CA 2007) and environmental water stress (IWMI Environmental Water Stress Index Map; Smakhtin et al. 2004) to identify locations where provision of irrigation water may be problematic. The two IWMI water scarcity/stress maps are regarded as proxies for the spatial distribution of irrigation water availability. Regions considered to have constraints in implementing irrigation or expansion of irrigation to meet ET requirements are: (a) areas presently experiencing or approaching physical water scarcity (where more than 60% of river flows are currently withdrawn, and water resources development is approaching, is expected to approach in the near future, or has already exceeded, sustainable limits) in the IWMI Water Scarcity Map; and (b) all river basins having an Environmental Water Stress Index (WSI) greater than 0.8 in the IWMI Environmental WSI Map. Coffee areas which coincide with these water-stressed regions (circled in red in Figure 6(b)) are identified and analysed to ascertain whether constraints to irrigation water availability are likely to affect productivity at these locations. It should be
Figure 5 | Groups of coffee-producing countries (top) and development pathways (bottom).
noted though that, in these areas, coffee yields may increase with small supplemental irrigation as opposed to other seasonal crops. The marginal value productivity of that additional irrigation could be much higher for coffee than for other irrigation-intensive crops.

Projecting CC impacts

Assessment of the impacts of changing rainfall and temperature (caused by CC) on ET, yield and the CWU of coffee is made for three scenarios specified in the Special Report on Emission Scenarios (SRES) (A1B, A2 and B1) of the Intergovernmental Panel on Climate Change (IPCC 2000). Downscaled climate data for the 2050s (Jones et al. 2009; Jones & Thornton 2012) from the two GCMs, CNRM-CM3 (Salas-Mélia 2002; Salas-Mélia et al. 2005) and MIROC MEDRES (Kawamiya et al. 2005; Nozawa et al. 2007), are employed for this purpose. The A1 scenario family assumes a world of very rapid economic growth, a global population that peaks in mid-century, and the rapid introduction of new and more efficient technologies. Scenario A1B further assumes a balance across all energy sources. The B1 scenario describes a convergent world with the same global population as A1, but with more rapid changes in economic structures towards a service and information economy; A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change (IPCC 2007). Scenarios A1B, A2 and B1 have been employed in the IPCC’s Fourth Assessment Report (IPCC 2007) and this study follows suit.

The reasons for selecting CNRM-CM3 and MIROC MEDRES models are primarily pragmatic:

(a) Spatially and temporally downscaled global precipitation, temperature and solar radiation data from these models are already publicly available at the downscaled GCM Data Portal (www.ccafs-climate.org) of CIAT, so that mapping at a finer resolution than that of the original GCM is possible.

(b) Other supplementary data needed to project future ET and yield are also available for these two models and can be downloaded (although at original GCM resolution) from the IPCC Data Distribution Centre (www.ipcc-data.org/ar4/gcm_data.html) unlike in the case of some other GCMs.

It is assumed that the physical area where coffee is expected to be grown in 2050 remains unchanged from that of 2000, since the projection of coffee areas in 2050 involves the analyses of a multitude of complex climatic and socio-economic parameters (e.g. Haggar & Shepp...
Projected CWU1 and CWU2 estimates for 2050 are made considering only the influence of the net change in climate parameters on ET and coffee yield, assuming that all other drivers remain the same as in 2000. However, if and when potential coffee areas in 2050 are identified with any degree of certainty, CWU1 and CWU2 may be projected on these new areas using the same methodology set out in this paper.

Actual ET in 2050 is projected at 5 × 5 min grid cell resolution based on the ratio of downscaled solar radiation at ground level between 2000 and 2050 by: (a) using satellite-derived monthly ET estimates for 2000 from Zhang et al. (2010) as a reference for ET processes; and (b) assuming maximization of effort for water management of coffee areas in both 2000 and 2050. Coffee yield in 2050 is also projected at the same resolution using the biomass growth and yield extraction method based on the normalized difference vegetation index (NDVI) from Bastiaanssen & Ali (2005), by considering actual yield in 2000 (as in You et al. 2006) as a biophysical reference. On the basis of a known yield in
2000, the yield model equation from Bastiaanssen & Ali (2003) was set up theoretically for both years 2000 and 2050. An algebraic manipulation was used between the two equations of 2000 and 2050 to remove non-calibrated factors relating NDVI to the absorbed photosynthetically active radiation (APAR), since the crop type is identical throughout the years. The new estimation makes use of the relationship between the rate of change of yearly biomass growth and incoming solar radiation at ground level to project changes in coffee yield from 2000 to 2050 based on CC scenarios. The Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) satellite remote sensing vegetation index, and especially its monthly NDVI (2000–2011) (MOD13C1: https://lpdaac.usgs.gov/products/modis_products_table/mod13c1), compiled by Strahler et al. (1999) and Huete et al. (1999), respectively, was linearly extrapolated to project NDVI in 2050. All datasets used in projecting coffee yield and ET into the 2050s are listed in Table 2. CWU1 and CWU2 in the 2050s are estimated using Equations (1) and (2) similarly to year 2000 (see section ‘CWU under CC and implications for present hot spots’; Figure 7(a)).

Projected mean annual effective rainfall in the 2050s is compared with that of 2000 to identify coffee areas which are likely to experience reduced effective rainfall in the future (Figure 7(b)). These locations are compared with the currently water-stressed locations in order to distinguish the high-risk areas for coffee production (with respect to water availability) in the 2050s.

**FIRST RESULTS AND DISCUSSION**

**Current CWU, the role of irrigation and differences between Arabica/Robusta coffee varieties**

Almost uniformly, low CWU1 values are observed in coffee areas in Vietnam, Thailand and India (in Asia), Zambia and Zimbabwe (in Africa), and Costa Rica (in Central America) (Figure 1(b)). On the whole, CWU1 is high throughout Africa, Central America, the Caribbean and the northern part of South America. It is relatively low in Asia, except in parts of Indonesia, Malaysia and Laos (Figure 1(b) and Table 3). A comprehensive analysis of the underlying factors contributing to the wide range of CWU1 values and how these factors may interact with each other in different locations is extremely complex and is beyond the scope of the current global scale study, especially considering the limitations and uncertainties associated with global level data. Nevertheless, this paper attempts to draw some generalized conclusions and overviews (in the following paragraphs) from initial results, which hopefully may lead to more focused region, country and site-specific analyses and concrete conclusions.

Low CWU1 values (average 8.6 m³/kg) are seen throughout the irrigated areas of Brazil, as opposed to the non-irrigated areas (average 18.4 m³/kg) (Figure 1(b)). These low CWU1 values are a result of increased yields triggered by supplemental irrigation (average 1,455 kg/(ha.year) in irrigated areas against 465 kg/(ha.year) in rain fed areas). The world average CWU1 is 18.9 m³/kg (which includes both irrigated and rain fed coffee), but the world average CWU1 of irrigated coffee alone is as low as 8.6 m³/kg while that of rain fed coffee is as high as 19.6 m³/kg (Table 3). The contribution from irrigation to the global average CWU1 is a mere 1% (Table 5), while the rest is provided by effective rainfall. This estimate is arrived at by separating and summing up the contribution from irrigation to CWU (IR in Equation (3)) in each month of the crop cycle, only within areas demarcated as having irrigated coffee in the HarvestChoice database. Actual contribution from irrigation may be slightly higher considering that some areas known to irrigate coffee are not recognized as such in the HarvestChoice dataset as explained in the introduction to this paper. Considering the lower average CWU1 for irrigated coffee as opposed to that for rain fed coffee, it may be reasonably inferred that although irrigation increases CWU2, the marginal increase in yield (and decrease in CWU1) with respect to increase in CWU2 may be significantly high in the case of irrigated coffee. These results point to the widely held perception that supplemental irrigation helps boost coffee yields and may provide a window of opportunity to the African continent, in particular, where CWU2 is still relatively low (Table 4), leaving ample room to multiply its irrigation efforts. However, it is vital to ensure that water withdrawals for such increased irrigation follow principles of ‘sustainable intensification’ (Royal Society 2009; Godfray et al. 2010), or the production of higher coffee yields from the same area of land, while...
reducing negative environmental impacts due to overdraft of water resources or over-irrigation.

Figure 3 shows all countries having a CWU1 less than or equal to 90 m³/kg and CWU2 less than 16,500 m³/(ha year) on a bubble graph. The CWU1 and CWU2 axes are limited to these values in order to bring more clarity to the figure. The sizes of bubbles represent the yield achieved by each country. Countries having irrigated coffee plantations are shown in blue while those having rain fed plantations are shown in green. The green dotted line represents the world average CWU2 (9,153 m³/(ha.year)), while the red dotted line represents the world average CWU1 (18.9 m³/kg). This bubble graph helps to visualize the relative position of major coffee producing countries against the two CWU metrics calculated in this study: CWU1, indicating how much water is consumed in producing one unit of crop, and CWU2, indicating how much water is used in one unit of land per year. Figure 4 shows a three-dimensional surface plot of the same metrics with CWU1 and CWU2 on the horizontal axes and yield on the vertical axis. The
The interpolated surface shows the position of each country on the CWU1, CWU2 and yield continuum. The surface does not intersect all data points exactly but only illustrates the combined topography of the three metrics with currently available data. The current lower limits for CWU1 and CWU2 are approximately 6 m³/kg and 5,200 m³/(ha.year).

It is seen that CWU1 decreases with increasing yield, while CWU2 displays an ‘optimum’ value (at Vietnam). Yields decrease with CWU2 on both sides of this optimum value. Considering the wide variation in CWU2 values among Asian countries having similar yields (for example Malaysia and India) and the wide disparity in yields among African countries having similar CWU2 values (for example Tanzania and Zambia), it may be reasonably inferred that annual quantities of water use in the field alone do not determine yield levels. The timing of water inputs is equally important as the quantity itself, as already pointed out by other studies (Carr 2001; Tesafaye et al. 2003). Apart from water, yield levels are also affected by soil type and depth, plant health and coffee variety planted (Njiongo et al. 1996; Carr 2001). Therefore it appears that higher coffee yields result from a combination of favourable conditions including sufficient water availability and proper timing to meet ET demands, soil health and plant health. While these conditions are largely determined by the natural, ecological variables of each location, they may be favourably altered through the use of technology. This paper divides technology into two broad categories as: water management and farming practices. Favourable water management practices consist of ensuring both sufficient water availability as well as proper timing of water inputs. Favourable farming practices may include fertilization, integrated pest management (IPM), soil amendment, horticultural management and the use of high-yielding coffee varieties.

There is a clear bright spot centred on Vietnam from an observational point of view (Figures 3 and 4). Although it is not possible to decipher all natural, ecological and technological conditions leading to the position of Vietnam (or any other country for that matter) on this continuum, it is inferred that the irrigation of coffee and enhanced farming practices in fertilization and pest management followed by Vietnam (Cong et al. 2002; Hendlund et al. 2004; Rios & Shively 2006) as a major producer – which may not necessarily be followed at the same level by other countries – and Vietnam’s environmental conditions are favourable for higher coffee productivity. An attempt has been made to identify groups of countries operating at different productivity levels based on their position on the continuum (Figures 3–5). The groups are provisionally named Optimum, Farming Practices and Water Management. The ‘Optimum’ group is centred on Vietnam, which has the highest coffee yield of 1,690 kg/ha against a world average of 725 kg/ha (Table 5). Some other countries in this group are Costa Rica, USA, Thailand, Zambia, China, Malawi and Cambodia, all of which lie on and around the highest plateau on Figure 4 above a yield value of approximately 1,200 kg/ha. The name ‘Optimum’ is used to identify this group simply because it appears to be the group currently operating under optimum conditions on the CWU1, CWU2, yield continuum. CWU1 values in this group generally range from 6 to 12 m³/kg while the CWU2 ranges from 6,000 to 11,300 m³/(ha.year). This optimum CWU2 range translates into 600–1,130 mm of ET per year. The high yields observed in this group result from a combination of:

(a) optimum water management practices (water is not limiting yield production by lack or excess and water inputs are timed appropriately); and (b) optimum farming practices

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**Table 3 | Comparison of CWU1 of irrigated/rain fed and Arabica/Robusta coffee varieties across continents**

| Continent                        | CWU1 (m³/kg) | Irrigated | Rain fed | Arabica | Robusta | Average |
|----------------------------------|--------------|-----------|----------|----------|---------|---------|
| South and Latin America and the Caribbean | 8.7          | 20.2      | 19.1     | –        | 19.1    |         |
| Africa                           | 8.2          | 26.3      | 18.7     | 29.3     | 25.9    |         |
| Asia                             | –            | 15        | 19       | 14.8     | 15      |         |
| Average                          | 8.6          | 19.6      | 19       | 18.7     | 18.9    |         |

**Table 4 | Comparison of CWU2 across continents**

| Continent                        | CWU2 (m³/(ha.year)) |
|----------------------------------|---------------------|
| South and Latin America and the Caribbean | 9,659               |
| Africa                           | 7,387               |
| Asia                             | 9,859               |
| Average                          | 9,153               |
Table 5 | Average CWUs of coffee for major coffee-producing countries

| Country               | Crop year | CWU1 (m³/kg) | CWU2 (m³/(ha.year)) | % from irrigation | Yield (kg/(ha.year)) |
|-----------------------|-----------|--------------|---------------------|-------------------|---------------------|
| Benin                 | Oct–Sep   | 43.5         | 5,803               | 0                 | 200                 |
| Bolivia               | Apr–Mar   | 13.6         | 9,633               | 0                 | 1,060               |
| Brazil                | Apr–Mar   | 13.8         | 8,647               | 2.5               | 943                 |
| Burundi               | Apr–Mar   | 15.4         | 7,491               | 0                 | 730                 |
| Cambodia              | Oct–Sep   | 10.2         | 8,838               | 0                 | 1,295               |
| Congo, Rep. of        | Jul–Jun   | 41.6         | 7,841               | 0                 | 283                 |
| Congo, Dem. Rep. of   | Oct–Sep   | 46.8         | 8,787               | 0                 | 282                 |
| China                 | Oct–Sep   | 7.16         | 6,297               | 0                 | 1,319               |
| Cameroon              | Oct–Sep   | 40.3         | 7,698               | 0                 | 287                 |
| Colombia              | Oct–Sep   | 19.0         | 9,455               | 0                 | 747                 |
| Costa Rica            | Oct–Sep   | 11.4         | 10,527              | 3.2               | 1,380               |
| Central African Rep.  | Oct–Sep   | 29.0         | 9,899               | 0                 | 512                 |
| Cuba                  | Jul–Jun   | 80.0         | 12,191              | 0                 | 230                 |
| Dominica              | Jul–Jun   | 24.0         | 14,174              | 0                 | 886                 |
| Dominican Republic    | Jul–Jun   | 63.3         | 11,660              | 0                 | 276                 |
| Ecuador               | Apr–Mar   | 25.2         | 8,156               | 0                 | 486                 |
| Equatorial Guinea     | Oct–Sep   | 42.6         | 10,439              | 0                 | 368                 |
| El Salvador           | Oct–Sep   | 25.1         | 11,762              | 2.5               | 701                 |
| Ethiopia              | Oct–Sep   | 19.1         | 8,127               | 0                 | 639                 |
| Gabon                 | Oct–Sep   | 86.2         | 9,221               | 0                 | 161                 |
| Ghana                 | Oct–Sep   | 55.1         | 5,992               | 0                 | 163                 |
| Guatemala             | Oct–Sep   | 16.1         | 11,780              | 0                 | 1,091               |
| Guinea                | Oct–Sep   | 24.9         | 6,681               | 0                 | 402                 |
| Haiti                 | Jul–Jun   | 35.6         | 12,292              | 0                 | 518                 |
| Honduras              | Oct–Sep   | 19.1         | 11,103              | 0                 | 872                 |
| Indonesia             | Apr–Mar   | 24.0         | 11,199              | 0                 | 701                 |
| India                 | Oct–Sep   | 11.4         | 7,338               | 0                 | 966                 |
| Ivory Coast           | Oct–Sep   | 24.4         | 6,603               | 0                 | 405                 |
| Jamaica               | Oct–Sep   | 43.4         | 14,926              | 0                 | 516                 |
| Kenya                 | Oct–Sep   | 17.7         | 6,565               | 0.8               | 558                 |
| Laos                  | Oct–Sep   | 18.2         | 9,578               | 0                 | 791                 |
| Madagascar            | Apr–Mar   | 33.8         | 7,369               | 0                 | 327                 |
| Malawi                | Apr–Mar   | 8.27         | 6,710               | 0                 | 1,217               |
| Mexico                | Oct–Sep   | 40.7         | 11,346              | 0                 | 418                 |
| Malaysia              | Apr–Mar   | 21.8         | 11,864              | 0                 | 818                 |
| Mozambique            | Apr–Mar   | 20.6         | 8,061               | 0                 | 587                 |
| Myanmar (Burma)       | Oct–Sep   | 44.9         | 6,358               | 0                 | 212                 |
| Nigeria               | Oct–Sep   | 19.4         | 5,429               | 0                 | 235                 |
| Nicaragua             | Oct–Sep   | 20.5         | 10,375              | 0                 | 760                 |
| Paraguay              | Apr–Mar   | 23.4         | 10,256              | 0                 | 657                 |

(continued)
A second group of countries, provisionally named ‘Farming Practices’, is centred on Brazil (Figure 5). These countries lie on the steep upward slope on the CWU1, CWU2, yield continuum (Figure 4) generally above a yield value of 600 kg/ha. This group has higher average CWU1 (6–25 m³/kg) and CWU2 (6,000–14,000 m³/(ha.year)) and slightly lower yields than the first group. It is envisaged that the apparent difference in yields between the ‘Optimum’ and ‘Farming Practices’ groups is caused by the application of different levels of farming practices rather than differences in water management practices, hence the name ‘Farming Practices’. However, this inference is inconclusive at this stage and needs further verification through ‘on ground’ comparisons.

The last group of countries (‘Water Management’ group in Figure 5) have relatively low yields (below 600 kg/ha) compared with the first two groups. The range in CWU1 values in this group is approximately 6–90 m³/kg while that of CWU2 is 5,200–16,650 m³/(ha.year). Countries in the top half of this group (above the blue dashed line through the USA) are water rich, yet they are not achieving correspondingly high yields (one possibility being excessive water availability). Jamaica, Haiti, Puerto Rico and Mexico are a few of the countries in this category. In the bottom half of the group below the blue dashed line through Zimbabwe (consisting of countries such as Ghana, Nigeria and Benin), water deficit is inferred to be the main cause of observed low yields. In countries lying within the two blue dashed lines, improper timing of water delivery rather than the annual quantity itself may be a prime reason for the resulting low yields, considering that their CWU2 levels are within the ‘optimum’ range identified (6,000–11,300 m³/(ha.year)). The ‘Water Management’ group lies furthest away from the ‘optimum’ water management point.

Table 5 | continued

| Country                              | Crop year      | CWU1 (m³/kg) | CWU2 (m³/(ha.year)) | % from irrigation | Yield (kg/(ha.year)) |
|--------------------------------------|----------------|--------------|---------------------|-------------------|---------------------|
| Peru                                 | Apr–Mar        | 17.2         | 7,705               | 0                 | 672                 |
| Panama                               | Oct–Sep        | 27.6         | 8,377               | 0                 | 456                 |
| Papua New Guinea                     | Apr–Mar        | 17.5         | 11,140              | 0                 | 954                 |
| Philippines                          | Jul–Jun        | 18.1         | 11,157              | 0                 | 923                 |
| Puerto Rico                          | Jul–Jun        | 35.7         | 12,363              | 0                 | 520                 |
| Sierra Leone                         | Oct–Sep        | 9.11         | 6,593               | 0                 | 1,086               |
| Sri Lanka                            | Oct–Sep        | 25.5         | 10,735              | 0                 | 631                 |
| Trinidad and Tobago                  | Jul–Jun        | 105          | 10,805              | 0                 | 154                 |
| Thailand                             | Oct–Sep        | 8.81         | 7,288               | 0                 | 1,240               |
| Togo                                 | Oct–Sep        | 30.1         | 6,304               | 0                 | 314                 |
| Tanzania, United Republic of        | Jul–Jun        | 27.7         | 7,166               | 0                 | 388                 |
| Uganda                               | Oct–Sep        | 29.6         | 9,383               | 0                 | 476                 |
| United States (Hawaii)               | Oct–Sep        | 11.9         | 11,291              | 0                 | 1,423               |
| St Vincent and the Grenadines        | Jul–Jun        | 63.6         | 16,614              | 0                 | 392                 |
| Venezuela                            | Oct–Sep        | 42.8         | 9,810               | 2.8               | 344                 |
| Vietnam                              | Oct–Sep        | 7.33         | 8,254               | 0                 | 1,690               |
| Zambia                               | Jul–Jun        | 9.92         | 7,020               | 0                 | 1,062               |
| Zimbabwe                             | Apr–Mar        | 6.34         | 6,172               | 0                 | 1,406               |
| World                                |                | 18.9         | 9,153               | 0.71              | 725                 |

Source of yield, crop area and irrigated area data: HarvestChoice database (http://harvestchoice.org/).
Source of crop year data: International Coffee Organization (ICO: www.ico.org/index.asp).
Note 1: CWU1 and CWU2 are as given in Equations (1) and (2), respectively.
Note 2: Only countries with yields ≥ 154 and CWU1 ≤ 105 are shown in this table.
on Vietnam (Figure 4). The potential for increasing yields through better water (quantity as well as timing) management is very high for this group of countries, through which they may move into the Farming Practices group and subsequently into the Optimum Group, hence the name ‘Water Management’. In their quest for higher yields, these countries also have a unique opportunity to test out more sustainable agronomic practices, such as establishing coffee agroforestry, which provides a host of additional ecosystem services (Pretty et al. 2006; Garcia et al. 2010; Ajayi et al. 2011; Davis & Méndez 2011; Cerdan et al. 2012; de Souza et al. 2012; Idol 2012; Reichhuber & Requate 2012; Toledo & Moguel 2012), apart from uplifting crop yields.

This study also attempts to trace different development pathways into the optimum group of countries from extreme countries through middle-level performers. Four such families of pathways are illustrated in Figure 5, provisionally named considering the nature of the necessary interventions (in terms of water availability and farming practices) to move over to the Optimum group from the Water Management or the Farming Practices groups. The first of these is the Farming Practices pathway which essentially traces the movement of countries from the Farming Practices group into the Optimum group through implementation of enhanced farming practices and agribusiness development. The second path is the Drainage/Farming Practices pathway, which does not necessarily mean that drainage is the solution, but simply that water in coffee areas might be in excess in countries lying on this path and this negatively impacts yields. The remedial measure here is to decrease water saturation in the soil to unlock yield potential while properly timing water inputs and increasing farming practices around fertilization and plant protection.

The third pathway (Timing/Farming Practices) is a combined intervention where the timing of water inputs needs to be re-investigated/redesigned appropriately in combination with farming practices to increase yields. The final pathway (Irrigation/Timing/Farming Practices) is the combined water availability improvement and farming practices development. This is the most traditional development pathway and involves first improving water management by increasing the efficiency (quantity and timing) of water delivery to the tree. It may be improved by simple means such as mulching and weed control (Carr 2001) and/or irrigation (supplemental, channel, subsurface, etc.) minimizing losses to non-root areas. Yield improvement can be through any form of cheap/available farming practices initially until substantial cash income is generated, when at such time IPM and fertilization can be jointly applied in increasing quantities.

It should be reiterated however that the scope of this paper is limited to illustrating a methodology for obtaining a comprehensive global overview of the CWU of coffee (and reasons for its differences, if any, between countries and regions), and that at no point have the initial observations discussed here been verified on the ground. The development pathways are intended to be indicative only of the direction that each country should follow, in order to reach the ‘optimum’ conditions identified. More detailed analysis on development pathways would need to investigate the triple relations (between CWU1, CWU2 and yield) in each group of countries considering various perspectives, including farming systems and agricultural economics as well as their historical development for the last century. In-depth studies may show that some development pathways are not necessarily the shortest paths on Figure 5, but involve more complex dimensions than just the three parameters used in this study. Although it would be even more beneficial to translate the optimum conditions identified here in terms of CWU1 and CWU2 to components of the natural water balance such as the distribution of annual rainfall, length of the dry season, irrigation water requirements during the dry period, and runoff availability, the extent of analysis required to perform it at the current global scale would be very large. Hence it is deemed best to be attempted as a separate analysis involving country- and region-specific parameters.

The world average CWU1 estimate of 18.9 m³/kg was compared with the world average estimates by Mekonnen & Hoekstra (2011), Pfister et al. (2011), and Siebert & Döll (2010), whose addition of green and blue components of the water footprints are 16.4, 15.4 and 15.1 m³/kg, respectively. The first reason why this paper’s estimate is higher than those by the other three studies is the accounting for non-productive years of the coffee tree (assuming that a coffee tree generally produces coffee beans only for 10 years out of its optimum productive life span of 15 years).
If only one productive year is considered as in the case of the other studies, CWU1 is 12.6 m³/kg, which is lower than the estimates from the other studies. Another reason is due to our use of actual ET estimates derived through remote sensing, rather than estimating potential ET by multiplying reference ET and the crop factor (Kc), the method used in the other three studies. Actual ET is generally less than potential ET. Last, but not the least, inherent deficiencies in the main coffee database used in this study (as already pointed out in the Introduction) may have influenced this result. When all four studies are compared, it can be generally inferred that the global average CWU1 of green coffee is approximately 10–12 times that of wheat, which is estimated at 1.5 m³/kg by Siebert & Doll (2010) and 1.8 m³/kg by Mekonnen & Hoekstra (2011).

The differences between CWU1 of Arabica and Robusta coffee varieties are not apparent at first glance. Table 3 shows the world average CWU1 for the two coffee varieties and a comparison across the three continents. The global average CWU1 of Arabica is 19 m³/kg while that of Robusta is 18.7 m³/kg. Arabica coffee seems to do better in terms of water use per unit of crop (CWU1) in Africa while the opposite is true in Asia, where Robusta coffee has a lower CWU1 than Arabica. However, it is inconclusive as to whether this result is influenced by the coffee variety planted, or by other factors such as the use of irrigation and high-yielding varieties. Although it would have been of interest to compare the performance of irrigated versus rain fed CWU1 of Arabica and Robusta coffee separately, the available data are not sufficiently detailed or accurate for such an analysis on a global scale.

**Current hot spots and bright spots**

The favourable conditions for coffee identified above are applied at grid cell level in this section in order to produce a spatially distributed global map of current coffee hot spots and bright spots (Figure 6(a)). All grid cells having yields less than 600 kg/ha, CWU1 higher than 25 m³/kg, and CWU2 below 6,000 as well as above 11,300 m³/(ha.year) are regarded as having highly unfavourable conditions for coffee (following the definition of different groups given above), and are thus classified as hot spots with very low productivity. Current coffee hot spots in the Americas are in the Caribbean Islands (Cuba, Haiti, Puerto Rico, Jamaica, Dominican Republic and St Vincent and the Grenadines), southern Mexico, northern Venezuela and southern Peru. Hot spots of a lesser degree (two unfavourable and one favourable condition) are seen in the northern parts of Brazil, Mexico, Venezuela and Colombia, and in localized areas of Bolivia, Ecuador, Panama, Nicaragua, El Salvador and Guatemala. On the other hand, current coffee bright spots (areas meeting all three favourable conditions) are in southern Brazil, central Colombia, Costa Rica, northern Peru and some localized areas within Ecuador and Bolivia.

Prominent coffee hot spots in Africa are in Ghana, Togo and Benin. Hot spots of a lesser degree are seen throughout Africa except in Zambia, Zimbabwe, Malawi and Sierra Leone which are definite bright spots. Kenya, Ethiopia, Tanzania and Guinea exhibit mixed results. Apart from the African continent, hot spots of a lesser degree are seen in both Madagascar and Yemen. Hot spots in Asia are seen in southern Malaysia and some parts of Indonesia, while lesser hot spots are seen in Myanmar and Laos. All other coffee areas in Asia (Vietnam, India, Thailand, parts of Indonesia and the Philippines) exhibit higher levels of productivity (at least two or more favourable conditions). Higher levels of productivity are more widespread in Asia than in the other two continents.

The identified hot spots and bright spots are further compared with the spatial distribution of net annual irrigation requirement and irrigation water availability (considering that the IWMI water stress maps serve as proxies for irrigation water availability). By doing so, an attempt is made to identify the role that irrigation/non-irrigation plays in yield levels at these locations.

Figure 6(b) shows the global distribution of net annual irrigation requirement of coffee for 2000 with physically and environmentally water-stressed regions of the world circled in red. Areas in green are where there is a net annual rainfall excess, while those in red and orange are where there is a net annual rainfall deficit (or where the net irrigation requirement is positive). It appears that many locations showing a positive net irrigation requirement are water-stressed too. It is possible that coffee at these locations is already irrigated since this study estimates actual ET in 2000, and a positive irrigation requirement
expresses the amount of actual ET met from sources other than effective rainfall in 2000. Although only some parts of Brazil, Venezuela, Costa Rica, El Salvador and Yemen are identified as having irrigated coffee by the Harvest-Choice database as shown on Figure 1(a), evidence that some coffee areas in countries such as India, Vietnam, Ethiopia and Cuba too are (at least partially) irrigated is provided by the work of Raghuramulu (2010), Rios & Shively (2006), Tesafaye et al. (2015) and Silva et al. (1991). However, further on-ground comparisons are necessary to establish whether coffee, at all locations with a positive net irrigation requirement, is actually irrigated.

In the Americas, locations with a positive irrigation requirement in 2000 (thus sourcing ET outside of effective rainfall) are Cuba, Haiti, Costa Rica, El Salvador, northern parts of Brazil, Venezuela, Colombia and Peru, southern parts of Bolivia and Ecuador and parts of central Mexico and Guatemala. Out of them Cuba, northern parts of Venezuela, Brazil and Peru, southern parts of Bolivia and Ecuador, and central Mexico are all classified as water-stressed and may face constraints in irrigating coffee (Figure 6(b)). Some of these coffee areas in Cuba, Mexico and northern Venezuela have already been classified as hot spots of low productivity (Figure 6(a)) earlier in this section on account of their high water consumption and low yields (averaging 230, 418 and 344 kg/(ha.year), respectively, against a world average of 725 kg/(ha.year)). They represent possible coffee hot spots where yields need to improve without utilizing additional water resources.

African countries having a positive net irrigation requirement are Zambia, Zimbabwe and parts of the Democratic Republic of Congo, Ethiopia, Kenya, Tanzania and Uganda. Out of them, central Ethiopia is classified as water-stressed and may face constraints in irrigating coffee. In Asia, a positive net irrigation requirement is exhibited in central India, southern Vietnam and Laos. Central India is likely to face constraints in irrigating coffee on account of its water-stressed status. Other water-stressed locations include Madagascar and Yemen which currently show rainfall excess on Figure 6(b), and are not categorized as hot spots. Yemen is not represented on Figures 3 and 6(b) since its high-intensity coffee areas are concentrated within a few pixels, and the calculated CWU2 depends largely on the ET data for these few pixels, which may not prove to be accurate. Immediate constraints on irrigation water availability for coffee are not envisaged within Madagascar and Yemen (since they show a net annual rainfall excess), although this can only be confirmed through site-specific studies.

In general this assessment recognizes the existence of two categories of hot spots which are at two opposite ends of the CWU2 spectrum. The first category includes locations such as Cuba and Mexico, where current annual levels of water use in the field are above the optimum range identified (6,000–11,300 m³/(ha.year)), are already sourcing water beyond effective rainfall and are classified as water-stressed (Figures 5, 6(a) and 6(b)), but are not achieving correspondingly high yields. On the other hand, countries such as Ghana, Benin and Togo use annual water quantities below or near the lower threshold of the optimum range (averaging 5,592, 5,802, 6,034 m³/(ha.year), respectively), achieve low yields as expected, exhibit annual rainfall excess (Figures 5 and 6(b)) while not being subject to water stress (leaving room for irrigation). Another notable category emerging out of Figures 3 and 6(b) is the West African countries such as Congo and Cameroon, which show rainfall excess, use almost the same yearly total water quantity on the field (7,841 and 7,698 m³/(ha.year), respectively) as Vietnam (8,254 m³/(ha.year)), cultivate the same coffee variety as Vietnam (Robusta), but reap vastly lower yields (283 and 287 kg/ha against 1,690 kg/ha). This may be due to improper timing of water delivery to the coffee tree. It is generally established that a period of water stress, induced either by dry soil or dry air, is needed to prepare flower buds for blossoming that is then stimulated by rain or irrigation. Water must also be freely available during the period of rapid fruit expansion to ensure large, high-quality seed yields (Carr 2001). It is presumed that the practice of timing water delivery at such critical periods is established at an advanced state in the bright spots on Figure 6(a) as well as in the optimum group of countries (see section ‘Current CWU, the role of irrigation and differences between Arabica/Robusta coffee varieties’ and Figure 5), resulting in higher outputs through lower water inputs.

The need for irrigation and its role in controlling the timing of flowering also depends on other factors such as the monthly rainfall distribution, the severity of the dry season, and the soil type and depth (Carr 2001). Carr (2001)
elaborates that these factors vary within the two geographic regions where coffee is present: areas close to the equator with a bi-modal rainfall pattern and those at higher latitudes with a single rainy season and an extended dry season. Further in-depth ground-based studies, at least within the two broad geographic regions, are required to quantify (as far as possible) the degree to which each of these factors influences coffee yields.

**CWU under CC and implications for present hot spots**

The median global average CWU of coffee in 2050, estimated using future ET and yield projections for the three SRES scenarios (A1B, A2 and B2) of the two GCMs (CNRM-CM3 and MIROC MEDRES), is 18.2 m$^3$/kg, simulated by both scenario A2 of model CNRM-CM3 and scenario A1B of model MIROC MEDRES (as against 18.9 m$^3$/kg in 2000). The slight decrease in CWU1 is due to a projected 2–3% increase in global average coffee yield (and a corresponding 2–3% increase in global coffee production) in all scenarios, whereas total ET from coffee plantations remains almost constant. Hence, the present study does not show dramatic differences in the global average CWU1 and CWU2 of coffee between 2000 and 2050. The global distribution of CWU1 of coffee for one of the median scenarios (scenario A2 of model CNRM-CM3) is shown in Figure 7(a) along with locations expected to receive reduced mean annual rainfall. The map for the other median scenario (scenario A1B of model MIROC MEDRES) looks similar to Figure 7(a) and is not presented in this paper. When comparing the spatial distribution of the CWU1 in 2000 (Figure 1(b)) with that of 2050 (Figure 7(a)), it is apparent that CWU1 does not change much from 2000 to 2050 throughout the globe except in India and Brazil. A general increase in CWU1 is seen within the two countries by the 2050s. The spatial distribution of CWU2 for both years 2000 and 2050 look very similar.

The change in mean annual effective rainfall in 2050 (in comparison to that of year 2000) was assessed for both the median scenarios (scenario A2 of model CNRM-CM3 and scenario A1B of model MIROC MEDRES) in order to identify areas likely to experience a reduction in mean annual effective rainfall (and, therefore, general water availability) under both scenarios. These areas were compared with the currently water-stressed coffee locations shown on Figure 6(b). A general decrease in annual effective rainfall is exhibited in most coffee areas of the Americas and the Caribbean by the 2050s. Decreases in annual effective rainfall (even in the order of 100 mm) are projected almost throughout the coffee growing regions of Brazil, Peru, Costa Rica, Mexico and the Caribbean islands (Cuba, Haiti, Puerto Rico, Jamaica, Dominican Republic and St Vincent and the Grenadines). Some areas already categorized as water-stressed (Cuba, northern parts of Venezuela, Brazil and Peru, southern Ecuador and central Mexico) are likely to see further reductions in effective rainfall by the 2050s. Achieving higher productivity per unit of water will be of paramount importance for all such locations, especially Cuba and Mexico, which are already high up on the CWU2 scale while being low on yields (Figures 3, 5 and 6(a)) and are thus categorized as current hot spots.

Much of the coffee growing regions of Africa are projected to receive higher effective mean annual rainfall except for the southern regions of Ghana, Togo and Benin and some locations in Guinea and Sierra Leone. In Asia, mean effective rainfall is likely to reduce throughout Thailand, Laos and Vietnam and in some parts of China and Indonesia. The same scenario is projected in southern Madagascar too. Affected coffee plantations may have to shift to other favourable locations, while rain fed plantations may need supplemental irrigation. It is acknowledged that the assessment of likely changes in the monthly distribution of effective rainfall is even more important than that of the annual quantity. The determination of more specific impacts of reduced mean effective rainfall and variations in its monthly distribution is best assessed through country- and location-specific studies.

**CONCLUSIONS**

The methodology developed in this paper provides the rationale and the means to assess the current and future CWU of green coffee production with a view to identifying the present status of and future risks to its sustainability. Secondary data sources used in the study have poor spatial resolution, yet provide public domain information on
global coffee production (http://harvestchoice.org/) and climate parameters (www.ccafs-climate.org). They may not capture all local variations though, particularly if those occur within a fraction of a pixel. Hence, there may be many more: (a) sub-pixel, scattered coffee plantations; and (b) localized irrigated coffee areas than those demarcated in the classified grids used. Some of these ‘extra’ irrigated areas may have already been identified by the net annual irrigation requirement map for 2000 produced in the study.

The Zhang et al. (2010) dataset used for estimating ET has been validated against FluxNet site measurements for a small set of representative biome types including natural forest. Since coffee is generally grown at forested sites and is a tree (although short), ET from coffee trees is assumed to be similar to that from natural forest in this methodology. However, it is acknowledged that irrigated coffee will generally have higher ET than natural forest, especially in the dry areas (which are less humid), and that irrigated ET may be underestimated in this procedure.

Actual ET in 2050 was projected using a simplified method based on the ratio of downscaled solar radiation at ground level between 2000 and 2050. However, the best approach to predicting future ET would be to improve on the Zhang et al. (2010) model for conditions in 2050 for a completely new future ET model.

Aggregation of data has been used both spatially and temporally. There may be regions within a country with very high yields, but other regions with completely different climate, soil or socio-economic conditions and very different yields. Analysing the country as a whole may not necessarily draw the right picture. Monthly variations in rainfall (monthly water availability) are also not considered in this assessment since only yearly totals are estimated.

The influence of soil characteristics on coffee yields was not considered, but may shed new light on the position of countries on the CWU1, CWU2, yield continuum, and on specific pathways to reach ‘optimum’ conditions. It is an important aspect that needs to be considered in any future development of this research, when disaggregating studies to region and country levels.

Although the same global coffee area as in 2000 was used in projecting CC impacts on the CWU in 2050, it is likely that CC may force a migration and a decrease in the areas suitable for coffee (e.g. Oxfam 2008; Läderach et al. 2009, 2010; Schroth et al. 2009). Although no significant change is evident here in the CWU of coffee from 2000 to 2050, this result may change if: (a) the validated spatial coverage of coffee areas in 2000 is very different from the HarvestChoice dataset; (b) possible changes in coffee area distribution, consumption patterns and global trade by 2050 are considered; (c) a different ET model (as suggested above) is formulated; (d) faster warming scenarios introduced after IPCC’s Fourth Assessment Report, such as those by Rowlands et al. (2012) and Schuur & Abbott (2011), which the authors claim represent plausible futures and are consistent with recent observed changes, are employed.

Conducting a similar analysis in a specific country, where reliable coffee data are available (such as in Vietnam), may prove very useful in testing out the procedures outlined here, until such time when reliable data are available for a comprehensive global analysis. Furthermore, coffee is a perennial crop that requires induced water stress in key periods of crop growth. In many instances, what is more important is scheduling of irrigation in the dry periods than the quantity itself. Hence, further understanding of conditions in a specific crop location on how CC may impact water requirements during critical periods of crop growth, and scheduling of irrigation, will also help to enrich results derived from a global study. It is hoped that the procedures illustrated in this paper will lead the way to enhanced understanding of current water use and future risks in global coffee production to ensure the crop’s continued sustainability. The same generic methodology may be applied to other crops too if sufficiently detailed spatial information on crop area, production and yield are available.

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