Strategies for GHG mitigation in Mediterranean cropping systems. A review

Sanz-Cobeña[1], A., Lassaletta, L.[2], Aguilera, E.[3], del Prado, A.[4], Garnier, J.[5,6], Billen, G. [5,6], Iglesias, A.[1], Sánchez, B.[1], Guardia, G.[1], Abalos, D.[7], Plaza-Bonilla, D.[8], Puigdueta, I[1], Moral, R.[9], Galán, E.[4], Arriaga, H.[10], Merino, P.[10], Infante-Amate, J.[3], Meijide, A.[11], Pardo, G.[4], Alvaro-Fuentes, J.[12], Gilsanz, C.[13], Báez, D.[13], Doltra, J.[14], González-Ubierna, S.[15], Cayuela, M.L.[16], Menendez, S.[17], Diaz-Pines, E.[18], Le-Noe, J.[4], Quemada, M.[1], Estellés, F.[19], Calvet, S.[19], van Grinsven, H.[2], Westhoek, H.[2], Sanz, M.J.[6], Sánchez-Jimeno, B.[20], Vallejo, A.[1], Smith, P.[21]

[1] ETSI Agronomos, Technical University of Madrid, Ciudad Universitaria, 28040 Madrid, Spain a.sanz@ump.es
[2] PBL Netherlands Environmental Assessment Agency, Bilthoven, PO Box 303, 3720 AH Bilthoven, the Netherlands
[3] Universidad Pablo de Olavide, Ctra. de Utrera, km. 1, 41013, Sevilla, Spain
[4] Basque Centre for Climate Change (BC3), Alameda Urquijo 4-4, 48008, Bilbao, Spain CNRS, UMR
[5] CNRS, UMR Metis 7619, BP105, 4 place Jussieu, 75005, Paris, France
[6] UPMC, UMR Metis 7619, BP105, 4 place Jussieu, 75005, Paris, France
[7] Department of Soil Quality, Wageningen University, PO Box 47, Droevendaalsesteeg 4, Wageningen 6700AA, The Netherlands
[8] INRA, UMR-AGIR, 24 Chemin de Borde Rouge –Auzeville, CS 52627, 31326 Castanet-Tolosan cedex, France
[9] Department of Agrochemistry and Environment, EPSO, Miguel Hernandez University, 03312 Orihuela, Alicante, Spain
[10] NEIKER-Tecnalia, Conservation of Natural Resources, Bizkaia Technology Park, P. 812, 48160, Derio, Bizkaia, Spain
[11] Bioclimatology, Georg-August-Universität Göttingen, Büsgenweg 2, 37077, Göttingen, Germany
[12] Soil and Water Dpt, Estacion Experimental de Aula Dei (EEAD), Spanish National Research Council (CSIC,), Av. Montañana, 1005, 50059 Zaragoza, Spain
[13] Mabegondo Agricultural Research Centre (CIAM-INGACAL), Xunta de Galicia, Carretera AC-542 de Betanzos a Mesón do Vento, km 7, 15318 Abegondo, A Coruña, Spain
[14] Cantabrian Agricultural Research and Training Centre, CIFA, c/Héroes 2 de Mayo 27, 39600 Muriedas, Spain
[15] Faculty of Pharmacy. Complutense University of Madrid. Ciudad Universitaria. Pza. Ramón y Cajal s/n, 28040 Madrid, Spain
[16] Departamento de Conservación de Suelos y Aguas y Manejo de Residuos Orgánicos. CEBAS-CSIC. Campus Universitario de Espinardo. 30100 Murcia. Spain.
[17] University of the Basque Country UPV/EHU, Department of Plant Biology and Ecology, Apdo. 644, 48080, Bilbao, Spain
[18] Institute of Meteorology and Climate Research, Atmospheric Environmental Research. Karlsruhe Institute of Technology. Kreuzeckbahnstr. 19, 82467 Garmisch-Partenkirchen, Germany.
[19] ICTA, Universitat Politècnica de València, Camino de Vera s/n 46022, Valencia
[20] Dirección General de Investigación Científica y Técnica. Ministerio de Economía y Competitividad. Gobierno de España. Pº. de la Castellana, 162, 28046 Madrid, España.
[21] Institute of Biological and Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, UK

Abstract
In this review we aimed to synthetize and analyze the most promising GHGs mitigation strategies for Mediterranean cropping systems. A description of most relevant measures, based on the best crop choice and management by farmers (i.e., agronomical practices), was firstly carried out. Many of these measures can be also efficient in other climatic regions, but here we provide particular results and discussion of their efficiencies for Mediterranean cropping systems. An integrated assessment of management practices on mitigating each component of the global warming potential (N_2O and CH_4 emissions and C sequestration) of production systems considering potential side-effects of their implementation allowed us to propose the best strategies to abate GHG emissions, while sustaining crop yields and mitigating other sources of environmental pollution (e.g. nitrate leaching and ammonia volatilization).

Key Words
Cropping systems, GHG, Mitigation, N_2O, Mediterranean climate, review.

Introduction
The Mediterranean climate is characterized by annual precipitation ranging from 275 to 900 mm. The average winter temperature is below 15°C, but the number of hours per year with temperatures below 0°C does not exceed 3% of the total. This climate presents seasonal dryness and many of its subtypes are classified as semi-arid. It is generally located on the west coasts of continents and between latitudes 32° and 42° north and south of the equator (Figure 1). Over one half of the area with Mediterranean-type climate worldwide is found in the Mediterranean Sea Basin (Aschmann, 1973), but it is also present in four other different regions of the world namely California (USA), Central Chile, the Cape region of South Africa, and South-West Australia. Pedoclimatic conditions in Mediterranean soils shape soil processes in Mediterranean cropping systems, leading to different N_2O emission patterns than in temperate soils (Aguilera et al. 2013a). Nitrification and nitrifier-denitrification, and not denitrification, are very often the main pathways leading to emissions of N

oxides in rain-fed Mediterranean cropping system (Aguilera et al., 2013b). These two processes are favored by conditions of soil water content (i.e., water filled pore space, WFPS) under saturation. Denitrification may play a predominant role in anaerobic soil microsites of intensively managed and irrigated systems (e.g., Sanz-Cobena et al., 2012). Consequently, different cumulative N_2O emission has been proposed for rain-fed crops (0.7 kg N ha^{-1} yr^{-1}) and for e.g., sprinkler irrigated crops in Mediterranean areas (4.4 kg N ha^{-1} yr^{-1}) (Cayuela et al., 2016). It is thus clear that the importance and potential for N_2O mitigation and the best mitigation strategy highly differ depending on the cropping system. Increasing the generally low C content of Mediterranean soils, which must be considered a GHG mitigation strategy, is one of the most important priorities to prevent erosion and improve soil quality.

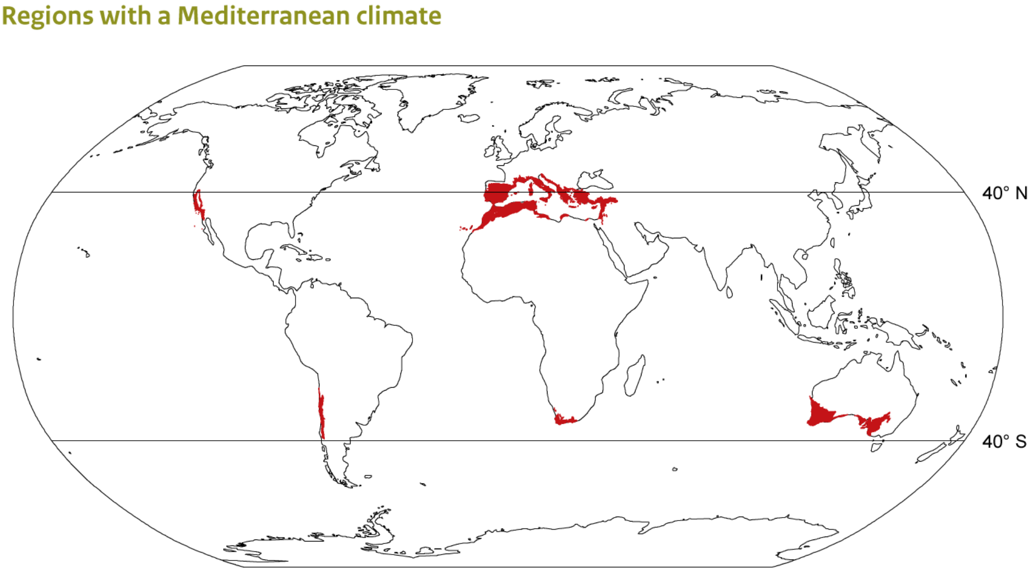

Figure 1. Regions of the world with Mediterranean climate and number of papers measuring field N_2O emissions in each region.

Methods

In this review we aimed to synthetize and analyze the most promising GHGs mitigation strategies in Mediterranean cropping systems. We herein describe measures based on the best crop choice and resources management by farmers and practices including the use of novel technological developments (e.g., urease and nitrification inhibitors and advanced irrigation technologies). We have reviewed the performance of agronomical GHG mitigation practices in Mediterranean cropping systems aiming to i) decrease soil N_2O emissions; ii) enhance CH_4 oxidation and decrease CH_4 emission rates; iii) enhance soil organic C stocks and iv) have a reducing or neutral co-effect on other sources of environmental pollution (e.g. NH_3 volatilization and NO_3^- leaching). The effect on the global warming potential (GWP) components of the selected strategies was analyzed to establish an order of priority. Finally, we explored the potential of structural measures at the agro-food system scale for reducing GHGs emissions: i) food waste reduction, ii) change in the composition of human diet,and iii) reconnection between crops and livestock at farm or regional scale for optimizing N use.

Results

The most promising measures enhancing C sequestration and mitigating N_2O and CH_4 emissions were selected considering the GHG balance in each specific Mediterranean agro-ecosystem (Table 1). The dominant GHG sources of each cropping system and each particular area (local pedoclimatic conditions) should be considered for prioritizing the adoption of efficient techniques, but also taking into account all practices that could provide and optimum balance between GHG mitigation and crop yields while saving/maintaining farm expenses or leading to an efficient use of available resources.
The study of Aguilera et al. (2015a) pointed out that the main GHG sources in herbaceous cropping systems in Mediterranean areas were emissions from machinery due to the low direct GHG emissions in these systems. Guardia et al. (2016), in a non-irrigated cereal-legume rotation, also confirmed that the relative weight of N_2O losses was lower than that of farm inputs and operations, while C sequestration was the main GHG mitigation

component under No-Tillage (NT) adoption. There are however some uncertainties and variability that could be attributed to the C sink (e.g., the depth considered for calculation, the decrease of annual sequestration rate in the long term) (Álvaro-Fuentes et al., 2014), it appears that practices such as NT/Reduced-Tillage combined with crop rotations including legumes combined with crop rotations including legumes and cover crops, without removing of crop residues, are the most promising for minimizing fuel consumption and external inputs (e.g. conservation agriculture practices, as conventional ones, might rely on the use of pesticides), and promote C sequestration. These practices may provide the best GHG balance in rain-fed Mediterranean herbaceous crops, without negative side-effects on crop yields or N losses. Adjusting N fertilization rates to crop needs may improve the GHG balance of rain-fed herbaceous cropping systems through two components (N_2O emissions and CO_2 equivalents from production and transport of fertilizers) while reducing farm expenses, so this practice must be encouraged in Mediterranean areas.
In summer irrigated crops, conditions are propitious for high N_2O losses (Aguilera et al., 2013b). Consequently, agricultural practices based on an improved management of irrigation water (e.g., drip irrigation), N fertilization (e.g., adjusting N rates and timing, use of nitrification inhibitors) and both (e.g., fertigation) are the most promising measures in these agro-ecosystems. Since fruit orchards are broadly characterized by efficient water and fertilizer use (e.g., drip irrigation and drip-fertigation), other promising techniques are cover cropping (thus minimizing fuel consumption) and pruning residues management for enhancing C stocks (Aguilera et al., 2015a). Methane emissions are the main component on GWP in paddy fields (Aguilera et al., 2015b), so mitigation efforts should focus on water management for minimizing these lossesReducing water consumption in vegetable cropping systems may lead to substantial GHG reductions (Aguilera et al., 2015a).

Table 1. Main component and mitigation practices associated of each cropping system in Mediterranean areas

	Main component of the GWP		Main mitigation practice		Other pollutants	
Crop type	***Rain-fed***	***Irrigated***	***Rain-fed***	***Irrigated***	***Rain-fed***	***Irrigated***
Herbaceous	Machinery/external inputs; C seq. (NT)	N_2O	Reducing fuel consumption and external inputs, reduced tillage, crop rotations (including legumes), adjusted N rates, NIs	Water management (e.g. drip irrigation), N fertilization (e.g. adjusted N rates, Nis*)	Increased NH_3	Increased NH_3, NO_3^-
Fruit orchards	C sequestration	N_2O	NA	Cover crops, pruning crop residues	NA	NA
Rice	NA	CH_4	NA	Water management	NA	Increased N_2O

*Nitrification inhibitors

Management practices aiming at optimizing N fertilization and irrigation show a large potential for N_2O mitigation from Mediterranean crops. Adjusting N fertilization to crop needs is a sound and feasible practice in both irrigated and rain-fed systems and presents an N_2O mitigation potential up to 50% compared with a non-adjusted practice. Substitution of N synthetic fertilizers by solid manure can be implemented in both irrigated and rain-fed systems, and may abate N_2O emissions by about 20% under Mediterranean conditions, besides the indirect mitigation potential due to energy savings and the observed positive effects in crop yields. Substituting synthetic fertilizers by slurries does not lead to N_2O reductions and had drawbacks in crop yields. The use of urease and nitrification inhibitors enhances nitrogen use efficiency of the cropping systems and may mitigate N_2O emissions up to 80% and 50%, respectively. Inhibitors can be used with both organic and synthetic fertilization but implies a higher fertilization cost.

Irrigation technology in the Mediterranean areas is a key driving factor on N_2O emissions. The mitigation potential of some irrigation systems in the Mediterranean region can be very high for some crops. Drip-irrigated systems have on average 80 % less N_2O emissions than sprinkler systems and drip-irrigation combined with optimized fertilization showed a reduction in direct N_2O emissions up to 50%. However, our analysis of the total life cycle emissions (including infrastructure production, electricity production, fertilizer production, and direct and indirect N_2O emissions) associated to irrigation and N fertilization revealed that all these factors beyond the plot scale may outweigh the reduction in N_2O emissions in some cases. The most suitable agronomical practices for potentially enhancing carbon stocks in Mediterranean soils are reduced soil tillage and a proper management of crop residues and by-products of the agroindustry. In all cases, significant effects on C sequestration have been observed in long term experiments, averaging 0.43 Mg C ha^{-1} yr^{-1}. Although assessments are needed due to specificities of these practices affecting GHG fluxes, they are extensible to irrigated and rain-fed systems and, in general, present economic opportunities for farmers due to savings in resources and increased crop yields.
We identified three structural measures with large potential to mitigate GHG emissions beyond the plot scale: i) food waste reduction, ii) change in the composition of human diet, particularly in the proportion of animal products, and iii) reconnection between crop and livestock farming at exploitation or regional scale to optimize the reuse of nutrients in animal manure. Between 3 and 15% of N_2O emissions could be suppressed by avoiding food waste at the consumer level. A reduction of 40% of meat and dairy consumption would reduce GHG by 20 to 30%. The reintroduction of the Mediterranean diet (i.e., a back reduction to ~35% of animal protein) would therefore result in a decrease of GHG emissions from agriculture. All these changes strongly depend on individual choices, so for its implementation it would be necessary to better understand the drivers that would lead to its accomplishment (social barriers and incentives for the behavior change) through a further multidisciplinary work.

Conclusion
The results of this review indicate that GHG mitigation in the Mediterranean climate areas requires a specific approach that is different from temperate regions due to particular pedoclimatic and agronomical conditions. Hydrological regime is playing a key role in rain-fed as in irrigated systems principally to define the contribution of N_2O to the total GHG emissions. Efficient implementation will require an integrative approach that considers co-benefits or trade-offs for yields and pollution swapping that are specific for semi-arid regions.

References

Aguilera, E., Guzmán, G., Alonso, A., 2015a. Greenhouse gas emissions from conventional and organic cropping systems in Spain. II. Fruit tree orchards. Agron. Sustain. Dev. 35, 725–737.

Aguilera, E., Guzmán, G., Alonso, A., 2015b. Greenhouse gas emissions from conventional and organic cropping systems in Spain. I. Herbaceous crops. Agron. Sustain. Dev. 35, 713–724.

Aguilera, E., Lassaletta, L., Gattinger, A., Gimeno, B.S., 2013a. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. Agric. Ecosyst. Environ. 168, 25–36.

Aguilera, E., Lassaletta, L., Sanz-Cobena, A., Garnier, J., Vallejo, A., 2013b. The potential of organic fertilizers and water management to reduce N 2 O emissions in Mediterranean climate cropping systems. A review. Agric. Ecosyst. Environ. 164, 32–52.

Aschmann, H., 1973. Distribution and peculiarity of Mediterranean ecosystems, in: Mediterranean Type Ecosystems. Springer, pp. 11–19.

Álvaro-Fuentes, J., Plaza-Bonilla, D., Arrúe, J.L., Lampurlanés, J., Cantero-Martínez, C., 2014. Soil organic carbon storage in a no-tillage chronosequence under Mediterranean conditions. Plant Soil 376, 31–41.

Guardia, G., Tellez-Rio, A., García-Marco, S., Martin-Lammerding, D., Tenorio, J.L., Ibáñez, M.Á., Vallejo, A., 2016. Effect of tillage and crop (cereal versus legume) on greenhouse gas emissions and Global Warming Potential in a non-irrigated Mediterranean field. Agric. Ecosyst. Environ. 221, 187–197.

Sanz-Cobena, A., Sánchez-Martín, L., García-Torres, L., Vallejo, A., 2012. Gaseous emissions of N 2 O and NO and NO3- leaching from urea applied with urease and nitrification inhibitors to a maize (Zea mays) crop. Agric. Ecosyst. Environ. 149, 64–73.

Cayuela, M.L., Aguilera, E., Sanz-Cobena, A., Adams, D.C., Abalos, D., Barton, L., Ryals, R., Silver, W.L., Alfaro, M.A., Pappa, V.A., Smith, P., Garnier, J., Billen, G., Bouwman, L., A Bondeau, A., Lassaletta, L. Direct nitrous oxide emissions in Mediterranean climate cropping systems: emission factors based on a meta-analysis of available measurement data. Agr. Ecosyst. Environ.Under review.