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## Editorial

## Mitigation and quantification of greenhouse gas emissions in Mediterranean cropping systems

## 1. Introduction

Mediterranean climate, found in some regions between latitudes 30° and 45°, is characterized by having mild winters and warm and dry summers. Over one half of the area with Mediterranean-type climate worldwide is found in the Mediterranean Sea Basin, but it is also present in four other regions of the world namely California (USA), Central Chile, the Cape region of South Africa, and South-West Australia (Aschmann, 1973). Precipitation during the summer period, when highest temperatures occur, is scarce, and crop yields are boosted by irrigation more than in temperate areas (Wriedt et al., 2009). Climate models have forecast a rise in temperatures and severe water scarcity, with major impacts on crop yields (Bindi and Olesen, 2011; Iglesias et al., 2011). In Mediterranean Europe, driven by climate change, annual precipitation has decreased whereas the frequency and intensity of extreme weather events (e.g. droughts, floods) increased, thus enhancing land degradation processes and the risk of desertification (Diodato et al., 2011; Garcia-Ruiz et al., 2011). The development of effective mitigation and adaptation strategies are therefore crucial for the future of the Mediterranean region. Additionally, the understanding of Mediterranean agroecosystems is also interesting in the context of increasing temperature and decreasing precipitation in many temperate areas (Trnka et al., 2011), which could lead to a process of “mediterraneization”. Indeed, climate models indicate that the Mediterranean climate range could expand by 15–32% in the Mediterranean basin and by 29–53% in South America (Klausmeyer and Shaw, 2009).

The temporal gap between maximum irradiance and temperature (early summer) and maximum water availability (winter), added to the specifically low organic matter (OM) content of cropped Mediterranean soils, are important drivers of the typically low productivity of rain-fed crops (Aguilera et al., 2013a). On the other hand, irrigated agriculture benefits from the solar radiation and extended frost-free periods to make these areas capable of high crop yields. Therefore, influenced by edaphic and climatic conditions, Mediterranean agriculture is characterized by contrasting cropping systems under rainfed or irrigated conditions, and large surfaces of permanent crops. Specific agro-climatic conditions suggest that biochemical processes responsible for soil greenhouse gas (GHG) emissions, which show distinct patterns in Mediterranean agro-ecosystems, for example in terms of carbon (C) sequestration (Aguilera et al., 2013a) and nitrous oxide (N<sub>2</sub>O) emissions (Aguilera et al., 2013b). These specific patterns

potentially affect the estimation of the net GHG footprint of agricultural products, as shown by life cycle assessment studies incorporating Mediterranean N<sub>2</sub>O emission factors (Biswas et al., 2008; Aguilera et al., 2015a,b) and C sequestration (Venkat, 2012; Aguilera et al., 2015a,b). As a general trend, the role of N<sub>2</sub>O in the GHG balance is relatively minor due to low N inputs and low emission factor (EF), while the role of C sequestration can be very relevant depending on management (Aguilera, 2016). These findings are also supported by another study directly measuring soil GHG fluxes (Guardia et al., 2016a). An increasing body of research has addressed GHG emissions in Mediterranean cropping systems, contributing to identify the best GHG mitigation practices. However, the level of understanding of soil processes responsible for GHG emissions and of the potential of agronomic practices to mitigate GHG emissions is still relatively low, for example when compared to that of temperate areas, indicating a need to synthesize and expand this knowledge. These are the two main objectives of this Special Issue.

The Special Issue begins with a descriptive review aiming to synthesize and analyze the most promising strategies for GHG mitigation in Mediterranean cropping systems. Sanz-Cobena et al. (in this issue) made an integrated assessment of management practices on mitigating each component of the total GHG budget (N<sub>2</sub>O and methane (CH<sub>4</sub>) emissions, and C sequestration) of production systems, considering potential side-effects, as well as regional barriers and opportunities for their implementation. This analysis allowed proposing best strategies to abate GHG emissions, while sustaining crop yields and mitigating other sources of environmental pollution.

## 2. Nitrous oxide emissions

A set of seven papers focuses on N<sub>2</sub>O emissions. Cayuela et al. (in this issue) performed a meta-analysis of N<sub>2</sub>O emissions from Mediterranean cropping systems to propose more robust and reliable regional emission factors (EFs) for N<sub>2</sub>O, distinguishing the effects of water management, crop type, and fertilizer management. These authors concluded that EFs are generally lower in Mediterranean cropping systems, mostly rainfed ones, than those used as tier 1 default EFs by IPCC, and that water regime (irrigation technique or precipitation amount) was the most important factor controlling the magnitude of soil N<sub>2</sub>O EFs from Mediterranean regions. Application of these new EFs would lead to a much lower

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N<sub>2</sub>O emission estimation at the country scale, as it is shown for the case of Spain (Cayuela et al., in this issue).

Five studies have provided original results from field work aiming to assess the effect of management practices on N<sub>2</sub>O emissions. The papers by Abalos et al. (in this issue) and Hube et al. (in this issue) focus on the potential of nitrification inhibitors to abate N<sub>2</sub>O emissions in contrasting environments and for different crops under Mediterranean climate. The former, using static chambers, examines the effect of rainfall variability on the effectiveness of the nitrification inhibitor DMPP (3,4-dimethyl pyrazole phosphate) to abate N<sub>2</sub>O fluxes in a rain-fed barley crop in Central Spain; the authors conducted a three year study showing EFs to be lower than the IPCC default value, thus suggesting that Mediterranean-specific EFs should be used. They also conclude that nitrification inhibitors are effective in mitigating N<sub>2</sub>O in semiarid Mediterranean environments, although the degree of mitigation depends on rainfall amount and distribution. The authors point out that, although in contrast to the traditional split application at planting and tillering, a single fertilizer application at tillering may provide a more effective management opportunity for N<sub>2</sub>O mitigation.

Hube et al. (in this issue) also evaluated the effectiveness of nitrification inhibitors, DCD (Dicyandiamide) in an oat crop cultivated in a Chilean volcanic ash soil and fertilized with different rates of urea. They also tested the potential of the urease inhibitor NBPT (N-(n-butyl)thiophosphoric triamide) to abate N<sub>2</sub>O and CH<sub>4</sub> fluxes. Similar to the findings of Abalos et al. (in this issue), EFs were lower than the IPCC default values, possibly due to specific physico-chemical characteristics of volcanic ash soils. The effects of inhibitors in abating N<sub>2</sub>O emission were not statistically significant. Related to crop yield, only the use of NBPT significantly increased productivity and N use efficiency, while DCD reduced yield-scaled N<sub>2</sub>O emissions.

The field study of Guardia et al. (in this issue) carried out in central Spain, evaluated different fertilization strategies based on application of pig manure (i.e. compost from the solid phase, liquid fraction of pig slurry (LFPS), with and without DMPP), and its interaction with irrigation system (sprinkler vs. drip) on GHG (N<sub>2</sub>O, CH<sub>4</sub>) and nitric oxide (NO) emissions, and maize yield, as opposed to the conventional use of synthetic N sources (namely urea). The authors observed that use of DMPP with LFPS was an effective practice to reduce N<sub>2</sub>O and NO emissions (40 and 32% reduction, respectively, compared to LFPS alone), and was also associated with the highest rates of CH<sub>4</sub> oxidation. Moreover, the treatment that used only organic fertilizer led to similar yield-scaled N<sub>2</sub>O emissions compared to urea. Regarding the irrigation system, drip irrigation was the most promising management practice to mitigate yield-scaled GHG emissions, though the side effects of increasing NO losses should be taken into account. This study showed that the use of organic fertilizers in irrigated maize is a suitable alternative for reducing GHG emissions without yield penalties in irrigated systems, but only if they are properly managed.

In a contrasting cropping system, Wolff et al. (in this issue) measured the mitigation effect of fertigation in an almond orchard of California (USA). These authors measured N<sub>2</sub>O production in a soil profile showing that application of urea ammonium nitrate produced the highest N<sub>2</sub>O emissions at 10–15 cm depth, while N<sub>2</sub>O was reduced to N<sub>2</sub> below 20 cm in all treatments. High-frequency fertigation with ammoniacal fertilizers did not mitigate N<sub>2</sub>O emissions, but nitrate-based fertilizers did, suggesting that nitrifier denitrification can be a major source of N<sub>2</sub>O with ammoniacal fertilizers applied through fertigation.

Two papers presented modelling approaches to assess the effectiveness of agronomic practices for N<sub>2</sub>O mitigation. On the one hand, Alvaro-Fuentes et al. (in this issue) used the Daycent model

(Del Grosso et al., 2011) to predict N<sub>2</sub>O emissions and to determine the impact of climate change and atmospheric CO<sub>2</sub> enrichment under different land uses (cropland, abandoned land and afforested land) in the Spanish Mediterranean region over an 85-year period. Model results showed that under climate change, water filled pore space (WFPS) could decrease (i.e. oxygenation increased) between 4% and 15%. The authors estimate that climate change would decrease soil N<sub>2</sub>O emissions in a range of land uses.

In the other modelling paper, Plaza-Bonilla et al. (in this issue), using the soil and crop model STICS (Brisson et al., 2008), tested the effect of a Mediterranean precipitation gradient on mitigation of N<sub>2</sub>O emissions under different management practices (e.g., N fertilizer type, grain legume introduction in crop rotations and crop residues management). Results confirmed the importance of climatic conditions for N<sub>2</sub>O emission and mitigation across an aridity gradient. The lower N<sub>2</sub>O emissions at the driest sites were associated with lower fertilization rates, but also with other factors, particularly the drier water regime. Among the management practices evaluated, incorporation of winter pea in traditional cereal-based rotations reduced N<sub>2</sub>O emissions the most.

### 3. Carbon sequestration

The study of C sequestration in Mediterranean cropping systems is of particular importance because the levels of OM in Mediterranean soils are generally low and are expected to decrease further (Davidson and Janssens, 2006). Management practices aimed at increasing soil organic C (SOC) stocks are therefore paramount. Five papers focus on the potential of different agricultural practices to enhance the SOC stocks in Mediterranean soils. Montanaro et al. (in this issue) evaluated the effect of so called sustainable management practices (zero-tillage, weed mowing, retention of above-ground residues and the import of organic amendments) on the C budget of an Italian peach orchard over a seven-year period. The field study revealed that these practices reduced the release of C via removal and storage of C in both soil and tree biomass, and increased the C stock at a mean rate 20 times higher than that of conventional practices, with associated benefits for soil structure and function (e.g. soil water holding capacity and biodiversity). Although both being sinks of C, the net ecosystem C balance of sustainably managed orchards was reported to be 8 times higher than that of conventionally managed ones.

The effect of reusing by-products or treated urban wastes on the GHG balance of these systems was also considered. Calleja-Cervantes et al. (in this issue) determined over 20 years the influence of continued yearly application of thermophilic digested sewage sludge at three different rates on soil C sequestration, as well as potential side effects in the form of other GHG emissions. Application rate was the most important factor in determining C and nutrient dynamics as well as crop response. The highest application rate of sludge (80 t ha<sup>-1</sup>) led to the largest increase in soil organic C and N, as well as GHG emissions. This was also the only case where crop yield decreased, due to irreversible lodging (crops falling over). In contrast, a lower dose of sludge (40 t ha<sup>-1</sup>), in combination with urea, increased soil microbial activity, which ultimately activates soil metabolism, and enhances C sequestration without increasing GHG emissions, in comparison with soils fertilized only with urea.

Following these two field studies, three modelling approaches complete the C sequestration section. The paper of Farina et al. (in this issue) reported a modelling study for soil C stocks and CO<sub>2</sub> emission changes over 20 years using the RothC-10N model (Coleman and Jenkinson, 1996) in a region of Southern Italy and across three agricultural land use types (arable land, pasture land, and permanent woody cropland), and also including actual

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