Green or blue water? The importance of soils

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ABSTRACT

In many countries in the Mediterranean basin, irrigation water demand exceeds the supply of renewable water resources. This study assesses the effect of soil water storage on green water (soil moisture provided by precipitation) use and blue water (irrigation) demand for crop production in the Republic of Cyprus over the past 15 years. A program was written, based on the dual crop coefficient approach of FAO Irrigation and Drainage Paper 56, to process daily data from 70 rain gauges and 34 meteorological stations, and compute the soil water balances of 83 different crops growing in 431 Cypriot communities, for the hydrologic years 1994/95-2008/09. There is a large uncertainty in the soil data; in the mountains soils are shallow and stony, but large areas have been terraced. Therefore, we conducted simulations with different soil physical properties: (1) best estimates based on the 1:250,000 soil map, with soil available water capacities ranging between 40 and 150 mm and (2) a uniform soil available water capacity of 150 mm, representing soil and water conservation practices on the shallow soils. With the higher soil water holding capacities of Run 2, average green water use for the 15 year period was 17% higher than the 319×10^6 m^3/yr of Run 1. On the other hand, average blue water demand decreased from 185×10^6 m^3/yr for Run 1 to 163×10^6 m^3/yr for Run 2. The potential savings of 12% of the average annual irrigation water demand emphasizes the importance of soil and water conservation practices.

INTRODUCTION

The climate of the Eastern and Southern Mediterranean region is characterized by low and highly variable precipitation. Access to irrigation is a determining factor for agricultural production in these semi-arid environments. However, in a number of these countries, irrigation water demand exceeds the supply of renewable water resources (Mediterranean Groundwater Working Group, 2007). Climate change model simulations are projecting the region to become not only hotter but also drier (Giorgi and Lionello, 2008). The IPCC (2012) identified the intensification of droughts and heavy precipitation events as an important climate change hazard, although both observed and projected changes in precipitation extremes in the Mediterranean are inconsistent among locations and models. Crop production systems on soils with good infiltration and water holding capacities are more resilient to climate variability and climate change because of their capacity to store water during high rainfall events and wet periods, which can be used to bridge subsequent dry spells (e.g., Rockström et al., 2009).

Precipitation is not only variable in time but also in space. Mountain areas are generally endowed with higher rainfall rates, but due to the sloping land and the often shallow and stony soils, limited precipitation can be stored. However, in many mountain environments agricultural land has been developed or improved through the construction of terraces. Soil and water conservation practices such as terraces, contour bunds or organic fertilization can have a substantial effect on the soil water storage capacity. But the Anthrosols that result from these practices tend to be underestimated on soil maps (ESBN, 2005).

Various global assessments of green and blue water use in crop production (e.g., Liu and Yang, 2010; Mekkonen and Hoekstra, 2011) have made use of the ISRIC-WISE soil data (Batjes, 2006). Similarly to the Harmonized World Soil Database (FAO et al., 2009), the ISRIC-WISE database assumed a standard 1-m soil depth, except for lithosols (0.1 m) and rendzinas or rankers (0.4 m or 0.3 m in FAO et al., 2009). Siebert and Döll (2010) also used the ISRIC-WISE data but for soil depth they used the effective rooting depths of the crops, based on Allen et al. (1998). Rooting depths for most rain-fed crops exceeded 1 m, thus higher green water use could be expected. On a global scale, the results of these three studies are surprisingly consistent, with blue water ranging between 899×10^9 and 1180×10^9 m^3/yr and green water between 4988 and 5771×10^9 m^3/yr. However, due to the differences in methods and data, it is difficult to assess the effect of soil depths.

In Cyprus, substantial funds have been spent by the government to aid farmers to build soil conservation works such as terraces and contour banks. Land owners could form Soil Conservation Divisions to carry out large scale soil conservation works, with the Government subsidizing up to half of the total cost (Christodoulou, 1959). In some places soil was transported from elsewhere and added to rocky land for the development of irrigated lands (Christodoulou, 1959). According to Michaelides (1988), since the approval of a soil conservation and land improvement program by the FAO in 1968, 1000 ha of land has been terraced and 150 ha has been leveled each year.

The objective of this study was to assess the effect of soil water holding capacities on green water (soil moisture provided by precipitation) use and blue water (irrigation) demand on the Mediterranean island of Cyprus, under varying precipitation patterns.

METHODS

The island of Cyprus is located in the far eastern corner of the Mediterranean Sea. This study deals with the southern two-third of the island, covering an area of 5760 km^2, which is governed by the Greek Cypriot community, and hereinafter referred to as the Republic of Cyprus. The geology of Cyprus is dominated by the Troodos Ophiolite, which reaches its highest point at 1950 m above sea level. This elongated, domal structure is a fragment of a fully developed oceanic crust, consisting of plutonic, intrusive and volcanic rocks and chemical sediments (GSD, 2012). Sedimentary formations cover the coastal plains in the south and the intermountain plain in the north. Most soils are shallow and stony, with lithosols or leptosols covering large parts of the island (Figure 1). However, the roots of fruit and nut trees often extend into the fractured geologic formations. The Troodos complex is drained by many steep and narrow valleys, with deeply incised streams. Agricultural areas in the mountains and along the streams in the foothills are often terraced (Figure 2).

Average precipitation over the Republic for the October-September hydro-meteorological years 1980/81-2009/10 was 466 mm (CMS, 2012). However, during the driest year (2007/08) of this 30-year period, just 272 mm precipitation was received, while the wettest year (1991/92) received 637 mm. The range between the driest and wettest location was even higher, from a 30-year average of 276 mm in the plain on the northern site of the Troodos to 1050 mm near the top of the mountains.

A model was developed to compute the daily soil water balances and blue water demand of all crops grown in Cyprus. Details of the model and input data can be found in Bruggeman et al. (2011); a brief summary is presented here.

Annual harvested areas for 83 crops for the 1994/95 to 2008/09 seasons were obtained from the national agricultural statistics (Cystat, 1997-2012). The country's main crops are barley, either grown for cereals or green fodder, olives, grapes, potatoes, citrus and almonds. The total harvested area ranged between 103×10^3 ha (2008) and 148×10^3 ha (2003). On average, 23% of the cropland was irrigated. The areas of the different crops were distributed over 431 communities based on data from the 2003 agricultural census (Cystat, 2006).

Soil physical properties for the units of the 1:250,000 digital soil map of Cyprus (Hadjiparaskevas, 2005) were estimated based on data from the 0.5 degree Harmonized World Soil Database (FAO et al. 2009) and from soil physical information for similar soils provided by the ESBN (2005). Soil water holding capacities (between field capacity and wilting point) for the different soil units ranged between 40 and 150 mm. The average soil water holding capacity was computed for the cropland area of each community, with the help of GIS.

Daily reference evapotranspiration was computed for 34 meteorological stations, using the Penman-Monteith equation (Allen et al., 1998). For the computation of crop evapotranspiration, the dual crop coefficient approach was used. The main equations can be expressed as follows:

$$ETc = (Kcb + Ke)\, ETo \tag{1}$$
$$ETa = (Ks\, Kcb + Ke)\, ETo \tag{2}$$
$$Ke = Kr\,(Kc_{max} - Kcb) \leq FEW\, Kc_{max} \tag{3}$$

where ETc is the crop evapotranspiration with no limits on water availability (mm/d), Kcb is the basal crop coefficient, Ke is the soil evaporation coefficient, ETo is the reference evapotranspiration (mm/d), ETa is the actual plant water use (mm/d), Ks is a stress coefficient (0-1), Kr is an evaporation reduction coefficient (0-1), Kc_{max} is the maximum possible evapotranspiration (1.05-1.3) and FEW is the fraction of the soil that is both exposed to radiation and wetting.

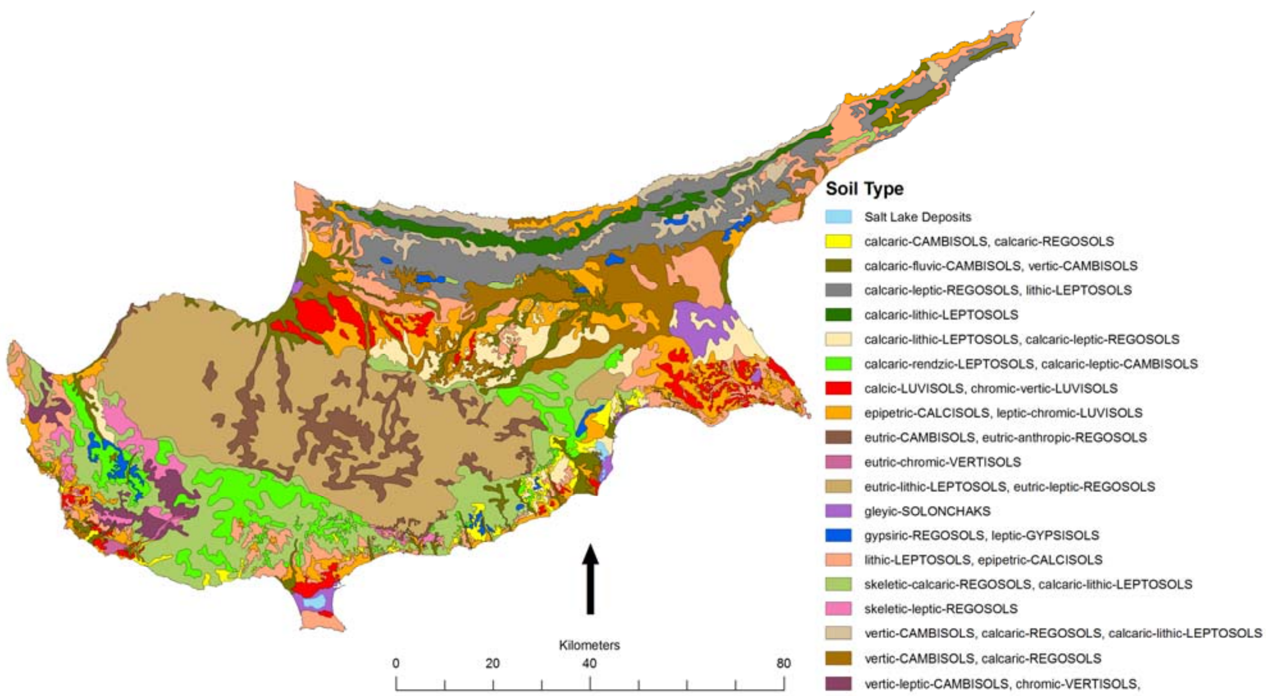

Figure 1. Soil map of Cyprus (Hadjipareskevas, 2005).

Crop coefficients were taken from Allen et al. (1998) and Allen and Pereira (2009). Crop development and planting and harvesting dates were obtained from local information and surveys.

For irrigated areas, it was assumed that irrigation was applied when the soil moisture fell below the readily available water content. A maximum irrigation depth of 50 mm was applied, based on local irrigation practices.

The effect of terracing and other uncertainties in the soil data was assessed assuming two different sets of soil water holding capacities, whereas the effect of the climate was analyzed by keeping the crop areas constant, at the 2003 land use. Thus, the following four simulations were performed for the 15-year record: (1) actual land use and best estimates of soil water holding capacities (40-150 mm); (2) actual land use and a uniform soil water holding capacity of 150 mm; (3) 2003 land use and best estimates of soil water holding capacities; (4) 2003 land use and a uniform soil water holding capacity.

RESULTS

The green water use and blue water demand for Run 1 and 2 are presented in Figure 3. For Run 1, with soil water holding capacities estimated from the soil map, green water use ranged between 169×10^6 m^3/yr in the 2007/08 drought year and 441×10^6 m^3/yr in the wet 2002/03 year. The harvested crop area for these years was 103,411 and 148,416 ha, respectively. For Run 2, with a uniform soil water holding capacity of 150 mm, the minimum and maximum green water use were found in the same years: 200×10^6 m^3/yr in 2007/08 and 499×10^6 m^3/yr in 2002/03. Average green water use for the 15-year period was 17% higher for Run 2 than for Run 1.

The increase in green water use was higher for the grapes, fruit, nuts and olive trees (20%) than for the annuals (16%). This can be explained by the fact that many of the terraces in the mountains are cultivated with grapes and trees, while cereals and vegetables are more common in the naturally deeper soils in the plains.

Blue water demand for the 15-year period ranged between 160×10^6 m^3/yr and 214×10^6 m^3/yr for Run 1. Blue water demand for Run 2 ranged between 141×10^6 m^3/yr and 192×10^6 m^3/yr. As a result of the improved soil water holding capacities, average blue water demand decreased by 12%.

The annual green water use for Run 3 and 4, without any changes in land use over time, is presented in Figure 4. The results are averaged over the 148×10^3 ha crop land and plotted as a function of the average precipitation over the country. While there is, as expected, an increase in green water use with an increase in precipitation, the distribution of the precipitation over the season plays definitely an important role. The effect of the rainfall distribution is most clearly illustrated by the results of the 2003/04 season, which was with 545 mm precipitation the third wettest season in the 15-year record, but had the second lowest green water use for Run 3. This season had indeed a very poor distribution of the precipitation with 52% of the seasonal precipitation falling in January, as compared to 20% for the long-term average, while almost no precipitation was received in March. For the higher soil water capacities of Run 4, green water use during the wet 2003/04 season was average. For both Run 3 and Run 4 highest green water use occurred during 2002/03, which was the second wettest season in the 15-year record. This season had indeed a much better distribution of the precipitation over the season, with 18% of the season's rain falling in March.

The higher slope of the relation between precipitation and green water use for Run 4, as compared to Run 3, indicate that the 150-mm soil water holding capacities are better able to capture the

Figure 2. Mountain terraces in Kampi village on the northeastern slopes of the Troodos mountains, Cyprus.

precipitation during the wetter years. The lower coefficient of variation (R^2) for Run 3, as compared to Run 4, indicate the effect of the soil water holding capacity on the relation between precipitation and green water use. Similarly to Run 1 and 2, the higher water holding capacities of Run 4 resulted in a 12% reduction in blue water demand, as compared with Run 3, while green water use was 16% higher.

DISCUSSION

The model results indicated the sensitivity of the daily crop water balance model to the soil water holding capacities in a typical Mediterranean environment with shallow, stony soils. On the contrary, Wisser et al. (2008) found that the sensitivity of global irrigation water use to a 50% increase in soil water holding capacities was less than 1%. However, their global water balance model does not seem to irrigate very efficiently, considering that the blue water use computed by their model ranged between 2200×10^9 and 3800×10^9 m^3/yr, which was more than double that of the global modeling studies mentioned previously.

In many areas in the Mediterranean region, terraces and agricultural land in the mountain areas are being abandoned (e.g., Petanidou et al., 2008; Garcia-Ruiz, 2010). In Cyprus, the areas of almonds and grapes, which are predominantly cultivated in the mountains, have decreased by 17 and 74%, respectively, over the past 30 years (Cystat, 1982; 2012). While part of the abandoned grape orchards were grown on sloping lands without terraces, most of the almonds are grown on terraced lands with good soils. Thus, the productive use of precipitation in agriculture is decreasing. On the other hand, agricultural irrigation water demand in Cyprus continues to exceed supply (Karavokyris and partners, 2010). Therefore, consideration needs to be given to the potential revitalizing of these mountain terraces with high value crops. On a global level, Rost et al. (2009), who applied a dynamic vegetation model, found that a 21% increase in net primary production could be achieved if water-harvesting practices were used to store 50% of the surface runoff for use during dry spells.

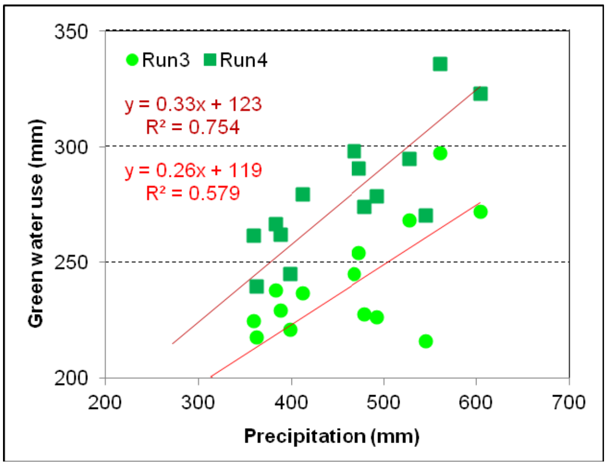

Figure 4. Annual average areal precipitation and green water use for the years 1994/95-2008/09, assuming no changes in land use, and best estimates of soil water holding capacities (Run 3) or a uniform 150-mm soil water holding capacity (Run 4.)

CONCLUSION

Higher soil water holding capacities can improve the productive use of precipitation in semi-arid environments such as Cyprus. The results of the 15-year simulations with a daily soil water balance model indicated that green water use was 16 to 17% higher for a country-wide, uniform soil water holding capacity of 150 mm, as compared to green water use with soil water holding capacities estimated from the soil map (40 to 150 mm). The higher soil water capacities also reduced blue water demand by 12% (22×10^9 m^3/yr, on average).

Considering the increase in irrigation water prices as a result of the European Water Framework Directive, mountain terraces may again become more competitive. Thus, from a water resources perspective, it would be wise to not abandon terraced agriculture, especially in the higher rainfall environments of the mountains.

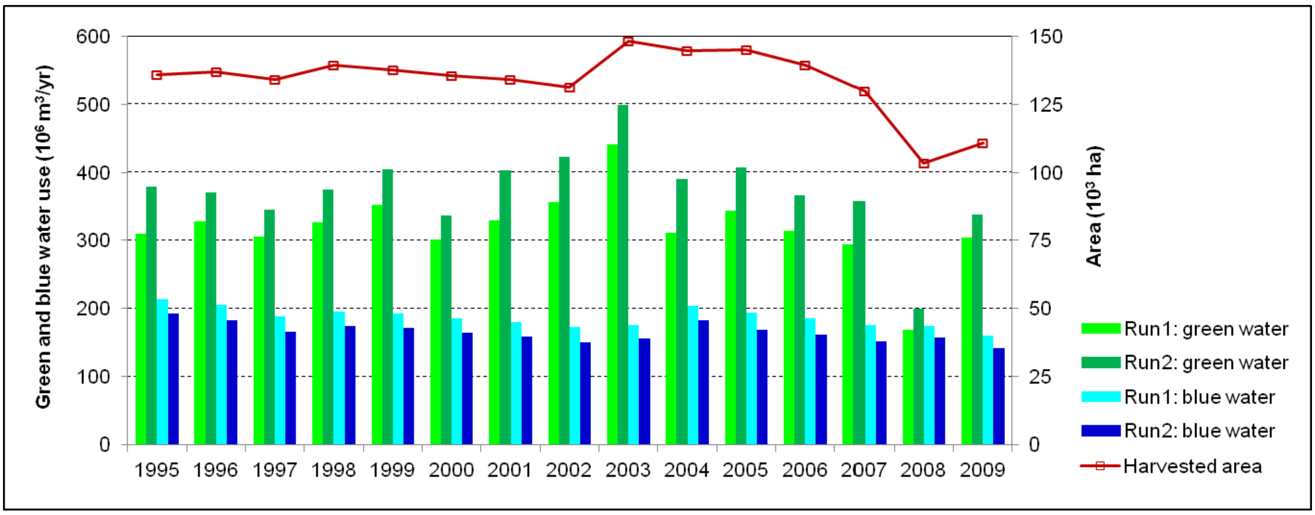

Figure 3. Green water use and blue water demand of the harvested crop areas during the years 1994/95 to 2008/09 in the Republic of Cyprus; Run 1 with soil water holding capacities between 40 and 150 mm and Run 2 with a uniform water holding capacity of 150 mm.

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