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Estimating Impacts of Land Use Change on Evapotranspiration for Three Agricultural Crops in Malta—A Preliminary Assessment

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Abstract

Estimating evapotranspiration is crucial for better management of catchment water resources. In this study, the FAO CropWat model was used to estimate reference evapotranspiration (ETo), crop evapotranspiration (ETc), and total gross water requirements for three economically important agricultural crops grown in Malta: potatoes, wheat, and vineyards for three years representative of a typically wet (2003), average (2009), and dry (2013) year. In addition, changes in ETc due to changes in land use were estimated for 2009 and 2013 relative to a 2003 baseline. Across all three years and crops, the average ETo rates were estimated to range between 3.7 mm day^{-1} (2003) and 4.0 mm day^{-1} (2013) while average ETc rates were estimated to range between 1.6 mm day^{-1} and 5.3 mm day^{-1}, respectively. For all three years, the highest total gross water requirement was estimated for wheat, reaching a maximum of 1450 mm in 2013. The results suggest that changes in land use between 2003 and 2013 were the main driver for changes in crop water demand. Differences in water demand compared to 2003 were estimated to range between -38% and 60%. This could have a substantial impact on the future sustainability of Malta's increasingly constrained water resources.

Keywords: catchment, irrigation, Penman-Monteith, model, water resources

1. Introduction

Water is an essential resource for supporting plant and animal life. In agricultural food crop production it is one of the main factors influencing plant growth and development, thus its availability has both national and global consequences. In addition, the demand for water is increasing steadily as a result of population growth, climate change and dietary changes associated with socio-economic development (Sun, Mcnulty, Myers, & Cohen, 2009).

Evapotranspiration (ET) can be defined as the loss of water from vegetative surfaces (transpiration) and from soil and water bodies (evaporation) through vaporization of liquid water (Allen, Pereira, Raes, Smith, & Ab, 1998). ET is a major component of the hydrological cycle which determines crop water requirements and the combined evaporative water losses from agricultural and natural land use in catchments. A major proportion of the total precipitation falling on the land surface is returned to the atmosphere by ET. Accurate quantification of ET in agroecosystems is crucial for the efficient use of water resources especially in arid or semi-arid environments where a lack of precipitation usually limits plant growth and yield, and negatively affects ecological balances.

Changes in ET are driven by two main factors: land use and land cover change (LUCC) and climate change (Vörösmarty, Green, Salisbury, & Lammers, 2000). The climate-driven changes in ET have been widely studied (*e.g.* Tang et al., 2011; Croitoru et al., 2013; Irmak et al., 2012; Peterson et al., 1995; Li et al., 2017) and, while temperature trends are generally reported to be increasing, surface evaporation is reported to be decreasing (Peterson et al., 1995; Roderick & Farquhar, 2002). Various studies have linked the decrease in ET to reductions in solar radiation and wind speed (Gao, D. Chen, Ren, Y. Chen, & Liao, 2006; Zhang, Liu, Tang, & Yang, 2007; Zheng, X. Liu, C. Liu, & Dai, 2009). At the regional scale, LUCC affects ET through changes in vegetation, agricultural development activities, and urbanization (Bronstert, Niehoff, & Gerd, 2002). A number of studies focusing on the impact of climate change and LUCC on ET suggest that the LUCC-driven impact outweighs the climate-driven impact; however, this finding is not consistent across different studies. For example, Li et al. (2017) reported that climate change was more significant than LUCC change in influencing ET in China between 2001 and 2013.

Several international studies have quantified the impacts of changes in land use on ET, but specific studies for the Maltese Islands are lacking. Among the European Member States, Malta is the most highly stressed country for indigenous water sources (Eurostat, 2018) with water supplies being heavily dependent on groundwater and desalination (Conrad & Cassar, 2014). The semi-arid climate of the Maltese Islands is typical of the Mediterranean with a mean maximum temperature of 22.3 °C and an annual total precipitation of 553.1 mm (Galdies, Said, Camilleri, & Caruana, 2016). Summer and autumn are typically the warmest seasons with low of rainfall for both seasons. In contrast for most years, the winters are cooler with sufficient rainfall to meet agricultural needs. However, rainfall is not sufficient to combat the warm dry springs when insufficient rainfall supports agricultural production and supplemental irrigation is needed (Vella, 2001).

The latest European Union (EU) Farm Structure Survey (FSS) using 2010 agricultural census data reported that in Malta the utilized agricultural area (UAA) represented 36.2% of the whole territory and covered 11450 ha, a 6.1% increase compared to 2003 (Eurostat, 2017). The cultivation of fodder crops which represents nearly half (48%) of the UAA in Malta, increased by 6.7% between 2003 and 2010. In contrast, a reduction in the production of potatoes was recorded over the same period (-2.1%). Vineyards also recorded a drop of 1.6% in 2010 compared to 2003; however, the crop still represented the most important permanent crop type (5.3 % of UAA in Malta (Eurostat, 2017).

Irrigated agriculture in Malta constitutes only 15% of the total agricultural land area but accounts for nearly 75% of total water use (Attard, Mangion, Micallef, & Albrizio, 2007). Between 2003 and 2010, the total irrigable area increased by 37%, from 2,300 to 3,150 ha with potatoes accounting for the largest proportion (630 ha, 23% of the total irrigated area) (Eurostat, 2017). With 430 ha of irrigated crops, vineyards were the second most important in terms of area (15%). In terms of the volume of water applied, 28.2 Mm^3 were reported to be used to irrigate 2,830 hectares of UAA in 2010: equivalent to about 10,000 m^3 per hectare (Eurostat, 2017).

Climate change is expected to play a major role in changing the availability of water for irrigated agriculture in future as extreme events such as the frequency of high intensity, short duration, and rainfall events are expected to increase (FAO, 2006; MEPA, 2011; Roberts, Cremona, & Knox, 2015). Thus, as water becomes increasingly scarce and more valuable and the demand for water becomes more important and competitive, understanding how changes in land use affect ET and the water requirement for the major crops is essential. This was therefore the focus of this study. Using the FAO CropWat model, we quantified the ET and crop water requirements for three major crop types grown in Malta for a representative dry, wet, and average year. In addition, the impact of land use change was analysed.

The study was organized as follows: First the methodology is described in Section 2 followed by the results and discussion in Section 3; which include estimates of ET, ETc (crop ET), and crop water requirements for the three crops for each climate year (dry, wet, and average). The impact of land use change on ETc was also analysed. Summary and conclusions are then presented in Section 4.

2. Method

In this study we used the Food and Agriculture Organization (FAO) CropWat model (FAO, 2018) to estimate reference evapotranspiration (ETo) for three separate years representative of a dry (2013), average (2009), and wet (2003) year in Malta. These years were chosen based on an aridity indicator known as the maximum Potential Soil Moisture Deficit ($PSMD_{max}$). Studies conducted in various countries have demonstrated the usefulness in using an agroclimatic indicator such as $PSMD_{max}$ to assess the impacts of climate variability on irrigation demand (Hallett, Sakrabani, Thompson, Deeks, & Knox, 2017; Knox, Weatherhead, & Bradley, 1997; Rodriguez Diaz, Weatherhead, Knox, & Camacho, 2007). The $PSMD_{max}$ has been previously estimated for a representative site in Luqa, Malta (35.8583° N, 14.4869° E; altitude of 91 m) for the period 1956 to 2015 by Hallett et al. (2017) from which the average, dry, and wet years were determined for this study. The average $PSMD_{max}$ in Malta is around 780 mm yr^{-1} but with large inter-annual variability. The $PSMD_{max}$ for each of year is given in Table 1.

Table 1. Maximum Potential Soil Moisture Deficit (PSMDmax) (mm) for a representative dry (2013), wet (2003) and average year (2009) for Luqa (Malta) as calculated by Hallett et al. (2017)

Year	$PSMD_{max}$ (mm)
2013 (dry year)	846
2009 (average year)	768
2003 (wet year)	694

CropWat is an irrigation planning tool developed by the Land and Water Development Division of the FAO, Rome with the assistance of Institute of Irrigation and Development Studies of Southampton, UK and National Water Research Center, Egypt. The primary use of CropWat is for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data. It uses the Penman Monteith method to calculate reference evapotranspiration (ETo) following the method developed by Allen et al. (1998). Monthly mean meteorological data which includes minimum and maximum temperature, wind, rainfall, relative humidity, and sunshine hours for each of the three years was obtained from the Luqa meteorological station. As limited soil data corresponding to the various crops grown was available for the Maltese Islands, loamy sand was assumed to be the dominant soil for all crop types in this study based on findings by Lang et al. (1960). For each climate year, crop evapotranspiration (ETc) was then calculated for three major crops in Malta; potatoes, wheat and vineyards; from this the corresponding irrigation demand was then estimated.

The European Union (EU) Farm Structure Survey (FSS) collects information on the structural characteristics of the agricultural holdings (*e.g.* land use, livestock, and labour force) from all EU Member States every 10 years as an agricultural census (http://ec.europa.eu/eurostat/web/agriculture/farm-structure; last accessed 19/08/2018). In addition, two or three intermediate sample surveys are carried out (Eurostat, 2017). In Malta, the first agricultural census carried out according to European legislation was FSS 2010, with the first sample survey conducted in 2003. To quantify the impact of changes in land use for the three major crops on ETc for each climate year, land use data from FSS 2003, 2010 and 2013 were used (NSO, 2016). Land use data for 2009 was not available; therefore it was assumed that the land use in 2010 was similar to that for 2009.

3. Results and Discussion

Estimated reference evapotranspiration (ETo) for 2013 (dry), 2009 (average), and 2003 (wet), together with the corresponding rainfall data, are illustrated in Figure 1. In 2013 the total rainfall amounted to ~480 mm followed by ~680 mm and ~901 mm for 2009 and 2003, respectively. Consequently, the highest average ETo rate was estimated for the dry year (4.0 mm day^{-1}) while the lowest average ETo rate was calculated for the wet year (3.7 mm day^{-1}).

In Malta, for all three years total rainfall was lowest in the summer months and highest in autumn and winter; however, rainfall peaks vary in magnitude (Figure 1). While 2013 was considered a dry year with total monthly rainfall ranging from ~0 mm (summer) to ~80 mm (winter), a peak in total monthly rainfall reaching ~180 mm occurred in November (Figure 1). In 2009 and 2003 total monthly rainfall levels reached a maximum of ~250 mm in January and September, respectively (Figure 1). In response to seasonal variations in rainfall as well as other meteorological variables such as temperature, wind and solar radiation, seasonal variations in ETo rates are consistent for all three years with low ETo rates rising during spring, peaking in summer (~7 mm day^{-1}) and declining through autumn and winter. Average ETo rates for 2013 range from ~1.8 mm day^{-1} (December) to ~6.4 mm day^{-1} (June). For the average year ETo rates span a wider range between ~1.5 mm day^{-1} (January) to ~6.9 mm day^{-1} (July) and from ~1.8 mm day^{-1} (January) to ~6.7 mm day^{-1} (July) in 2003.

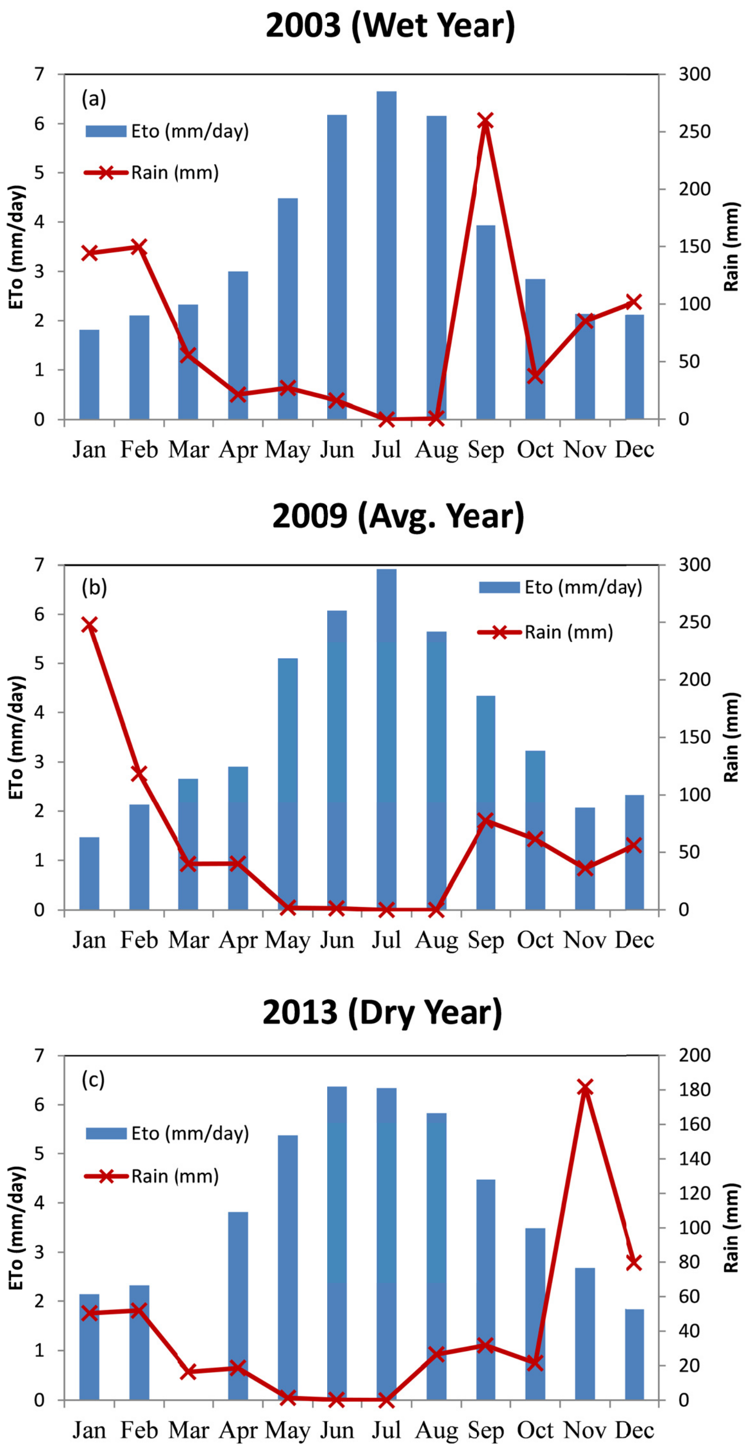

Figure 1. Reference evapotranspiration ETo for (a) 2013 (b) 2009 and (c) 2003 shown as blue bars. Red lines show total rainfall for each year for Luqa (Malta). NB The rainfall scale for panel (c) differs from that of panel (a) and (b)

For each climate year the average ETc rate for potatoes, wheat, and vineyards is shown in Figure 2. The average ETc rate for potatoes ranges from 4.9 mm day^{-1} (2003) to 5.3 mm day^{-1} (2013). Similarly for wheat crops and vineyards, the dry and wet years (2003 and 2013) represent the high and low end of average ETc rates, respectively. Average ETc rates for wheat crops range from 4.1 mm day^{-1} to 4.5 mm day^{-1} and between 1.6 mm day^{-1} and 1.8 mm day^{-1} for vineyards. Thus, for all crops considered, the average ETc rate is highest for the representative dry year and lowest for the representative wet year. The average ETc rate is estimated to be generally higher for all three year for potatoes followed by wheat and vineyards.

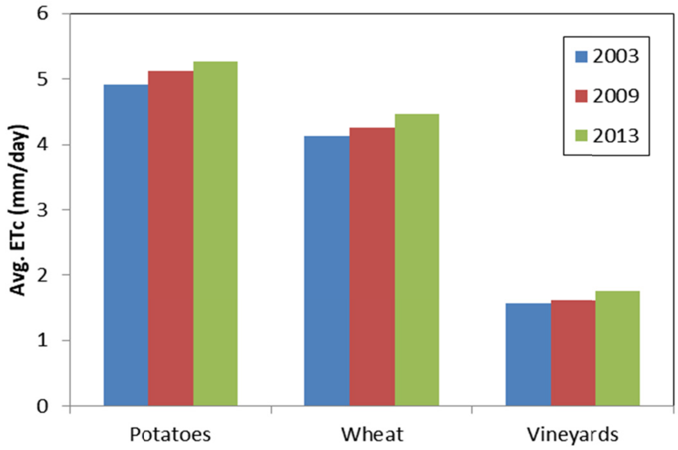

Figure 2. Average crop evapotranpiration (ETc) for potatoes, wheat and vineyards in 2003, 2009 and 2013

The total gross water requirement was estimated for each crop and year (Figure 3). For all three years, the highest gross water requirement was estimated for wheat, in particular for 2013 reaching ~1450 mm (Figure 3). In contrast, for all three years, the total gross water requirement was lowest for vineyards (consistent with low average ETc rates for vineyards). In agreement with ETc results, for potatoes and wheat the total gross water requirements between the years was highest for 2013 and lowest for 2003 ranging from 798 mm to 944 mm (potatoes) and from 959 mm to 1450 mm (wheat), respectively (Figure 3). However, this is not consistent for vineyards as the total gross water requirement for 2003 was marginally higher than the 2009 estimate (387 mm compared to 366 mm). The total gross water requirement for all three crops in 2009 and 2013 was higher than that of 2003 except for vineyards which showed a reduction in 2009 compared to 2003 (~-6%).

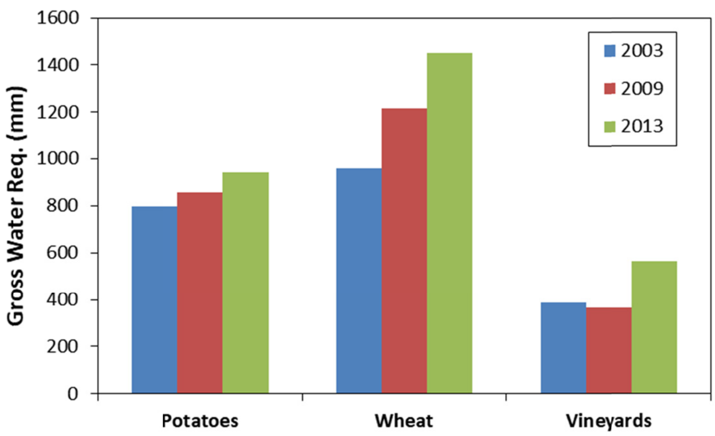

Figure 3. Total gross water requirement (mm) for potatoes and wheat crops and vineyards for 2003, 2009 and 2013

Using land use data for potatoes, wheat and vineyards for each climate year (Table 2), the influence of changes in land use on ETc was estimated. The utilized agricultural area (UAA) for potatoes reduced from 1210 ha in 2003 to 701 ha (~-42%) in 2009 and to 689 ha (~-43%) in 2013. The UAA for vineyards showed a minor reduction between 2003 and 2009 (~-1%). In contrast, an increase in the UAA for vineyards was recorded in 2013 compared to 2003; 683 ha compared to 620 ha, approximately a 10% increase. For both 2009 and 2013, an increase of 7% and 2% in UAA by wheat was noted, respectively compared to 2003.

Table 2. The Utilised Agricultural Area (UAA) for potatoes, wheat and vineyards in 2003, 2009, and 2013 (NSO, 2016). Differences in UAA between 2009 (2013) and 2003 are also included

	UAA cropped area (Ha)			% Difference	
	2003	2009*	2013	2009	2013
Potatoes	1,210	701	689	-42%	-43%
Wheat	5,200	5,553	5,290	+7%	+2%
Vineyards	620	614	683	-1%	+10%

Note. *The UAA from FSS 2010 was used for 2009 as no land use data was available for 2009.

Using the product of gross water requirement (Figure 3) and land use data estimates (Table 2), the total gross water requirement was estimated. Between 2009 and 2013 the water demand for potatoes is estimated to to reduce by ~38% and 33% respectively compared to 2003 (6 and 6.5 Mm^3 compared to 9.7 Mm^3). The gross water requirement was higher for both 2009 and 2013 compared to 2003 (Figure 3); however, the relatively large change in land use over the same period (-42% and -43%) results in an overall reduction in water demand. In contrast, the water demand for wheat increased for both 2009 and 2013 compared to 2003 by 36% and 54% respectively (from 49.9 Mm^3 (2003) to 67.6 (2009) and 76.7 (2013) Mm^3). This is mainly due to increases in both the UAA by wheat and the gross water demand for 2009 and 2013 compared to 2003. The water demand for vineyards was 60% higher in 2013 compared to 2003 but lower for 2009 (-7%) as a result of reduction in land use as well as gross water requirement for 2009 compared to 2003.

Table 3. Water demand for three main crops in Malta: wheat, potatoes, and vineyards for 2003, 2009 and 2013 (Mm^3) and the percentage difference for 2009 and 2013 with respect to 2003

	Water demand (Mm^3)			% Difference	
	2003	2009	2013	2009	2013
Potatoes	9.7	6.0	6.5	-38	-33
Wheat	49.9	67.6	76.7	36	54
Vineyards	2.4	2.2	3.8	-7	60

4. Summary and Conclusions

In this study the reference evapotranspiration (ETo) was calculated using the FAO CropWat model for three contrasting agroclimatic years. The highest average ETo rate (4.0 mm day^{-1}) was estimated for the dry year (2013) with a total rainfall of ~480 mm. On the other hand, the lowest average ETo rate (3.7 mm day^{-1}) was calculated for the wet year (2003) with total rainfall of ~901 mm. In response to seasonal variations in various meteorological variables such as rainfall, temperature, wind, humidity and solar radiation, the seasonal variation in ETo rates is consistent for all three years. The ETo rates are highest in summer reaching ~7 mm day^{-1} and decline through autumn and winter.

The average crop evapotranspiration (ETc) for all three crops and all three years was also estimated. Consistent with ETo rates, for all three crops, the lowest average ETc rate was estimated for the wet year (2003) while the highest average ETc rate is estimated for the dry year (2013). Across the crops, the average ETc is highest for potatoes ranging between 4.9 mm day^{-1} (2003) and 5.3 mm day^{-1} (2013) but lowest for vineyards ranging between 1.6 mm day^{-1} (2003) and 1.8 mm day^{-1} (2013). As a result of changes in ETc, the total gross water requirement varies by crop and year. For all three years the highest gross water requirement is estimated for the wheat crop reaching a maximum of 1450.4 mm in 2013. In contrast, the lowest total gross water requirement across the years is estimated for vineyards.

Land use data from FSS 2003, 2010, and 2013 was used to estimate the impact of change in land use on water demand. Results of this study show that the water demand for potatoes in 2009 and 2013, compared to 2003, reduced by ~38% and ~33% respectively. This is due to relatively large reductions in UAA by potatoes (-42% and -43% respectively). In contrast compared to 2003, the water demand for wheat crops increases for both 2009 and 2013 by 36% and 54% respectively. The water demand for vineyards is 60% higher compared to 2003 but lower for 2009 (-6%) which again reflects changes in land use. Thus changes in UAA between 2003 and 2009 or 2013 are found to be the main driver for changes in crop water demand.

The results of this study were primarily limited by the lack of data for the Maltese Islands, for example data describing the soil textures and their spatial extent corresponding to each crop. Another limitation was the use of meteorological data for one station. The FSS are not conducted every year, which introduces limitations for studies during years where no surveys were conducted. Future work should seek to primarily make use of crop and soil data specific to Malta by for example conducting surveys. This will improve such studies as different variables would be specific to the region of study.

This study, with its unique focus on Malta, estimates the ETo, ETc, and total gross water requirement for three important crops; potatoes, wheat, and vineyards for three years presentative of a wet year (2003), an average year (2009), and a dry year (2013). In the future, extreme events such as increased frequency and amount of precipitation as well as drought are likely to occur more often leading to changes in the total gross water requirement. In addition changes in land use also drive changes in water demand which compared to 2003 range between -38% and 60%.

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