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Improving Soil and Water Management for Agriculture: Insights and Innovation from Malta

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Abstract: Maltese soil resources are a precious and finite natural resource of great agricultural, environmental, and cultural value. They have been subject to human influence over a considerable time and, owing to prolonged intensive land use, have suffered from degradation by erosion, loss of organic matter, structural deterioration, and contamination from excess nitrates, agrochemicals, and salinity. Similarly, water resources (both quantity and quality) in Malta are also under severe stress owing to socio-economic development, over-abstraction for agricultural irrigation and from diffuse pollution. This paper briefly explores the key soil and water challenges facing farmers and the agricultural sector in Malta. Selected technology based and management innovations to improve resource use efficiency, sustain productivity, and support the agricultural sector are identified and discussed. The evidence forms part of FOWARIM 'Fostering water-agriculture research and innovation in Malta', an EC H2020-funded twinning project that is building research capacity, supporting knowledge exchange to practitioners, and providing evidence to inform policies for government and the agricultural sector in Malta.

Keywords*:* agriculture, soil, nutrient, irrigation, management, maps, water resources.

Maltese soils are a precious and finite natural resource of great agricultural, environmental and cultural value across the islands. They have been subject to human influence over a considerable time and, owing to prolonged intensive land use, have suffered from degradation by erosion, loss of organic matter, structural deterioration, and contamination from excess nitrates, agrochemicals, and salinity. The Maltese Islands occupy a strategic position between Europe and Africa, experiencing a typically semi-arid Mediterranean climate. Malta has many geographic similarities with surrounding countries and common challenges, such as soil erosion and desertification processes, are concerns that require swift attention.

Changes in agricultural practices as well as increases in urban development have intensified environmental problems and accentuated pressures on agricultural land and Malta's fragile semi-natural ecosystems. Characterization, mapping, and the on-going monitoring of the properties of Maltese soils is thus essential for the future protection of this precious resource. A driving force is the ongoing demand from decision-makers, planners, environmental managers, agriculturists, and engineers for ecosystem services from soil resources. Given Malta's small area (316 km^2) it is imperative to make informed decisions regarding its soil and land resource management.

FOWARIM (Fostering Water-Agriculture Research and Innovation in Malta) is a research programme seeking to strengthen the research capacity of the Malta College of Arts, Science, & Technology (MCAST)'s Water Research and Training Centre across four crucial themes related to the field of water use in agriculture: (a) decreasing water demand; (b) making better use of alternative sources of water; (c) renewable desalinization, on-farm desalinization, and utilization of saline water; and (d) reducing the negative environmental externalities caused by nutrient-rich farm waters. This will be achieved by creating a favourable environment for capacity building targeting researchers, research institutions networking, and research policy development. MCAST will be supported in addressing research deficiencies and networking gaps by EU partners of established scientific excellence in the targeted research topics. Activities are planned over three years and articulated across five work-streams, including management and coordination, capacity building through advanced training courses, short-term

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staff exchanges, summer schools, and virtual training; research networking and knowledge sharing through providing technical assistance to establish demonstration sites to promote innovations and best practices in agricultural water management, helping foster new collaborations through co-design of research questions, and developing a joint strategy for high-impact research and dissemination. Collectively, this will strengthen MCAST's research and S&T capacity in water use in agriculture, enhance collaboration between the research institutions, increase academic outputs and complement Malta's Smart Specialization Strategy.

Soils and nutrients

Malta has an important horticultural sector, providing food both for the local population and tourists, as well as a source of income from exported produce. Protecting and sustaining the production of healthy crops is therefore a key strategic goal for the country. The total cultivated area is around 10,000 hectares (ha), with approximately 1,100 ha used for the traditional production of tomatoes. Potatoes and tomatoes for processing are Malta's two most important commodity crops (Figure 1). Previously, most of the agricultural land on which tomatoes were grown was under dryland conditions and, with no water available on site, tomato yields rarely exceeded 13 t ha^{-1}. However, over the past decade, Maltese farmers have started to install drip irrigation and yields have improved year on year.

Figure 1 Typical mixed agricultural landscape on Gozo (Malta) showing the mosaic of field-scale arable and horticultural cropping (Photo credit: Zuzana Vlacilova, 2016)

In managing agricultural soils, fertilizers are usually applied to supply the essential elements of nitrogen (N), phosphorus (P), and potassium (K) in order to sustain plant growth. These elements are not present in pure form in fertilizer: the plant cannot absorb these directly from pure elements. Instead, the ingredients of fertilizer are chemical compounds containing these essential elements. Fertilizers are graded to represent the percentage of nitrogen, available phosphorus (as P_2O_5) and potassium (as K_2O) in the material; a 'compound' fertilizer of say 8:16:16 grade, for example, contains the equivalent of 8% nitrogen, 16% P_2O_5, and 16% K_2O. Nitrogen may be added to soil in several ways, typically as urea, ammonium nitrate, or ammonium sulphate. In preparing land for crops, it is important to have knowledge of the state of the soil and its potential. Soil fertility is built up so plant roots can easily reach the nutrients. In growing tomatoes, for example, it is important to provide sufficient phosphates and potash to produce stocky plants bearing top-quality fruit. Fertilizer grades of 5:8.1:10 can be used for supporting tomato growth. Other compounds such as calcium, magnesium, sulphur, copper, manganese, and zinc are also required to complete the soil preparation.

The specific amount of fertilizer applied to soil is critically important. With too little, plants suffer and do not produce vigorous growth and healthy fruiting. With too much, apart from the additional cost to the farmer, excess fertilizer can pass through the soil and leach into groundwater aquifers used for providing potable (drinking) water supplies. Most vegetables require well-drained fertile soils with plenty of moisture throughout the growing season. These conditions may be met by appropriate management and conservation, using organic manures and inorganic fertilizers as necessary to maintain the soil at its required state of fertility. Testing levels of nutrients in the soil is an important part of understanding and working with the soil resource.

Soils of the Maltese Islands, their protection and use

Malta has two principal limestone bands, separated by a narrow outcrop of blue clay. The higher parts of the main island are underlain by the Globigerina limestone (the main building material) which contains an aquifer at around 15m depth perched on the blue clay stratum that underlies it. Maltese soils are categorised in three major groups: Carbonate raw soils Terra soils, and Xerorendzina soils Groundwater in the older Lower Coralline limestone is much deeper and suffers from saline intrusion through over-extraction. Groundwater is abstracted either from boreholes or pumped from man-made underground caverns to meet c.40% of consumption. The other 60% is from reverse osmosis desalinization plants.

The climate of Malta and Gozo provides an example of typical Mediterranean conditions, with hot dry summers having high rates of evaporation with limited rain; warm and showery autumns normally with a rainfall deficit; and short cool winters with enough rainfall for agriculture in most years, but leaving insufficient reserve in the soil to combat the warm drying springs again having a rainfall deficit (Vella 2000). Almost all the rain falls between September and April (Agnew and Anderson 1992). This semi-arid climate has been the influence for the restricted range of soils found in the islands and for the typical absence of noticeable humus horizons, and total soil organic matter being generally low. There are groundwater aquifers which are used for water abstraction; for example, the perched aquifer in the Upper Coralline limestone in the north of Malta, resting on the Blue Clay deposits.

High levels of calcium and magnesium carbonates are commonly found through the whole soil profile (Vella 2000). Although the high calcium carbonate influences plant growth by affecting uptake of certain nutrients, it also prevents the accumulation of sodium in the exchange complex, hence minimizing alkalinity hazards as a result of irrigation with highly sodic water. The relatively raw, newly exposed soils developed on the heavy Blue Clay are sometimes markedly alkaline and slightly saline. These soils are either unused or produce only very poor crops because they are very difficult when wet and are hard and rock-like when dry. In some locations, heavy textured soils of the Xerorendzina group are salinized and not suited for agricultural cropping.

The depth of the soil and soil material are also very variable (Vella 2000). On the ridges, plateaux and plains (erosion surfaces), the soils can be shallow, ranging from <20 cm to 60 cm, deeper soils occurring only in isolated pockets. In the erosional and structural valleys, soils are deeper (150 cm) but patches of shallow soils are still very common, especially near the valley edges. There is also evidence to suggest that salinity is a soil constraint for agricultural production (Vella 2000). The hydrogeological features of the islands, the Mediterranean non-leaching climate, and the scarcity of fresh-water resources, constitute predisposing factors for the accumulation of salts and provide the setting for salinity-related phenomena to emerge and develop. Irrigated land is by far the most productive agriculturally. However, much irrigated land has already become saline, as is the case in the Pwales valley, where owing to seawater intrusion and over-abstraction of groundwater, salt crystals may be observed on the soil surface. Studies by the Department of Agriculture have indicated that the problem of soil salinity is most relevant to greenhouse-production systems (Camilleri 1999).

A distinction may be observed between dryland and irrigated farming but this can become blurred as land management practices change. A common agricultural rotation is potatoes-melons-beans-wheat but there are also a range of other cucurbits, tomatoes, brassicas, salad crops, artichokes, and strawberries that are grown. Potatoes are planted in the new year and harvested in the autumn with irrigation in their early stages, often from an on-farm borehole. A spring crop of earlies are then planted and often sold to Holland in April. The pattern of growing potatoes can be the same on some fields, year on year, leading to potential concerns with pests and disease owing to short rotations. Malta has a 12-month growing season and achieving two or more crops per year is standard.

Malta joined the EU in 2004; in preparing for accession, the Maltese government undertook work to characterize the environment of the islands. A range of European directives on various agro-environmental issues needed to be addressed – many of which have special significance for the soil environment. Examples include the Nitrates Directive (91/676/EEC); Framework Directive on Waste (75/442/EEC); Drinking Water Directive (80/778/EEC); the Environmental Assessment Directive (85/337/EEC); Sewage Sludge in Agriculture Directive (86/278/EEC); Pesticides Registration (91/414/EEC); Habitats and Species Directive (92/43/EEC) and the Integrated Pollution Prevention and Control Directive (96/61/EEC).

One of the important responses to these challenges was to conduct a two-year project to survey the soils of Malta and produce maps for a range of soil characteristics. The work was conducted between 2003 and 2004 by staff from the Ministry of Agriculture with the assistance from the Soil Survey in Cranfield University (UK). The Maltese Soil Information System (MalSIS) led to the creation of an electronic map of soil properties, with gridded observation points located on a 1-km^2 grid across Malta, Gozo, and Comino (Figure 2).

Figure 2 The MalSIS grid survey points used for recording soil properties across the Maltese Islands, showing the 1-km^2 grid spacing

Before MalSIS, the only other detailed study of the soils of Malta and Gozo was undertaken by Lang (1960) with a soil map of the islands published at 1:31,680 (2 inches to the mile). Lang's objective was to provide basic soil descriptions of the soils and map their distribution and chemical, physical and biological characterisation as an aid to agricultural planning. The key intent of the MalSIS National 1-km grid soil inventory was to provide background information on soil properties and any soil contamination across the islands. This 'soil inventory' was intended to support agricultural and other land management and related policy development, with information and knowledge derived being applied in the elaboration of a Code of Good Agricultural Practice for the Maltese Islands as a basis for fertiliser recommendations, for salinity diagnosis, and general environmental monitoring. Key soil parameters investigated included (i) soil chemico-physical properties: particle size distribution, pH, EC (1:2), OM; (ii) soil fertility: N, P, K, Ca, Mg, SO_4^{2-}; (iii) soil salinity: EC, Cl, NO_3^-, SAR. Once analysed, data were captured in an electronic database suitable for further geospatial analysis and presentation.

The MalSIS study also allowed determination of the extent of soils with a calcic horizon (Calcisols or calcic soil types). Calcisols may be seen to be the dominant soils in the islands (51% of sites investigated). This soils information is now incorporated in the Soil Map for Europe, at a scale of 1:1,000,000 (Panagos 2006) (esdac.jrc.ec.europa.eu/resource-type/european-soil-database-soil-properties). The soils of Malta and Gozo can be considered immature, as pedological processes are slow in such calcareous soils. Maltese soils have also had significant alteration by centuries of agricultural practice.

In-field diagnostics for determining soil nutrients and salinity

Farmers can derive significant benefit from monitoring and testing their soil nutrient status. There are a range of potential means to do this, but one easily accessible and inexpensive method involves the use of a specialist paper strip to determine the presence of nitrate, ammonium, and chloride in the soil. The soil sample is mixed with deionized water, shaken, and a test strip dipped into the solution. The strip then changes colour in accordance with the amount of the respective nutrient available. These strips are commercially available for specific plant nutrients. Quantifying the amount of these parameters relies on a visual inspection of the change in colour of the strip, against a palette of reference colours (Fig. 3a). As reading the amount of nutrient by visual comparison from palette of colours can be subjective, (Fig. 3b) the use of a hand-held device is recommended to improve accuracy (Fig. 3c). This innovative approach could be valuable for farmers seeking to assess the levels of nutrients (nitrate and ammonium) present in their soil and chloride (indicating issues with salinity). The approach uses a field-based diagnostic tool to provide a quick estimation of nutrient levels. Owing to its limited precision and accuracy, it does need to be assessed initially with more accurate conventional laboratory analyses to determine situations where it will be fit for purpose.

(a)	(b)	(c)

Figure 3 Test-strip approach for monitoring soil chemical nutrient conditions, showing the colour palette for measuring ammonium (a), nitrate (b), and portable measuring device (c)

When using this apparatus, the test strips are placed on a measuring slide with an inbuilt reference pad which is moved into the instrument along a measurement head. While moving in and out of the instrument, the test strip is measured 'refectometrically', a pre-defined light source in the machine being used to illuminate the test pad. A detection unit then measures the intensity of the reflected light at three different wavelengths. From this information, remission values are calculated, with the timing of the measurements varying depending on test strip and parameter. Use of this equipment permits instant readings to be derived for soil samples taken and tested in this manner. Useful tests for farmers could therefore include (i) nitrate/nitrite (10–500 mg/L NO_3^- / 0.5–80 mg/L NO_2^-), (ii) ammonium (10–350 mg/L NH_4^+); and (iii) chloride (0.1–10 mg/L Cl^-). Readers interested in further details on the apparatus and approaches are referred to http://www.mn-net.com/tabid/11779/Default.aspx.

Soils and water

The Maltese Islands experience a typical semi-arid Mediterranean climate, with hot, dry summers and mild, wet/humid winters. The rain season falls between September and March, the last rainfall occurring typically in April. The average rainfall is *c*.524 mm, with the temperature varying between 7°C and 15°C in June, to between 25°C and 35°C in August. However, climate change is expected to alter rainfall patterns. In particular a changing climate is expected to increase the frequency of high intensity, short duration, rainfall events (FAO 2006). These changes will have significance for the island's aquifer recharge as high-intensity rainfall events are likely to reduce the proportion of rain that infiltrates, with a higher percentage of water lost to surface water runoff and evaporation. This, combined with a predicted decrease in total annual rainfall will place increasing pressure on aquifers. Agriculture represents the main use of groundwater resources on the islands, with other domestic, tourism, and industrial demands in competition, but abstraction from aquifers currently exceeds estimated aquifer recharge and is therefore not sustainable (FAO 2006). For future security, a more strategic approach to water use will be needed in agricultural systems in Malta.

Soil plays an important role in regulating and storing water. While soil texture determines, to a greater extent, key drainage and retention properties of the soil, soil management also plays a pivotal role. A healthy soil will have an optimal distribution of pore sizes for its textural type. Larger macropores (>1 mm) enable infiltration of rain and irrigation water, drainage of water through the soil profile, and help regulate oxygen levels within the root zone. Smaller pores (<1 mm) act to retain water in the soil between rainfall and irrigation events. As pore size decreases, water in that space is held under increasing tension. Plants are able to utilize water held in the soil up to a limit. Readily available water (RAW) defines water held between field capacity (maximum water capacity after drainage by gravity) and a threshold refill point, which is specific to the crop being grown (Allen 1998). A crop is also able to make use of water held tighter than RAW to a limit described as the permanent wilting point. However, the exertion required by a plant to extract water held tighter than RAW increases the stress levels within the plant as it becomes less able to meet transpiration demands. Some water stress may be agronomically advantageous as it can stimulate plants to produce more flowers and reduces water use; however, too much water stress can adversely impact crop yield and quality (Celebi 2014).

More strategic water use on the islands should take account of specific soil characteristics. Soil management approaches that impact detrimentally on soil structure can also impact efficiency of water use. Soil capping caused by the impact of raindrops and the redistribution of soil particles at the soil surface reduces the refile of water in the soil profile. Refile is reduced where the rate of infiltration at the soil surface is reduced, increasing the risk of runoff and associated soil erosion. Also, water held on the soil surface is vulnerable to evaporation, reducing the volume of water available to infiltrate the soil. The risk of soil capping can be reduced by maintaining a higher soil organic matter content, maintaining a cover crop on the surface or by protecting the soil surface with a mulch (e.g. straw or compost).

Soil compaction within or at the base of the topsoil zone (c.0–30 cm) can also restrict the drainage within the soil profile and can cause a temporary perched water table which can increase the risk of plant fungal diseases in some crops. Compaction in the topsoil zone can also limit the volume of soil over which plant roots can forage for water and nutrients. This can limit the effective use of irrigation water, as well as fertilizer, as plants may be unable to extend their root systems as deep as the water percolates and more frequent irrigation may be required in order to maintain water levels in the accessible soil layer. Soil compaction in topsoil layers can be avoided by limiting the area over which the soil is travelled either on foot or by vehicles, and by reducing the surface contact pressure of vehicles (e.g. using low pressure tyres). Topsoil compaction can be alleviated by ploughing or potentially by bioengineering traits of crops in a rotation.

Soil moisture content not only influences plant growth and yield, but also tillage operations and nutrient uptake. Optimizing soil moisture to plant requirements can bring economic benefits: through the prevention of over- or under-irrigation; loss of nutrients, pesticides, and other chemicals to groundwater in excess water; waste of water resources (from evaporation and drainage); and wasted energy consumption from over-irrigation. Optimal yields do not require soil moisture content to be maintained at field capacity. However, the extent to which soil moisture is allowed to diminish without reducing crop yield and quality varies depending on the crop species and its stage of development (Rao *et al*. 2000). To ensure that soil moisture remains above a crop threshold value requires more than just intuition. In situ soil moisture measurements that provide measured data related to the amount of water at a given point in the soil profile and can be used to help schedule irrigation according to crop water demand.

The ability of soil to supply water to plant roots is governed by its water content and matric potential. Each soil texture has a unique relationship between soil water content and matric potential, determined by pore-size distribution, and which can be expressed with a soil moisture release curve. Therefore, sensors that either measure soil moisture or matric potential can be used to schedule irrigation once the soil moisture release curve has been defined. A single sensor on its own can provide only limited information. However, multiple sensors can reduce error (averaging data over multiple points and allowing outlier values to be filtered out), be used to monitor vertical distribution of soil water in the root zone (if positioned at different soil depths), and can help schedule variable irrigation in different zones (e.g. within a field or farm). Sensors placed at multiple depths can also help reduce irrigation requirements owing to the increased confidence in the knowledge that water stored in the deeper soil can be used by the plant, even if shallow surface layers are much drier. Sensor data can be collected manually. However, technology will soon enable reliable wireless connectivity of multiple sensor points in a field (Greenwood *et al*. 2009). Foreseeably, this wireless technology could transmit sensor data at pre-determined times to a control centre where the data would be processed and could be used to remotely control irrigation equipment and deliver water according to need across the field (Monaghan *et al*. 2013). Such advanced irrigation technology will contribute to the future sustainability of irrigated production on the islands.

Water resources and irrigation demand

Water resources

Malta is the most water-scarce country in Europe, ranking among the top ten globally in terms of water scarcity (MBB 2014a). It has virtually no exploitable surface water resources and water supplies are heavily dependent on groundwater and desalination (Conrad and Cassar 2014). The former is under intense pressure owing to over-abstraction with rates considered unsustainable based on current rainfall recharge estimates (MBB 2014). Amongst competing water uses on the island, irrigated agriculture accounts for nearly three-quarters (75%) of all abstraction despite representing only 15% of the total agricultural land area (Attard *et al*. 2007). There is currently limited data on the nature and composition of agricultural abstraction including the locations and volumes used; all water use figures have typically been estimated and modelled based on varying sources (FAO 2006; MEPA 2011; Roberts *et al*. 2015). Widespread illegal groundwater abstraction is known to occur but not captured in official agricultural records (Conrad and Cassar 2014). Understanding current and future water demands for agriculture and its impacts on water resources therefore represents a major strategic and environmental priority. The impacts of a changing climate with greater extremes and drought risk on water demand and available supplies will only exacerbate the current situation (MEPA 2011; Roberts *et al*. 2015).

In the context of developing an environmentally sustainable agricultural sector on Malta, Dwyer *et al*. (2014) and MEPA (2011) reported on the need to significantly reduce groundwater abstraction, as well as promoting greater efficiency in water use via increasing substitution of groundwater with renewable surface-water supplies. To date, efforts to reduce consumption and improve water efficiency have been extensively applied in the leisure and business sectors (MBB 2014b) but no significant efforts have been successful in addressing such challenges in agriculture (Roberts *et al*. 2015). Malta needs urgently to learn from and adopt new innovative science and technology practices developed in other European countries to underpin a more comprehensive scientific understanding of the water challenges it faces and to support the creation of a long-term strategic island water plan. Similar water issues exist in other Mediterranean islands. Whilst Malta's water scarcity and aquifer pressures are well documented, there remains widespread contention and ignorance regarding the choices available to ameliorate the problem, the related issues, and the scale of the problem (Roberts *et al*. 2015). Water management vision is reported to lack transparency and trust in the government's ability to manage water issues (Xerri *et a*l. 2016). According to FAO (2006a), the Maltese water crisis is partly due to a lack of good governance. The main issues of governance are due to separate water and agriculture policies, fragmented decision-making, and low awareness of the consequences of mismanagement of water resources (Zammit 2016).

Furthermore, Malta's entry to the EU raised further interest and need for engagement in environmental policies, with pressure on Malta to fulfil its water regulatory requirements, notably the Water Framework Directive (WFD) (Xerri *et al*. 2016). Malta also lacks a training and extension advisory service for its farmers, which has been reported to be a critical element for improving resource efficiency, productivity, and a sustainable agricultural sector (Swanson 2008). A fundamental challenge for the islands is therefore in establishing systems for efficient water governance that take into account social, economic, and environmental requirements which are adaptable to a changing climate (Bezzina and Scicluna Laiviera 2016). There are, understandably, a number of key barriers to progress in increasing the productivity of Maltese agriculture. The main issues include acute water scarcity, rising costs of productive land, land fragmentation, and high labour costs. The relatively low cost of groundwater has resulted in over-abstraction, causing aquifer degradation.

Limited water resources have inevitably constrained agricultural productivity. With an increasingly competitive market, irrigation is becoming an essential component of production to increase crop yields and make them more reliable (reducing both in-field and inter-annual yield variability). Product quality has become an important driver for change too, particularly for high-value horticultural produce. Considering Malta's strategic geographic location between Europe and northern Africa, food security is also essential with Maltese agriculture providing a critical role in the local food supply chain. There are also higher consumer demands for premium quality fresh food with the ongoing development of tourism and improvement in the quality of life in recent years.

Agroclimatic variation and irrigation water demand

Detailed statistics and geospatial information on irrigated production and water use for agriculture in Malta are limited and of variable quality. A marked increase in irrigated area was reported based on data from the Censuses of Agriculture conducted in 1982 and 2001. In 2001 the reported irrigated area was *c*.15% of the utilizable agricultural area (UAA) (NSO 2007). By 2010, the irrigated area had increased to 36% mainly in response to increased water availability and efficiencies in water distribution owing to the introduction of new technologies (Attard and Azzopardi 2005). The main irrigated land use comprises horticultural vegetable crops (notably tomato) (39%) and potatoes (18%), private gardens (17%), vineyards (12%), and fruit and berry plantations (6%) (Eurostat 2012). The most common method of irrigation is low-flow localized drip irrigation and overhead pressurized sprinkler irrigation. Figure 4 shows, for example, a typical drip irrigated tomato crop in NE Malta.

As in many semi-arid countries, the demand for irrigation in Malta varies from year to year, depending on the summer weather. Long-term average rainfall is around 600 mm year^{-1}, but with only 10% occurring between April and August. Average annual evapotranspiration (ET) is *c*.1100 mm yr^{-1}, with ET rates rising during spring, peaking in mid-summer and then declining through autumn. On a peak summer's day, ET rates are typically 4 to 5 mm day^{-1}, but can reach 8 mm day^{-1} (Figure 5). Summer cropping is therefore almost entirely dependent on irrigation (Attard *et al.* 2007) with the value of production from irrigated land reported to be at least 3.5 times that derived from dryland farming (Attard and Azzopardi 2005).

Figure 4 Field-scale tomato production with shallow buried drip irrigation installed in each ridge under plastic mulch

For any given site, the main climatic drivers of irrigation demand result from the daily balance between inputs of rainfall and outputs of ET. Various studies in both temperate climates such as the UK (Knox *et al.* 1997), semi-arid countries including Spain (Rodriguez-Diaz *et al*. 2007) as well as more tropical countries such as Sri Lanka (de Silva *et al*. 2007) have demonstrated the utility in using an agroclimatic indicator to assess the impacts of climate variability on irrigation-water demand. These studies all used an index termed potential soil moisture deficit (PSMD). In this study, a similar approach was used for a representative site (Luqa (35.8583° N, 14.4869° E) in Malta. To estimate PSMD, a daily time-step water balance model was used, working from long-term historical rainfall and reference evapotranspiration (ETo) data for the period 1956 to 2015. The variable PSMD is calculated from:

$$PSMD_i = PSMD_{i-1} + ET_i - P_i \quad [1]$$

Where;

$PSMD_i$ = potential soil moisture deficit at the end of day i, mm

ET_i = reference evapotranspiration on day i, mm

P_i = rainfall on day i, mm

On days where $P_i > (PSMD_{i-1} + ET_i)$ any initial soil moisture deficit is assumed to have been filled and $PSMD_i = 0$. In Malta, soil moisture deficits typically start to build up in early spring as ET starts to exceed P, peak in mid-summer (July) and then decline through autumn and winter as P begins to exceed ET. The maximum value over the 12 months is defined as $PSMD_{max}$ and represents the agroclimatic index for that year. The main advantage of this index in relation to others such as wetness index is that in PSMD the distribution of rainfall and ET through the year is taken into account. For Luqa, the $PSMD_{max}$ was calculated and the data then ranked by year.

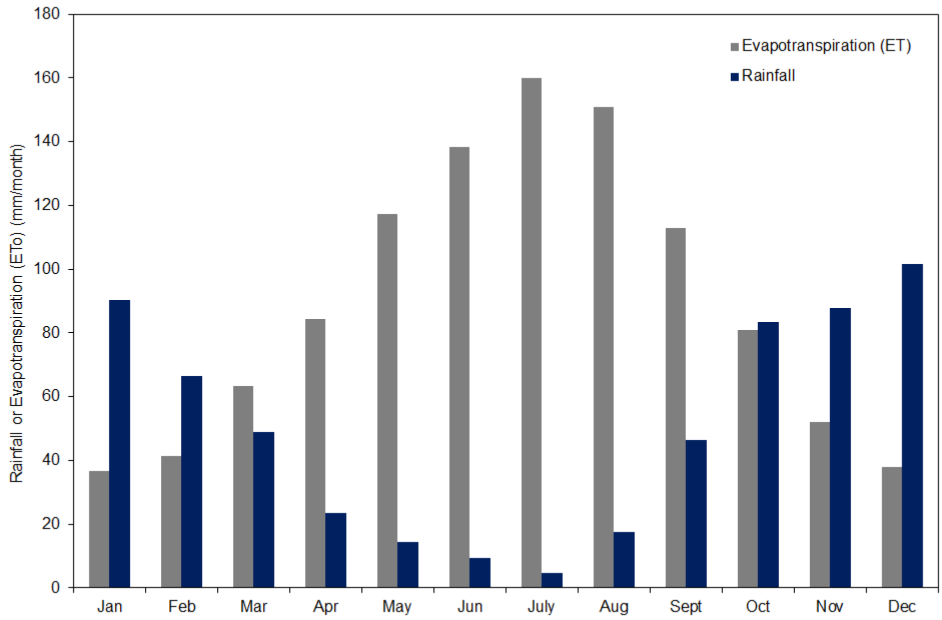

Figure 5 Mean monthly rainfall and reference evapotranspiration (ETo) (mm/month) for Luqa (Malta) based on daily historical climate data for 1953–2015

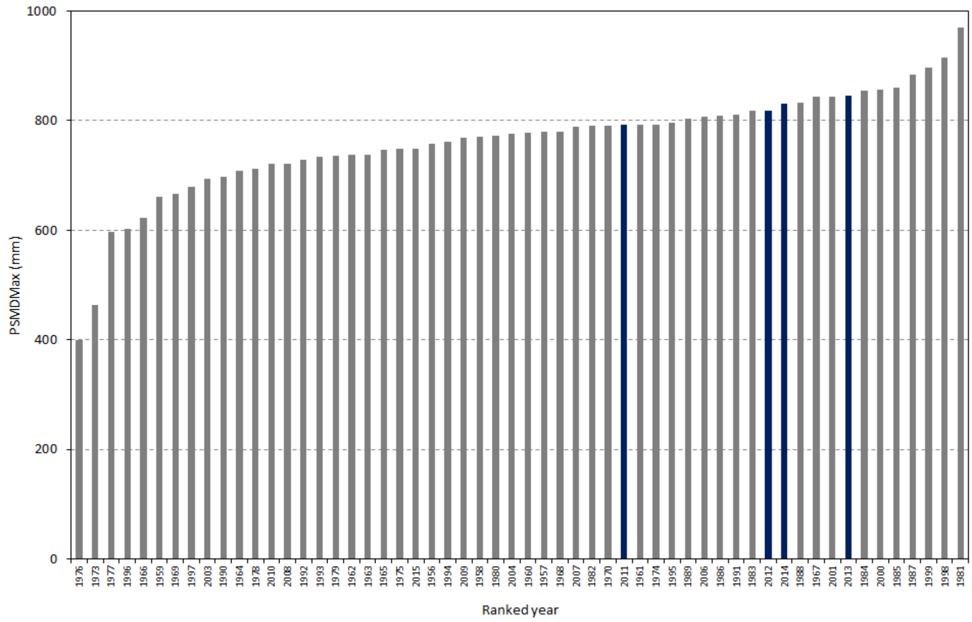

Figure 6. Ranked annual maximum potential soil moisture deficit ($PSMD_{max}$) (mm) for Luqa (Malta) based on daily historical climate data for 1953–2015. Recent drought years marked in blue

This shows that the average $PSMD_{max}$ is around 780 mm yr^{-1} but there is wide inter-annual variation in aridity; the index clearly highlights particularly dry years in terms of irrigation need, and the spate of recent very dry years between 2011 and 2014 (marked in blue).

Previous research including Rodriguez-Diaz *et al*. (2007) and de Silva *et al*. (2007) correlated the aridity index ($PSMD_{max}$) against reported actual irrigation demands (derived from volumetric meter readings) and modelled theoretical demands to assess the impacts of climate change on future water requirements key commodity crops. Such an approach would be invaluable for application in Malta if accurate water abstraction data were available together with estimates of irrigated area and crop mix. Unfortunately, datasets on the spatial and temporal patterns of water abstraction for agriculture in Malta are not currently available, although efforts are being made to formalize a register of abstraction points. Such data would facilitate more accurate demand forecasting for agriculture and help in planning water-resources management and allocation more effectively, particularly given predicted conditions of increasing drought and water scarcity for the Mediterranean region.

Way forward: Innovations in agricultural management and practice in Malta

Both management and technology innovations will be needed to support agricultural development in Malta. These will also need to be supported by a programme of capacity building and knowledge-exchange activities to practitioners and stakeholders to ensure there is successful translation of research into practice. Two selected areas for future focus are highlighted below.

Soil and nutrient management

The use of paper strips needs to be used with caution by ensuring that they are well correlated initially with conventional laboratory methods through preliminary assessments for particular soil types and crops. Once these assessments have been verified, the use of paper strips can potentially reduce laboratory costs of analysis and provide opportunities for more accurate use of fertilizers. The ease of use of paper strips could also allow opportunity for the use of treated sewage effluents or animal slurry as renewable sources of fertilizers provided that the accuracy and precision of this approach was not compromised. Farmers can also share the costs for purchasing the hand-held device and use it as a common resource amongst neighbours due to its portability; this could be an innovative and cost-effective option for promoting the uptake of new technology to support improved decision-making in nutrient management.

On-farm demonstration and knowledge exchange

Key to the successful adoption of best practices for soil and water management by the farming community in Malta is knowledge-exchange to share ideas, promote best practices, and demonstrate innovation in management and technology. In the FORWARIM project, one approach that has been successfully to foster knowledge exchange has been through organisation of an on-farm demonstration day. In June 2017, an on-farm demonstration event was held in a field growing tomato at Burmarrad, near Naxxar (Lat. 35.934376°, Lon 14.428976°). The event attracted approximately100 farmers from across Malta, as well as researchers, academics, consultants, agronomists, and government agency staff responsible for policy formulation. The day was focused on promoting innovations in agricultural soil and water management. It included technical presentations, hands-on demonstrations, and practical guidance in crop and soil management including irrigation and water resources. Sessions presented included (i) understanding soils and nutrient management; (ii) evaluating nutrient valorisation from renewable irrigation sources in Maltese agriculture; (iii) improving crop yield and quality – benefits and challenges in irrigation scheduling, and (iv) innovations in climate and irrigation water management. The target audience was principally farmers but it was also intended to be relevant to stakeholders in the agricultural sector, policy and technical advisors, researchers, and academics, and others engaged in providing technical services to agriculture (e.g. agronomists, consultants). The timing was important and chosen to coincide best with the farming community and to fit in with a period when crop production was well advanced, when irrigation was well underway, and when farmers would have elevated levels of interest in agricultural soil and water management.

Field demonstrations were provided concerning in-situ testing for soil nutrients and salinity; investigating the plant root zone and compaction; use of tape irrigation techniques for water conservation; and ground-water salinity challenges. A further demonstration of the outputs of the Maltese Soil Information System (MalSIS) project was provided, offering a unique overview of the soil characteristics across the three islands.

(a)	(b)
	
(c)	(d)

Figure 7 Farmers attending the inaugural on-farm demonstration event on a tomato farm in Malta (June 2017). Participants were given technical guidance on land use mapping and soil nutrients (a), the importance of soil structure for rooting (b), understanding climate variability and evapotranspiration (ET) (c), and practical application of in-situ soil moisture sensors for irrigation scheduling (d).

Concluding comments

Soil and water resources for agriculture in Malta are under intense pressure. Rising demands on land resources for food production and urban development coupled with rising demands for water abstraction to support irrigated agriculture, population growth, and tourism will require a collective and coordinated approach from all sectors to identify the most sustainable pathways for development. Trade-offs between socio-economic growth, the environment, and managing natural resources to avoid depletion are urgently needed, with appropriate policies then implemented to support more sustainable development. Managing soil and water resources better will be key to securing a viable future for the agricultural sector in Malta.

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