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To cite this article: Luis Lassaletta *et al* 2021 *Environ. Res. Lett.* **16** 073002

ENVIRONMENTAL RESEARCH
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RECEIVED
17 November 2020

REVISED
16 March 2021

ACCEPTED FOR PUBLICATION
11 May 2021

PUBLISHED
23 June 2021

TOPICAL REVIEW

Nitrogen dynamics in cropping systems under Mediterranean climate: a systemic analysis

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Keywords: nitrogen fertilization, nitrogen pollution, Mediterranean region, nitrogen–water interaction, adaptation and mitigation synergies, regional strategies

Supplementary material for this article is available online

Abstract

Worldwide, Mediterranean cropping systems face the complex challenge of producing enough high-quality food while preserving the quantity and quality of scarce water for people and agriculture in the context of climate change. While good management of nitrogen (N) is paramount to achieving this objective, the efficient strategies developed for temperate systems are often not adapted to the specificities of Mediterranean systems. In this work, we combine original data with a thorough literature review to highlight the most relevant drivers of N dynamics in these semi-arid systems. To do so, we provide an analysis at nested scales combining a bottom-up approach from the field scale, with a top-down approach considering the agro-food system where cropping systems are inserted. We analyze the structural changes in the agro-food systems affecting total N entering the territory, the contrasting response of yields to N availability under rainfed and irrigated conditions in a precipitation gradient, the interaction between N management and climate change adaptation, the main drivers affecting the release of Nr compounds (nitrate, ammonia, nitric oxide and nitrous oxide) compared with temperate systems and finally, the behavior of N once exported to highly regulated river networks. We conclude that sustainable N management in Mediterranean cropping systems requires the specific adaptation of practices to particular local agro-environmental characteristics with special emphasis on water availability for rainfed and irrigated systems. This approach should also include a systemic analysis of N input into the territory that is driven by the configuration of the agro-food system.

1. Background

The Mediterranean biome, characterized by its climate with warm, dry summers and mild, wet winters, is located between 30° and 45° latitude and is present in five areas of the world, namely, the Mediterranean Basin, California (USA), Chile, South Africa and Australia (figure 1) (Aschmann 1973). Mediterranean-type ecosystems are biodiversity hotspots concentrating a disproportionately high level of endemism (Myers *et al* 2000, Vogiatzakis *et al* 2006), making this biome a global conservation

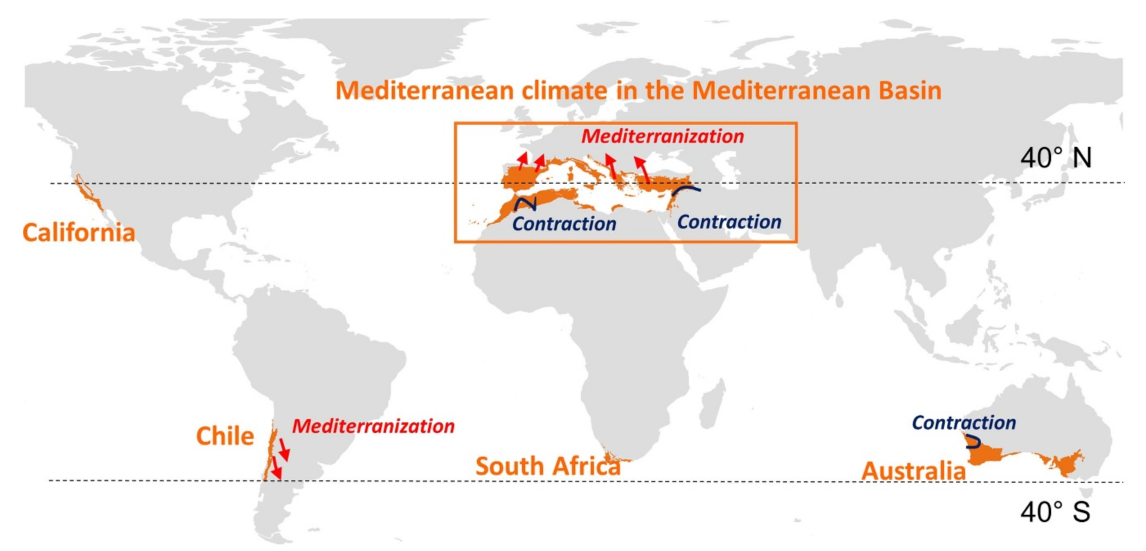

Figure 1. Global distribution of the Mediterranean biome (Olson *et al* 2001) including potential areas of expansion (red arrows, 'Mediterranization') and contraction (blue lines). Adapted from Klausmeyer and Shaw (2009).

priority (Olson and Dinerstein 2003). The total area covers 2.6 million km^2 and in 2010 had a population density of 95 inh km^{-2} (i.e. 310 M inhabitants).

The land area of the Mediterranean Basin accounts for 66% of the world's Mediterranean biome. The sustainability of this region for people and ecosystems is at stake due to: (a) scarcity of water (García-Ruiz *et al* 2011), (b) significant land-use changes, notably urbanization and abandonment of pastoralism (Malek *et al* 2018, Aguilera *et al* 2020), (c) increasing air and water pollution (Sanz-Cobena *et al* 2017), (d) biodiversity loss (Sala *et al* 2000) and (e) accelerating impacts of climate change, as well as other drivers of change (Cramer *et al* 2018, Zampieri *et al* 2020), making this region a 'climate change hotspot' (Giorgi 2006).

Due to global warming, some Mediterranean regions are expected to expand ('Mediterranization') into currently temperate areas in South America and Europe, while contracting in others, such as Australia and North Africa, giving way to a more arid climate (Klausmeyer and Shaw 2009, Hernández 2017). A key characteristic of the Mediterranean climate is the asynchronicity between the maximum water availability (from autumn to spring) and the maximum irradiance and temperature, with important consequences for agricultural production. It is also characterized by flash floods and droughts, which are projected to be exacerbated (Michaelides *et al* 2018).

During thousands of years of evolution, agriculture in the Mediterranean Basin has been adapted to environmental conditions of relative instability, rainfall variability, and summer water stress through the selection of crops, varieties and rotations, as well as hydraulic infrastructure and management practices, resulting in diverse and unique agricultural systems (Blondel 2006). This diversification permits the cultivation of rainfed crops such as cereals, legumes, oilseeds and some vegetables during the winter, as well as of drought-resistant permanent crops such as almonds, grapes and olives. Efficient irrigation can increase crop yields from 10% to 90%, depending on the annual water stress and the technology (Wriedt *et al* 2009). Irrigation also allows for the cultivation and expansion of horticultural crops, maize, tobacco and citrus fruits in these semi-arid areas. As a result, irrigation is a common practice in traditional Mediterranean cropping systems, and it has expanded more than in temperate areas in the past 20 years (figure 2).

Climate change is affecting the entire planet, and Mediterranean climate zones are no exception. As it is occurring on the entire planet (Klausmeyer and Shaw 2009), climate change impacts Mediterranean biomes (Famiglietti *et al* 2011), where it is expected to increase water scarcity via sustained warming and decreasing precipitation, consequently leading to an increase in evaporative demand and in the intensity, duration and frequency of droughts (García-Ruiz *et al* 2011, Spinoni *et al* 2018). Without adaptation, crop yields will likely be impacted (Iglesias *et al* 2011), (Zampieri *et al* 2020). Irrigation requirements may increase substantially with climate change (Fader *et al* 2016) and therefore irrigation techniques will have to be adapted as water resources may turn out to be insufficient (Malek and Verburg 2018).

Together with water, nitrogen (N) is the main limiting factor in agricultural production and must be properly managed to sustain crop yields (Mueller *et al* 2012, Quemada *et al* 2020a). According to Lassaletta *et al* (2014a) a robust hyperbolic relationship exists between N harvested yield, expressed as integrated N content over a whole crop rotation cycle, and annual total N input to the soil. The maximum achievable N yield corresponding to a given pedoclimatic, technical, and agronomic context, $Y_{max,}$ can

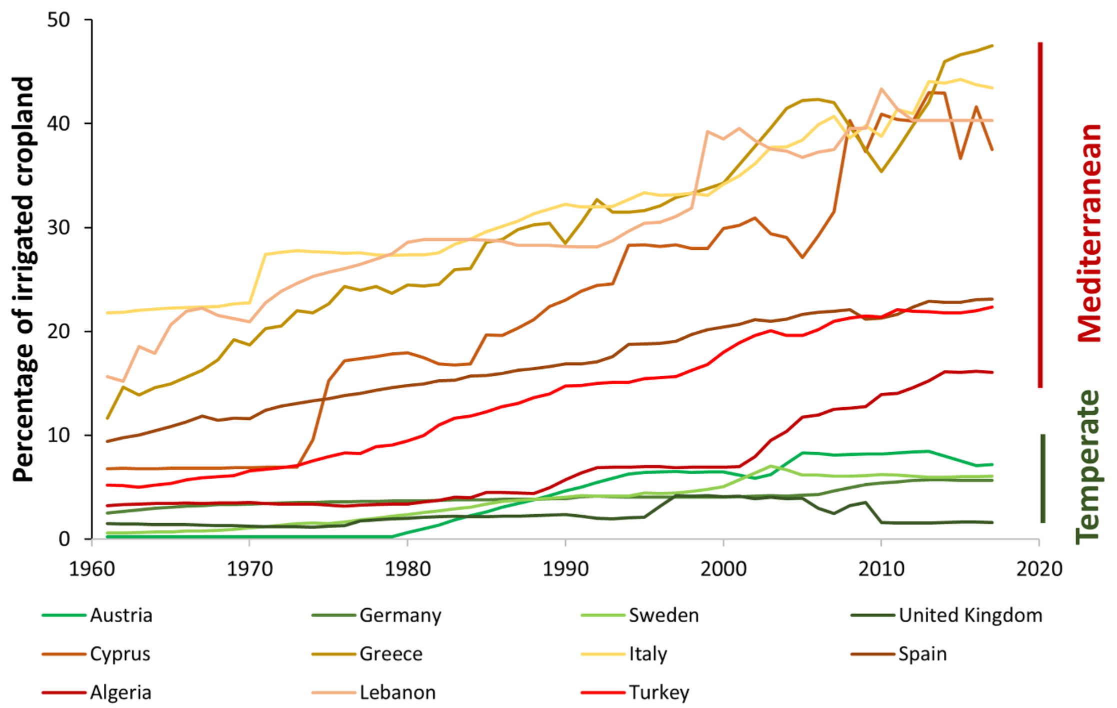

Figure 2. Evolution of cropland fraction equipped for irrigation in several Mediterranean countries (all with more than 50% of their agriculture under Mediterranean conditions) and a sample of temperate countries in Europe (based on FAOSTAT, 2020).

be derived from it. This relationship implies that not all N applied to the soil is recovered with the harvested crop. Overall, N use efficiency (NUE) of the world cropping systems is less than 50% (Bouwman *et al* 2013, 2017, Lassaletta *et al* 2014a). Most of the N surplus, i.e. the amount of N input to soils not exported by harvested crops, is released into the environment, where it undergoes a series of transformations, impacting different ecosystem compartments through the so-called N cascade (Galloway *et al* 2003, Billen *et al* 2013). In agricultural systems, reactive N (Nr, all N species except N_2) (Leach *et al* 2012) is preferentially emitted in the form of volatilized ammonia (NH_3), an aerosol precursor and soil-acidifying compound (van Damme *et al* 2018) that causes biodiversity losses when deposited (Ochoa-Hueso *et al* 2011), nitrous oxide (N_2O), a potent greenhouse gas (Thompson *et al* 2019), and nitric oxide (NO), which promotes the formation of tropospheric ozone (O_3) (Guardia *et al* 2017b). N can also be leached as nitrate (NO_3^-), which is a threat to drinking water resources and freshwater biodiversity (van Grinsven *et al* 2010) and promotes the eutrophication of coastal waters (Garnier *et al* 2010). The emission of these compounds imposes a high economic cost for society (Sutton *et al* 2013, van Grinsven *et al* 2013) and their adequate management has been linked to nine of the United Nations Sustainable Development Goals (Morseletto 2019).

The total N input to the world's Mediterranean cropping systems in 2010 was 5.9 Tg N, most of which was in the form of synthetic fertilizers. 75% of this N is applied in the crops of the Mediterranean Basin under a Mediterranean climate (see the supplementary information for a complete N budget of Mediterranean cropping systems (available online at stacks.iop.org/ERL/16/073002/mmedia)). Adequate crop management in the Mediterranean biome involves the simultaneous control of water and N input (Sadras 2005, Sadras *et al* 2016). Two contrasting situations are experienced: rainfed systems subject to important spatiotemporal variability, which complicates the adjustment of optimal fertilization doses (Ryan 2008, Ryan *et al* 2009, Quemada and Gabriel 2016) and irrigated systems dealing in many cases with water supply limitations and the high risk of NO_3^- leaching (Causape *et al* 2006, Barros *et al* 2012, Malik and Dechmi 2019). Other intrinsic characteristics of the Mediterranean systems, such as high temperatures and low carbon content of the soil (Aguilera *et al* 2013a, Rodríguez Martín *et al* 2016, Aguilera *et al* 2018) have a strong impact on the microbial activity that drives the form in which N is emitted and the magnitude of the flow from croplands to other compartments (Sanz-Cobena *et al* 2017). N_2O emission factors (EFs), for example, are lower than those in temperate systems (Cayuela *et al* 2017).

Sustainable N management, adapted to the particularities of the Mediterranean biome, depends on knowledge of specific processes at the plot and farm scale (bottom-up approach), but also on the understanding of the agro-food system that controls the new N entering a territory (top-down approach). Organic manure may be efficiently recirculated at the regional scale, reducing the demand for new fertilizers, while different agricultural commodities can be locally produced or imported, all of which configure the structure of the N cycle (Billen *et al* 2014, 2015, Le Noë *et al* 2017, Mueller and Lassaletta 2020). For example, in Spain, the input of new N into the national territory (NANI, net anthropogenic N input) (Howarth *et al* 1996) has increased fourfold during the past 60 years, contributing to important yield improvements, but also to significantly increased N pollution. Once N reaches the water bodies, the high regulation of freshwater resources for crop irrigation and drinking water supply can affect N dynamics in Mediterranean watersheds. The fraction of run-off exported to coastal waters is lower than in temperate watersheds, increasing the risk of pollution of aquifers, rivers and lakes (Bartoli *et al* 2012, Romero *et al* 2016).

Worldwide, Mediterranean cropping systems face a complex challenge under the climate change context of producing enough high-quality food for an often-increasing population, together with the need to preserve the quantity and quality of scarce water resources for people and agriculture, while also reducing their impact on air pollution. We present this review with the overall aim of analyzing, from a systemic perspective, the particularities of N dynamics in Mediterranean cropping systems associated with the emission of Nr compounds. Our approach aims to extend from the plot or farm-scale to the agro-food systems in which these cropping systems are embedded.

This study combines primary data with a literature review in order to provide an analysis at nested scales of: (a) the evolution of the N cycle in agro-food systems at the regional scale, including crop N budget, (b) water and N interaction in contrasted irrigated and rainfed systems along a precipitation gradient, (c) the implications of climate change adaptation for N management, (d) the main drivers affecting the release of Nr compounds compared with temperate systems, (e) the behavior of N in Mediterranean watersheds and (f) the resulting policy recommendations for the design of agro-environmental strategies tailored to Mediterranean conditions. The work mainly focuses on the Mediterranean Basin, which forms a unique, conterminous and coherent territory, suitable for developing a systemic analysis covering the agro-food system to the river basin. We postulate that the main lessons learnt with regard to these semi-arid systems managed under rainfed and irrigated conditions are also relevant, not only for the rest of the world's Mediterranean areas, but for new areas undergoing 'Mediterranization' due to climate change.

2. Methods

We analyzed the evolution of the N cycle in the agro-food system at the regional scale. Crop production and pasture production are connected with livestock farming to supply food to the local population, and also with the export or import of agricultural products to or from other regions. Using N embedded in proteins or in N fertilizers as a marker, the structure of the agro-food system is presented in a diagram showing N flows through the main transformation compartments involved in the system, namely, crop and grass production, livestock breeding, food processing, international trade and final human consumption (General Representation of Agro-Food Systems, GRAFS) (Billen *et al* 2014, Le Noë *et al* 2017, Billen *et al* 2018).

To construct the GRAFS diagrams, and since some statistics were available at the country scale only, we considered 11 out of the 22 countries in the Mediterranean Basin. In these countries, more than 50% of the crop and grassland area is under Mediterranean conditions: Portugal, Spain, Italy, Albania, Greece, Turkey, Cyprus, Israel, Tunisia, Algeria and Morocco (supplementary table S1). Countries presenting a marked temperate-to-Mediterranean gradient (France) or with incomplete observations (Palestine) or those with relevant data missing for other reasons (Syria and Libya), were not included. In total, the selected countries comprise 91% of the crops and grasslands under the Mediterranean climate in the Mediterranean Basin and 61% of the crops and grasslands under the Mediterranean climate worldwide. The crop mix at country level was estimated by clustering crop data from FAOSTAT into generic groups, namely, cereals, legumes, roots, oilseed, horticulture, permanent crops, etc. N budgets in cropping systems of the Mediterranean biome were calculated by combining spatially explicit, crop-specific data sets on crop and livestock distribution, yield and N input with country-level data from FAOSTAT (see a full description of the procedure in the supplementary information).

Water–N interaction was analyzed in Spain as a putatively representative Mediterranean country with a strong precipitation gradient with cereal crops under rainfed and irrigated conditions. Data on yearly crop-specific yield and N fertilization rates (synthetic and organic) were provided by the Spanish Ministry of Agriculture for wheat cultivation, split into rainfed and irrigated systems at provincial level (40 Spanish provinces with Mediterranean climate) for 26 years (1990–2015). Yield instability during that particular period was calculated separately for rainfed and irrigated conditions at provincial level by means of the coefficient of variation of crop yield in each province. Yearly precipitation data were obtained from the CRU global data set (Seager et al 2019). Irrigation water application was estimated for each crop in each province at monthly time steps based on crop evapotranspiration, which was calculated as described in Vila-Traver et al (2021). Crop water requirements were calculated by subtracting the effective precipitation from crop evapotranspiration. Irrigation water application was calculated by dividing the crop water requirement by the water efficiency of each type of irrigation technology (Wriedt et al 2009).

Regional crop nutrient budgets at the Spanish provincial level include synthetic and organic N fertilizers and atmospheric deposition, as inputs (Nin), and N extracted from the main harvest as outputs (NY). NUE corresponds to NY/Nin and N surplus to Nin−NY (Zhang et al 2020). The averaged NY versus Nin response curves was estimated for each province and fitted by the one-parameter hyperbolic curve:

$$\mathrm{NY} = \mathrm{Y_{max}Nin}/\left(\mathrm{Nin} + \mathrm{Y_{max}}\right),$$

where the parameter Y_{max} = (Nin × NY)/(Nin s−NY) represents the maximum yield under N saturation conditions. This is commonly used in regional and large-scale approaches (Lassaletta et al 2016, Mueller et al 2017, Mogollón et al 2018).

3. Trajectories of N use in the whole agro-food system in the Mediterranean Basin

The structure of the agro-food system for the periods 1961–1965 and 2009–2013 in the selected Mediterranean countries is represented in diagrams showing N fluxes through the main compartments. The components involved are crop and grass production, livestock breeding, food transformation, international trade and human consumption (figure 3). In the early 1960s, Mediterranean countries as a whole (as defined in section 2) were close to self-sufficiency for feeding their population of 166 million inhabitants, with a diet composed of 3.1 kg N cap^{-1} yr^{-1} of proteins from vegetal origin, and 1.5 kg N cap^{-1} yr^{-1} of animal proteins, including 0.2 kg N cap^{-1} yr^{-1} from fish. Livestock manure, together with symbiotic fixation of atmospheric N_2 and atmospheric deposition of Nr, was the dominant form of N fertilizer input to cropland, even if synthetic fertilizers already contributed significantly at that time. Livestock, dominated by ruminants, thus played a major role by conveying N from permanent and semi-natural grassland to cropland soils. Imported feed was of limited significance, and approximately 60% of crop production was dedicated to animal feeding. The remaining crop production was used for local human nutrition together with animal produce, such as meat and milk. Net imports of animal and vegetable food products were minimal.

During the past 50 years, the population of the Mediterranean Basin countries increased by 80% and its diet changed as a result of the total protein ingestion increasing by 30% (from 4.6 to 6.1 kg N cap^{-1} yr^{-1}), while the share of animal proteins in this total rose from 32% to 43%. This transition has been more evident in European Mediterranean countries and Israel than in the rest of the basin. However, these changes prevented protein consumption per capita from falling below WHO recommendations at any time. But these changes also indicate the gradual abandonment of the so-called Mediterranean diet, which was replaced by a 'Western-type' diet that totally alters the recommended relative proportions of each food group and negatively affects human health (Blas et al 2019). This dietary change has profoundly impacted the structure of the entire agro-food system, with a considerable intensification of animal breeding; livestock production increased 3.5-fold, mostly in terms of monogastric animals feeding on grains.

Despite a concomitant intensification of cropping systems, increasing its use of synthetic N fertilizers by a factor of three, the production of forage and cereal was not enough to feed the livestock. The rising demand for feed occurred in parallel to a change in the crop mix of the region. The cultivation of cereals was reduced by 16% of the region's total cropland area during the past few decades. Only Morocco significantly increased cereal cropping areas. Legume crop surfaces decreased in European countries, but not in south and east Mediterranean countries. On the other hand, the cultivation of oilseed with potential allocation to animal consumption has almost doubled, although today its share is still too low to provide a sustained source of protein (5.2% of cropland).

Massive imports of feed, namely, soybean and maize from the Americas were required for livestock production (Lassaletta et al 2014b, Leip et al 2015, Billen et al 2019). In addition, considerable net imports of animal food and cereals were needed to feed the human population. As a result, the external dependency of the agro-food system of Mediterranean countries, defined as the ratio of net import of food and feed proteins to the local animal and human ingestion rose from 6% in 1960 to 30% in 2013. This trend contributes to surpassing the carrying capacity of the region by a factor of 2.5 (Galli et al 2015).

Trends in agro-food system components from both the demand side and supply side indicate massive temporal changes (figure S2; supplementary information). The gradual increase in animal and human consumption cannot be met by the increase in cropland yield and the stagnation of grassland production, requiring recourse to increased importation. Thus, the level of external dependency parallels this gradual increment (figure S3; supplementary information).

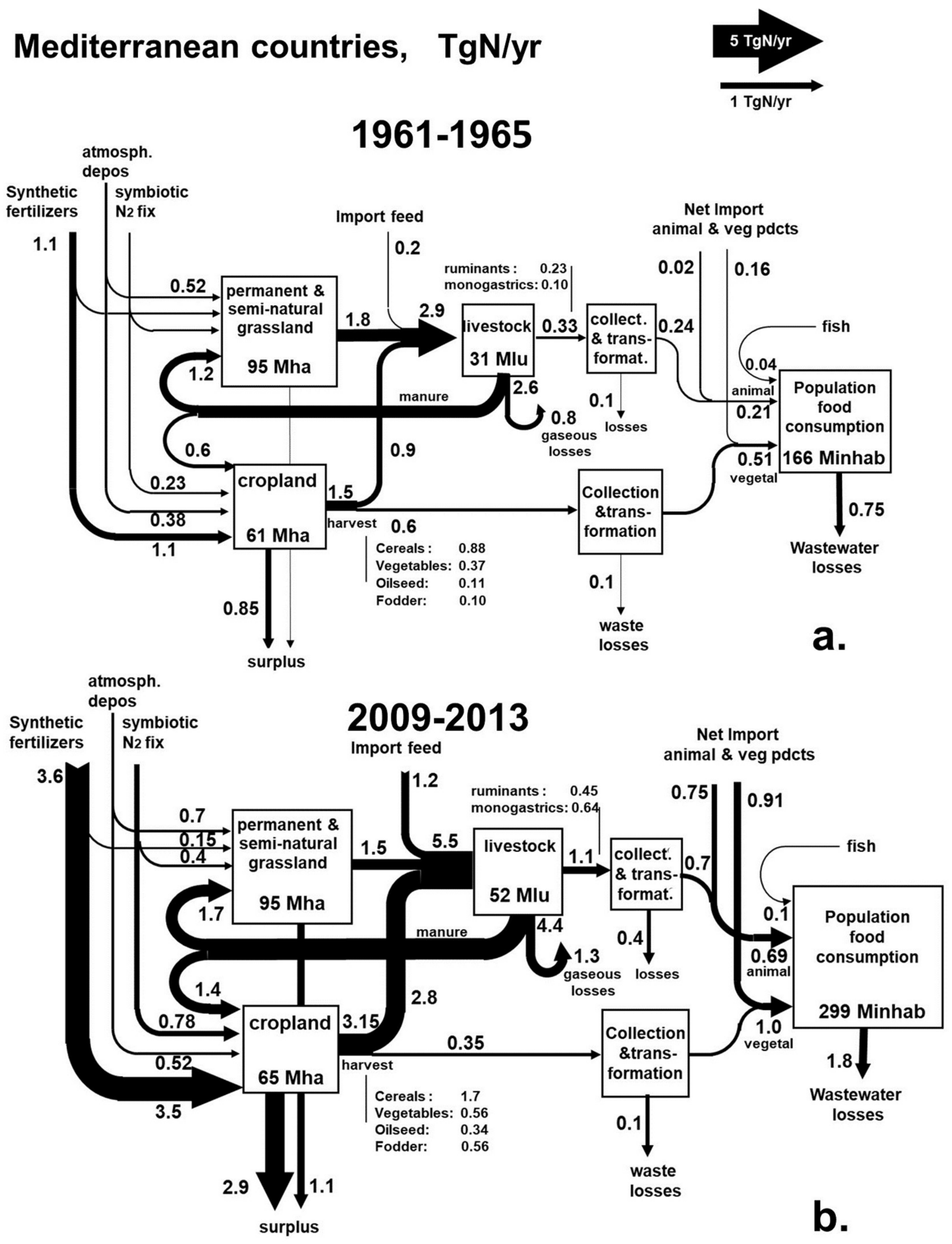

Figure 3. GRAFS diagramatic representation of countries in the Mediterranean Basin with more than 50% of their agricultural land under Mediterranean climate (11 selected countries, see section 2), in 1961–1965 (a) and 2009–2013 (b).

The yield of arable land increased by a factor of two over the past 50 years. This is largely the result of increased N fertilization. The trajectory of N yield versus soil N input follows the same distinct hyperbolic relationship with a $Y_{\max}$ of approximately 60 kg N ha^{-1} yr^{-1} until the end of the 1970s (figure 4). From this time onwards, improvements in yield were achieved with much lower increases in fertilization than in the previous decades. Consequently, the surplus, i.e. the excess total N soil input over N in harvested products, increased until the early 1980s and then leveled off until the present period. Crop NUE decreased from 60% in the early 1960s to 44% in the 1980s, and then increased again up to 50%. There are several reasons to explain the changes observed in the aggregated N crop yield and NUE. On the one hand, the expansion of irrigated land (see figure 2) and other agronomic improvements, such as better fertilization and irrigation techniques, as well as the development of improved crop varieties through

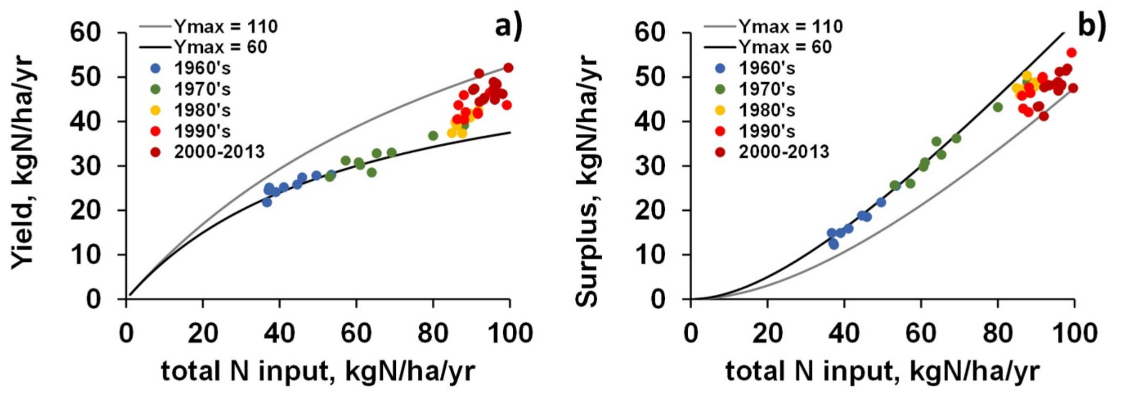

Figure 4. Intensification and improvement of cropping practices of countries in the Mediterranean basin over the period 1961–2013: relationship between yield (in terms of protein content of harvested products per hectare) and total N soil input (a) and corresponding surplus (b), N soil input in excess over harvested N.

breeding and selection, had a significant effect on the observed yield increases. For example, wheat and tomato yields grew between two- and three-fold, and two- and four-fold, respectively. On the other hand, over-fertilization may have moved the system to the inefficient part of the yield versus N input response curve. In addition to these agronomic factors, the aforementioned changes in the crop mix may have had an important effect on the NUE of the system (Zhang *et al* 2015). High N input/N output systems, such as cereals, were replaced by low N input/low N output systems such as permanent crops, systems that have doubled in existence. This is linked to the specialization of Mediterranean agriculture in vegetables, fruits and olive oil for export to temperate European countries. Counterintuitively, the cultivated area with high N input/low N output systems, such as horticulture has been reduced in European Mediterranean countries while their total production has increased, indicating high intensification practices (e.g. greenhouses). By contrast, both the agricultural area and productivity of horticulture substantially increased in south and east Mediterranean countries.

The intensification of animal production, accompanied by an increase in the share of monogastric animals (representing 10% of the livestock units in 1961 and 27% in 2013), resulted in a limited improvement in aggregated protein conversion efficiency from 8% in the 1960s to 13% (at the herd level and considering edible protein only) in recent years. These NUE values aggregate many contrasting types of livestock systems. The most intensified systems have increased N efficiency significantly, gradually reducing the total demand for feed (expressed as dry matter) to produce 1 kg of meat during the past decades and subsequently reducing the N excretion kg^{-1} meat during recent years (Lassaletta *et al* 2019, MAPA 2020a, 2020b). These systems strongly depend on imported feed, causing the externalization of N impact (Bai *et al* 2014, Quemada *et al* 2020a) and increasing the input of new N embedded in the feed via international trade.

Alongside the intensification of both livestock and crop farming, environmental N losses increased considerably, as shown by the rise in NANI from 620 to 1900 kg N km^{-2} yr^{-1} (figure S3; supplementary information). While the input of synthetic N fertilizers was stabilized from 1985, the net import of food and feed steadily increased and today accounts for 2 Tg N yr^{-1}, i.e. 50% of synthetic fertilizers. This massive and increasing amount of feed, largely transformed into manure, represents a huge challenge for cropping and livestock systems. As a result of these changes, agricultural surplus and gaseous N emission from livestock breeding have also increased. Clearly, the trend towards losing self-sufficiency of the agro-food system was accompanied by the opening of nutrient cycles. The period from 1960 to the 1980s experienced the fastest increase in environmental losses, mostly from cropland. A stabilization of these losses was observed in the latest period in parallel to NUE increases.

4. Relevance of the interaction between N and water exemplified in Spanish regions

The crop yield response to water and N availability was stated as a paradigm of co-limitation, the simultaneous limitation of plant productivity by multiple resources. This co-limitation has been well studied in cereal crops of Mediterranean-type environments in Australia and Europe (Cossani and Sadras 2018). Prolonged water stress leads to yield reduction and decreased N uptake as well as NUE, whereas insufficient N may limit water response and water use efficiency (WUE) (Savin *et al* 2019). The implication of co-limitation is that strategies aiming to maximize crop response to both resources should ensure that water and N are equally available (Quemada and Gabriel 2016, Hochman and Horan 2018). In addition, water is one of the main drivers of N losses at the cropping system level, as excessive water input leads to leaching loss and favors denitrification, thereby enhancing N_2O emission (section 6). As a consequence, the proper management of the interaction between NUE and WUE is required in many cropping systems in order to reach a compromise between productivity and environmental sustainability.

Water availability is thus a limiting factor that determines the pattern of land use in Mediterranean areas (López-Bellido 1992). High solar radiation and extended frost-free periods make these regions capable of attaining high crop yields. When water is not available, agricultural systems are either adaptations of woody crops to xeric conditions (i.e. olive orchards, vineyards and oak dehesas) or low-productivity rainfed arable crops (i.e. barley, wheat, sunflower and leguminous grain) subject to high yield variability. N application in these rainfed systems tends to be opportunistic, depending on the weather forecast, and the NUE attained is determined by the adjustment of fertilization to the actual crop growth limited by rainfall (Sadras *et al* 2003). Water application to compensate for the frequent spring and summer droughts contributes not only to stabilized productivity, but to crop diversification, providing the opportunity for more complex rotations including highly profitable crops (i.e. horticultural) usually characterized by a demand for large input including N. However, this increase in productivity is not always associated with an enhancement of NUE because crops are frequently over fertilized or over watered in order to achieve high yields (Quemada *et al* 2013, Salazar *et al* 2019), thereby generating a high risk of N leaching (section 6). Therefore, increasing WUE and NUE in the Mediterranean regions is challenging and requires the development of specific practices adapted to rainfed and irrigated systems.

The analysis of the N budgets for wheat cultivation under rainfed and irrigated conditions at the province scale in Spain clearly illustrates the agro-environmental implications of N–water co-limitation. This analysis includes information on N input and wheat yields for 40 Spanish provinces (administrative units ranging from 5000–20 000 km^2) over 26 years (1990–2015). These provinces have a Mediterranean climate but different levels of annual precipitation (province range 341–869 mm yr^{-1}), temperature (province annual mean temperature range 11 °C–18 °C) and latitude (province range 36.5°–42.8° latitude N). The average yield per province ranged from 0.9–2.5 t ha^{-1} yr^{-1} for rainfed systems and 2.6–5.5 t ha^{-1} yr^{-1} for irrigated systems.

Yield instability was significantly lower in irrigated than in rainfed systems in all the provinces (figure 5(a)). Thus, irrigation consistently homogenized yields across Mediterranean regions. We found a strong relationship between the mean total water input (precipitation and irrigation) and mean yield in rainfed and irrigated systems (R^2 = 0.79), explaining the strong effect of water on yield (figure 5(b)). In response to the higher yields expected in irrigated systems, N fertilization rates are significantly higher (figure 5(c)). Water–N interactions in Mediterranean rainfed systems were revealed through the robust relationship ($R^2 = 0.46$) between precipitation and Y_{max} in rainfed systems (figure 5(d)), new water input through precipitation increase Y_{max} and therefore the capacity of the crop to respond to new N addition. In irrigated systems, the relationship is lost, there is no water limitation, and other factors affect crop response to N addition.

This relationship has important implications for the agro-environmental management of fertilization in rainfed systems. In regions with water scarcity, crop N uptake is rapidly saturated, and N surplus accompanied by pollution (e.g. leaching during rainfall events) could occur at low fertilization rates (e.g. Albacete province, figure 6). However, in areas where water availability is higher, together with other drivers, such as less heat, which is common in the more northern latitudes, rainfed systems had higher Y_{max} values that were closer to those of irrigated systems. Here, the same fertilization rates may lead to higher yield responses (e.g. Burgos province, figure 6). Even in these wetter regions, a dry year can significantly reduce Y_{max}, increasing N surplus and therefore the risk of N leaching.

In summary, for rainfed systems, farmers have the difficult task of adjusting fertilization in order to maximize yields while reducing N surplus in a highly variable environment. The mean fertilization rates per province ranged from 42–150 kg N ha^{-1} yr^{-1} in rainfed systems and from 77–186 kg N ha^{-1} yr^{-1} in irrigated systems. In general, the actual fertilization rates (estimated as the basis for the national inventories of greenhouse gas emissions) are lower in the rainfed systems of those provinces with lower precipitation and faster N saturation (figure 7), and, with some exceptions, moderate N surplus (usually lower than 50 kg N ha^{-1} yr^{-1}). Poor planning with high fertilization rates in a very dry year results in disproportionately low NUE and significantly high emissions of Nr to the environment. As described in section 3, increasing livestock production is generating a growing amount of manure that has to be properly managed and recirculated to crops. The application of this manure has to take into account the distinct response of cropping systems to N application. For example, the EU Nitrates Directive limits the application of N in manure to 170 kg N ha^{-1} yr^{-1} for areas considered as NO_3^- vulnerable zones. These rates, albeit legal, would strongly reduce NUE in the drier regions, severely impairing the environment (figure 7).

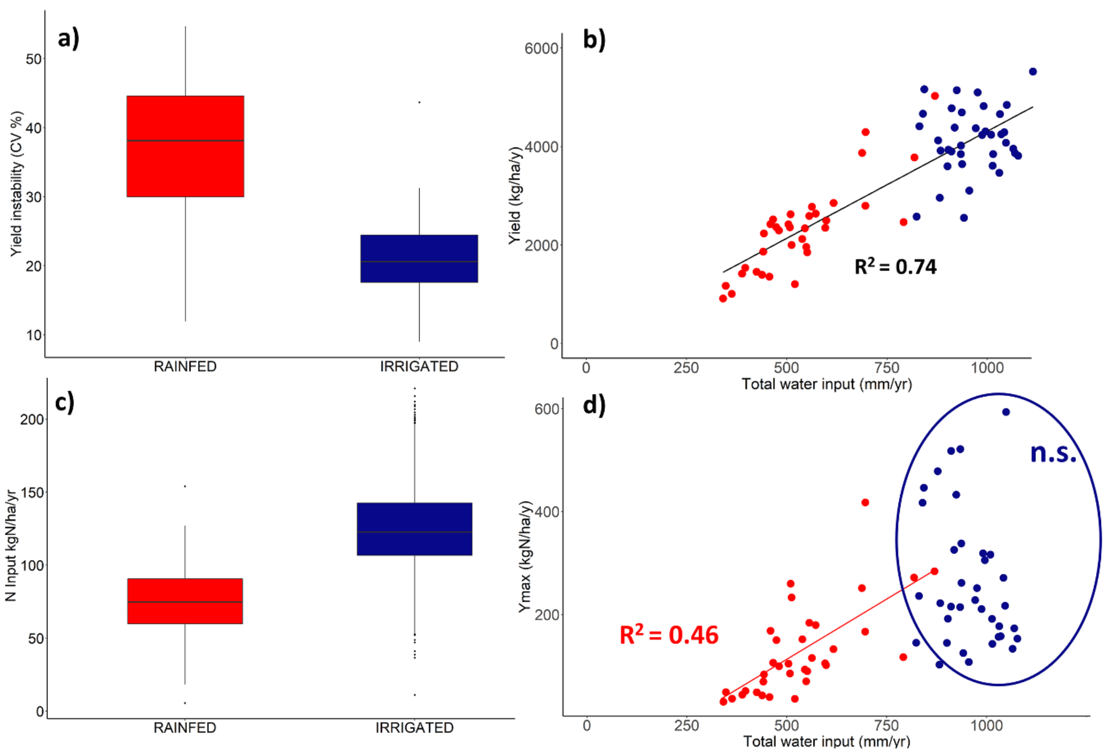

Figure 5. Yield instability of wheat in rainfed and irrigated systems for the 40 Spanish provinces under Mediterranean conditions (1990–2015) (a); relationship between mean water input (precipitation + irrigation) and mean yield for each of the 40 provinces for rainfed and irrigated systems (b); mean N fertilizer input (1990–2015) of the 40 provinces for rainfed and irrigated systems (c); and relationship between total water input and Y_{max} (the parameter of the hyperbolic response curve that relates yield and N inputs representing maximum yield at saturating N rates), $R^2 = 0.46$ for rainfed systems, and no significant (ns) relationship for irrigated crops (d).

5. Interaction of N use with adaptation to climate change

As a summary of the climate change conditions in the Mediterranean regions described in section 1, increases in the maximum and minimum temperatures and in atmospheric CO_2 concentration are expected to be associated with decreased and more unpredictable precipitation. These changes combined will result in stronger fluctuations in water stress for crops (figure 4; supplementary information). In addition to these climatic effects, 'elevated atmospheric CO_2 concentration' (hereafter eCO_2) also affects plant N dynamics. Therefore, under climate change scenarios with eCO_2, N dynamics with water and temperature interaction have to be comprehensively studied. These effects are in general less understood. However, during the past few decades, free air CO_2 enrichment (FACE) experiments (O'Leary *et al* 2015) and other laboratory or modeling studies indicate that CO_2 might enhance photosynthesis in C_3 plant species, such as wheat, rice and barley (Ainsworth and Rogers 2007), especially under dry conditions (Bishop *et al* 2014), as well as N fixation by legumes (Parvin *et al* 2018). This might increase the total N crop requirements to build more biomass (Ainsworth and Rogers 2007). Under elevated CO_2 conditions, transpiration benefits from reduced stomata opening to capture the same amount of CO_2. Therefore, low stomatal conductance, more conservative water use and higher transpiration efficiency may jointly increase WUE as well as biomass and total water use (Houshmandfar *et al* 2018). On the negative side, a lower N content in wheat grain has been reported under high CO_2 conditions (Tausz *et al* 2017). For legumes, however, reduced N content in grain following a heatwave might be restored with eCO_2 (Parvin *et al* 2020).

Adaptation to climate change in Mediterranean cropping systems needs to take into account these interactions and how they are modified by heat and water stress, as both of these adverse conditions for crop growth are projected to occur more frequently in the future (Trnka *et al* 2014). Briefly, positive (crop growth stimulation and water saving) and negative (grain N dilution) eCO_2 effects alike may be diminished under stressful conditions (Ainsworth *et al* 2008, van der Kooi *et al* 2016). In addition, stress limits the crop response to N, as some part of the fertilizer cannot be used while crop growth is water- or temperature-limited (Savin *et al* 2019). This implies low NUE and high N surplus and greenhouse gas emissions (Quemada and Gabriel 2016) (section 4). Under these conditions, the adaptation of annual crops in Mediterranean environments usually implies the use of varieties with high transpiration efficiency

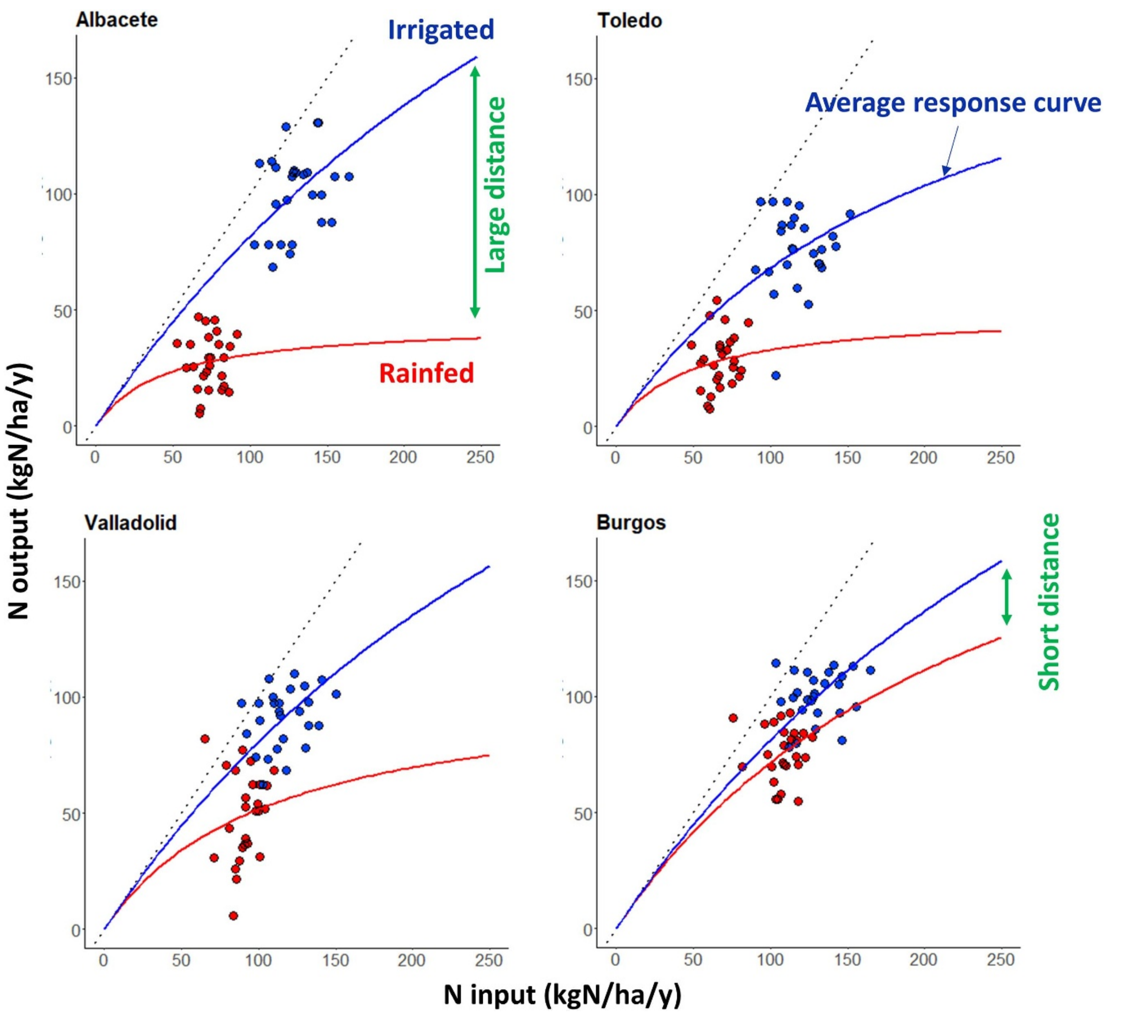

Figure 6. Yield versus total N input (1990–2015) in four contrasting Spanish provinces. Curve is the mean yield fertilization response curve estimated by using the average input and yield during the study period (1990–2015) for rainfed (red) and irrigated (blue) systems. Annual mean precipitation: Albacete (388 mm yr^{-1}), Toledo (426 mm yr^{-1}), Valladolid (465 mm yr^{-1}) and Burgos (688 mm yr^{-1}).

traits and early sowing dates (Porter *et al* 2014). The aim of these strategies is to increase water accumulation over the crop cycle and restore the duration of the vegetation period shortened by warming, which accelerates crop development. The target then is to identify the optimum combination of crop phenology and sowing date, selecting the earliest possible sowing date to ensure that: (a) there is enough soil water for successful germination, emergence and canopy establishment, (b) the crop will flower after the last spring frosts and before late spring–early summer heatwaves, and (c) most of the grain filling happens before the dry summer period (Kirkegaard and Hunt 2010, Christy *et al* 2018, Ruiz-Ramos *et al* 2018). These are already the goals of current strategies recommended in Mediterranean systems, together with management for conserving soil moisture and reducing soil and canopy temperature. For climate change adaptation, the main novelty is that the suitable sowing window could become narrower in the future, as may the range of suitable varieties in terms of phenology, potential yield and resistance to stress. Therefore, in these systems, the fulfilment of mitigation targets to reduce Nr emissions within the limit of effective adaptation will require the combination of new or existing tailored varieties, optimized management for soil and water conservation, and improved efficiencies, supported by knowledge and technological solutions (Springmann *et al* 2018).

Farm-level management options, such as agroforestry are currently studied in detail for their potential to improve the sustainability of the Mediterranean farming system, especially under climate change (Arenas-Corraliza *et al* 2016, Mosquera-Losada *et al* 2018). Among others, they offer access to deeper soil water tables (Cardinael *et al* 2015) and they reduce evaporation due to the wind-break effect of trees (Campi *et al* 2012), thereby enhancing groundwater recharge (Kay *et al* 2019), which are important issues regarding climate projections for the Mediterranean regions. While it has been shown that agroforestry can increase soil fertility and nutrient availability

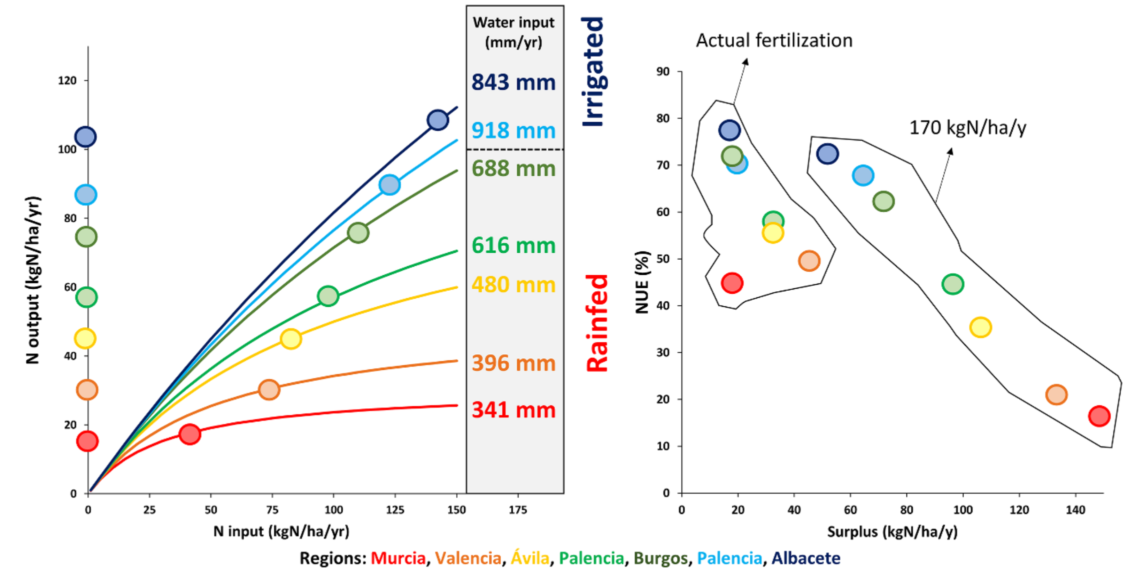

Figure 7. Left panel represents N yield (N output) versus fertilization response curves under rainfed and irrigated conditions in several Spanish provinces in a precipitation gradient (period 1990–2015). Water input (mm yr^{-1}) is the mean annual water input including precipitation and irrigation. Averaged fertilization rates and yields (1990–2015 averages) are provided by the Spanish Ministry of Agriculture. Right panel represents N surplus and NUE resulting from the current fertilization rates and also after applying a hypothetical rate of 170 kg N ha^{-1} yr^{-1}, which is the legal limit of the application of N in manure in the Nitrate Vulnerable Zones.

in Europe (mostly Mediterranean cases) and North Africa (Torralba *et al* 2016, Zayani *et al* 2020), and that tree–legume interaction maintains a sufficient level of N fixation under the shade of trees in a Mediterranean agroforestry system (Querné *et al* 2017), the implications of agroforestry for nutrient acquisition under water and heat stress are still poorly understood (Guillot *et al* 2019). As stated by (Isaac and Borden 2019), extensive research is needed on how agroforestry practices stabilize key nutrient acquisition patterns in the face of environmental change.

Conservation agriculture—with no (or reduced) tillage, permanent organic soil cover and crop diversification—is another innovative agricultural system that has been suggested for climate mitigation and adaptation in the Mediterranean due to its soil and water conservation capability (Kassam *et al* 2012). The physical, chemical and biological properties of soil have been improved, resulting in higher yields for dry conditions due to improved soil moisture availability (Mrabet 2002). Although authors logically hypothesize on improved nutrient availability, studies indicate that extractable N is not significantly greater under CA (López-Garrido *et al* 2011). Measurements at all soil depths are needed to better understand the effect of CA on nutrient distribution and its potential contribution to sustainable Mediterranean agriculture (Mrabet *et al* 2012). Moreover, in an Italian dry environment, the limited amount of wheat crop residues during the transition phase to CA required high N fertilization to maintain yields (Galieni *et al* 2016).

6. Emission of Nr compounds: drivers and adapted solutions

6.1. Ammonia

Similar to temperate agroecosystems, the main pathways of Nr loss from fertilized crops under Mediterranean conditions are NH_3 volatilization to the atmosphere and NO_3^- leaching to hydrosystems (Jarvis 2011, Quemada *et al* 2013, Sanz-Cobena *et al* 2014). NH_3 volatilization in cropping systems mainly occurs following NH_3 production through mineralization or application of NH_4^+-containing fertilizers, urea- or manure- and other organic-based N fertilizers. The process of NH_3 volatilization is physicochemical (Walker *et al* 2013). Meteorological conditions (air temperature, wind speed near the soil surface, atmospheric stability and rainfall), soil properties (e.g. texture, cation exchange capacity and pH) and N management options are the main drivers involved (Bouwman *et al* 1997). Most of these factors are greatly determined by Mediterranean unique pedoclimatic conditions and management practices, the latter being shaped by the dominant types of crop and livestock systems present in these areas (Sanz-Cobena 2010).

Atmospheric conditions greatly influence NH_3 volatilization rates (Cape *et al* 2009). Typical stable atmospheric conditions with calm periods of wind (commonly associated with high pressures) under Mediterranean conditions may lead to low volatilization rates following fertilization, mainly in the winter and during the night (Theobald *et al* 2015). Lower EFs (the percentage of applied N that is lost as

NH_3) are expected for winter crops compared with irrigated summer crops, even if similar agricultural practices are used. The rainfall regime is also critical for the enhancement (or mitigation) of NH_3 loss. Sanz-Cobena *et al* (2011) showed that more than 7–14 mm of water application immediately after fertilizer application is an effective strategy for abating NH_3 volatilization due to enhanced solubilization and the incorporation of the fertilizer into the upper soil. In contrast, under low rainfall (i.e. 3 mm) conditions, NH_3 volatilization increases because high concentrations of soluble N forms might be kept at the soil surface and hydrolysis rates are triggered following urea application (Sanz-Cobena *et al* 2011). Based on this, applying water immediately after surface fertilization would be an efficient NH_3 abatement strategy in irrigated Mediterranean agroecosystems. In rainfed crops, as the Mediterranean climate is characterized by a limited number of rainfall events, the possibility of NH_3 mitigation due to rainfall requires a good weather forecast.

Regarding fertilization practices, in Mediterranean cropping systems, even under conditions of high atmospheric stability, the risk of NH_3 volatilization is greater if urea or liquid manure (i.e. slurries) is surface-applied (Marchetti *et al* 2004, Sanz *et al* 2010, Abalos *et al* 2012, Yagüe and Bosch-Serra 2013, Bosch-Serra *et al* 2014, Recio *et al* 2018, Sanz-Cobena *et al* 2019). The use of urea as a synthetic N fertilizer has increased in recent decades in Mediterranean cropping systems, as in the rest of the world (IFASTAT, 2020). However, the large NH_3 losses associated with its application, triggered by the hydrolysis-mediated increase in soil pH, necessitate the implementation of specific NH_3 abatement strategies for this fertilizer (Bittman *et al* 2014). The most common abatement practices are the incorporation of urea immediately following application, mechanically or by means of water (Sanz-Cobena *et al* 2011, Rochette *et al* 2013), or the use of urease inhibitors (Sanz-Cobena *et al* 2014, Recio *et al* 2020). These synthesized compounds reduce the rate of urea hydrolysis, thus allowing for its incorporation into the soil (Sanz-Cobena *et al* 2008, 2017, Turner *et al* 2010, Fu *et al* 2020). Pollution swapping (such as N leaching) might also occur if these strategies are improperly managed (Sanz-Cobena *et al* 2017). In contrast, due to the predominant nitrifying conditions in rainfed systems under Mediterranean conditions, the decreased NH_4^+ pool induced by urease inhibitors can have a co-benefit due to mitigated N_2O emissions from this microbiological process (Sanz-Cobena *et al* 2016). The incorporation of urea by water in irrigated systems is facilitated (Sanz-Cobena *et al* 2011), thus avoiding excessive soil compaction as well as greenhouse gas emissions from machinery. The increasing generation of animal manure in certain Mediterranean areas (e.g. Italy and Spain) has triggered NH_3 emissions due to the surface application of slurries. Although less effective than injection (Sanz-Cobena *et al* 2019), the possibility of adapting existing on-farm equipment to mix the slurry with the soil makes this option technically suitable and cost-effective (Bittman *et al* 2014).

6.2. Nitrous oxide

Studies on N_2O emissions in Mediterranean cropping systems are underrepresented compared to other temperate areas (Aguilera *et al* 2013b), and studies deciphering N_2O formation pathways are conspicuously few. The few published studies to date point to nitrification and nitrifier-denitrification as particularly relevant mechanisms in Mediterranean soils (Zhu *et al* 2013). The prevalence of distinct formation pathways in Mediterranean soils, driven by the specific climatic conditions and agronomic practices, will ultimately determine the best N_2O mitigation strategies.

There is ample evidence that N_2O EFs (the percentage of applied N that is lost as N_2O) in Mediterranean rainfed cropping systems (EF: 0.27% according to Cayuela *et al* 2017) are significantly lower than in other temperate areas (0.9% according to Stehfest and Bouwman 2006). However, as irrigation is a common practice in Mediterranean cropping systems in the summer, it changes the moisture pattern and substantially increases the total amount of water in the soil. As a consequence, EFs in irrigated crops (0.63%) are significantly higher than in rainfed crops (0.27%) (Aguilera *et al* 2013b, Cayuela *et al* 2017).

In both rainfed and irrigated systems, the adjustment of N application to crop needs is one of the best recommended strategies to mitigate N_2O emission (Guardia *et al* 2018). In addition, the use of nitrification inhibitors with both synthetic and organic N fertilizers (Sanz-Cobena *et al* 2012, Abalos *et al* 2014, Gilsanz *et al* 2016, Guardia *et al* 2017b) is also an effective mitigation strategy.

The type of irrigation directly determines N_2O emissions (Cayuela *et al* 2017). Localized irrigation systems such as drip irrigation significantly abate N_2O losses due to a highly localized moist area. In contrast, sprinkler-irrigated fertilized systems are an important source of N_2O emissions due to the increased soil moisture in large surface areas (Guardia *et al* 2017b). Nevertheless, recent studies show how optimized sprinkler irrigation systems can considerably reduce N_2O emissions in intensive maize crops (Franco-Luesma *et al* 2019, 2020).

Precipitation following long drought periods promotes high N_2O emissions. This is very common in Mediterranean soils in the summer or following the first rainfall in the autumn (Cárdenas *et al* 1993). A recent meta-analysis demonstrates that flooding the soil after extended periods of drought produces a larger pulse in N_2O emissions, compared with soils that were already moderately wet before the flood event (Barrat *et al* 2020). These pulses are likely more common under Mediterranean conditions than in temperate agroecosystems where pulses are usually due to freeze–thaw events (Sanchez-Martin et al 2010).

Another important factor modulating N_2O emissions in Mediterranean cropping systems is soil pH. Mediterranean soils are predominantly neutral or alkaline (Slessarev et al 2016) and this has important implications for the final ratio of denitrification products. Cayuela et al (2013) found an average $N_2O/(N_2 + N_2O)$ ratio of 0.4 in five Mediterranean high-pH soils, whereas the average value for other temperate soils was 0.8. This implies that the last step of denitrification (the transformation of N_2O to N_2) was enhanced in Mediterranean soils. A recent global meta-analysis of 1104 field measurements found soil pH to be the most relevant parameter defining regional N_2O emissions, with significantly lower EFs for soils with increasing pH (Wang et al 2018).

6.3. Nitric oxide

Together with N_2O, NO is a by-product of nitrification (Medinets et al 2015), and is thus particularly common in Mediterranean rainfed systems (Vallejo et al 2005, Meijide et al 2007, 2009, Sanchez-Martín et al 2010, Sanz-Cobena et al 2012, Guardia et al 2017a, 2017b, Recio et al 2019). Significant emissions of NO, a precursor of tropospheric O_3, have been reported after N fertilization with either organic or synthetic N fertilizers and in both rainfed and irrigated systems, particularly if drip-irrigation is performed (Guardia et al 2017a). These authors associated increased NO fluxes with enhanced nitrification in the proximity of the wet front that surrounds the irrigation bulb. There is evidence that NO_x (both NO and NO_2) emission exponentially increases with temperature and that, after soil rewetting, strong pulses of NO_x emission are produced in high-temperature regions (Garrido et al 2002). In the Mediterranean region, as mentioned earlier, the pulses that occur after rewetting result in high contributions to the total NO budget. Analyzing the different agroecosystems, irrigated crops are also important contributors of NO, because the importance of nitrification and the temporal pattern of soil moisture occurred when the soil temperature was high, with frequent irrigation–drying cycles. Abating soil NO_x emissions should be considered in future efforts to improve regional air quality in the areas surrounding irrigated crops, because these emissions contribute to the high concentration of O_3 found in many rural areas in the Mediterranean region (Calvete-Sogo et al 2014).

6.4. Nitrate and loss to the hydrosphere

In Mediterranean irrigated agriculture, NO_3^- leaching is strongly dependent on water application. Intensive irrigation together with over-fertilization is the main cause of NO_3^- leaching (Isidoro et al 2006, Cavero et al 2012, Laspidou and Samantzi 2014, Lasagna and De Luca 2019). Excessive water is often applied either to avoid salt accumulation in the soil or to compensate for the heterogeneity of the water-delivery system, enhancing NO_3^- leaching during crop growth (Díez et al 2000). Low crop N availability is then compensated by increasing fertilizer rates leading to a vicious cycle characterized by low WUE and NUE. Therefore, the two main drivers of NO_3^- leaching are water percolation and soil inorganic N accumulation, and strategies to mitigate loss are oriented towards keeping these processes below sustainable thresholds.

Strategies to improve water management rely on adapting water application to crop requirements and are mainly based on improving irrigation schedules or technologies. Irrigation should be scheduled to avoid over-irrigation and limit water percolation (Zinkernagel et al 2020). In addition, water delivery technology may have a major impact on the main N processes governing N losses. Drip and sprinkle irrigation have the potential to localize water in the root zone and limit percolation and NO_3^- leaching (Causape et al 2006, Vazquez et al 2006, Cavero et al 2012, Garcia-Garizabal et al 2014, Malik et al 2019), whereas with flood irrigation it is difficult to achieve high water efficiency and control leaching loss (Garcia-Garizabal et al 2012).

Adjusting N fertilization, both synthetic and organic, to crop requirements remains crucial in order to avoid soil N accumulation and mitigate NO_3^- leaching (Quemada et al 2013). Intensive livestock farming associated with irrigated land is common in Mediterranean areas, and avoiding the excessive application of manure to cropland is highly recommended (Mantovi et al 2006, Nikolaidis et al 2009, Yagüe and Quilez 2010). In the Po valley, establishing a N balance to minimize N surplus was identified as the first step towards mitigating the effect of high livestock concentration that leads to poor water quality (Perego et al 2012).

Replacing the traditional fall–winter fallow by cover crops in irrigated areas reduced NO_3^- leaching by 35% on average in a meta-analysis of irrigated land (Quemada et al 2013). Compared to fallow soils, cover crops minimize the risk of N leaching by reducing water percolation due to an increase in evaporation, assimilating the soil residual N after harvesting the summer crop, thus reducing NO_3^- concentration in the leachate, and enhancing microbial N immobilization associated with C input from cover crop roots (Gabriel et al 2012, Benoit et al 2016, Thapa et al 2018). Replacing the fallow with a non-legume is more efficient than with a legume in reducing leaching, and mixes of grass/legume greatly reduce leaching with respect to the fallow (Tosti et al 2014). In addition, the combination of N recycling and the boost of soil N mineralization in the short and long term after cover crops may allow one to reduce fertilization rates without affecting yields. Indeed, the increase in N_2O emissions caused by legume cover crops could be offset by the N fertilizer savings and its associated indirect CO_2 emissions (Guardia *et al* 2019, Quemada *et al* 2020b). Mediterranean irrigated soils are generally prone to high mineralization rates, and strategies that enhance soil stable organic compounds, allow for the recovery of soil physical properties and fertility in the long term, and contribute towards mitigating NO_3^- leaching loss (Diacono and Montemurro 2010, García-González *et al* 2018).

An additional pathway of N loss that is influenced by practices, such as irrigation and cover cropping is, the leaching of dissolved organic N (DON). Soil water content regulates the ratio of DON and inorganic N forms in Mediterranean soils, being DON dominant under various plant communities during wet periods (Delgado-Baquerizo *et al* 2011). In an irrigated maize field in central Chile, DON leaching under a grass cover crop was twice the rate of NO_3^- leaching, even if the total N loss wasreduced compared with the fallow (Salazar *et al* 2019). Although the full ecological significance of DON loss remains unclear, it may represent a large part of the total dissolved N, and monitoring DON leaching may contribute towards mitigating diffuse pollution from agricultural systems.

Loss to hydrosystems from rainfed agriculture in the Mediterranean basin is mainly associated with dissolved N in runoff or attached to soil-eroded particles (section 7). In rainfed cropland, NO_3^- leaching was shown to be relevant after intense rainfall events or wet periods that are common in semiarid (Ruiz-Ramos *et al* 2011) or humid (Arregui and Quemada 2006) Mediterranean areas. High winter NO_3^- flows from upland cereals are very common when winter fertilization is applied (Lassaletta *et al* 2009, 2010). Finally, the transformation of rainfed into irrigated fields may greatly enhance NO_3^- leaching and become a major risk for water pollution if it encompasses large areas (Merchan *et al* 2015). During the transition period, N mineralization may release a large amount of NO_3^- until the soil organic matter (SOM) content reaches a new equilibrium (Quemada and Gabriel 2016). Promoting temporary soil mining by minimizing N fertilizer application may help mitigate the risk of NO_3^- pollution (Vazquez *et al* 2006). The main pathways of environmental N loss from rainfed and irrigated cropland are summarized in figure 8.

7. From the croplands to the aquatic continuum

7.1. Soil erosion and N flows

Mediterranean soils are particularly vulnerable to water erosion, due to frequent intense rainfall events (Cortesi *et al* 2012, Merheb *et al* 2016), typical steep slopes (Tarolli *et al* 2012) and climatic conditions that make Mediterranean regions prone to wildfire, often associated with soil erosion (Shakesby 2011). While annual precipitation in many Mediterranean regions is expected to decrease under climate change (Cramer *et al* 2018, Brogli *et al* 2019), several studies highlight an expected increase in extreme precipitation events (Hagos *et al* 2016, Polade *et al* 2017, Tramblay and Somot 2018), which could lead to increased soil erosion (Morán-Ordóñez *et al* 2020).

It has been estimated that globally 23–42 Tg N is moved by soil erosion each year, which is of the same order of magnitude as N applied as chemical fertilizer and N removed by harvested crops (Quinton *et al* 2010). In spite of this, the transport of N has been largely neglected in soil erosion studies, which mostly focus on the impact of erosion on the redistribution of SOM and associated phosphorus (Garnier *et al* 2015). N is a structural component of SOM (Tipping *et al* 2016). Hence, the transport of SOM after extreme rainfall events affects soil N stocks. The redistribution of SOM is associated with the dynamics of sediment transport and deposition (Boix-Fayos *et al* 2015). As such, SOM may be deposited in common depositional landscape units, including river bars, floodplains and reservoirs (Fissore *et al* 2017) (see also section 7.2). The impact of soil erosion on SOM dynamics is still open to debate. Eroded SOM may be subject to mineralization during transport, potentially leading to increased SOM decomposition (Lal 2004), depending on the travel time and distance (Quinton *et al* 2010). In contrast, the deep burial of SOM-rich sediments may lead to reduced SOM decomposition rates (Berhe *et al* 2007). Due to heterogeneous land use configurations, the transport of sediment and SOM in Mediterranean catchments is highly complex (Boix-Fayos *et al* 2015), making it more difficult to assess how SOM, and consequently N, is redistributed in Mediterranean environments.

7.2. N retention in Mediterranean river basins

N losses from agricultural land reach water bodies by surface runoff and leaching to groundwater, as well as by soil erosion and atmospheric deposition. Once in the aquatic system, N undergoes different processes of transport, storage, transformation and elimination to gaseous forms, and part of it is finally exported to coastal areas.

Mediterranean climatic features, including high temperatures and low rainfall, often concentrated in a few large precipitation events, favor N retention in the watersheds—i.e. considering retention as the sum of storage, transformation and elimination processes. High temperatures are accompanied by high evapotranspiration rates, so runoff mainly occurs after intense events. Moreover, the irregular precipitation patterns and recurrence of summer droughts have driven intensive hydraulic management to secure water availability (Castaldelli *et al* 2013, Soana *et al* 2017, 2019, Romero *et al* 2021), and most rivers comprise numerous dams, reservoirs

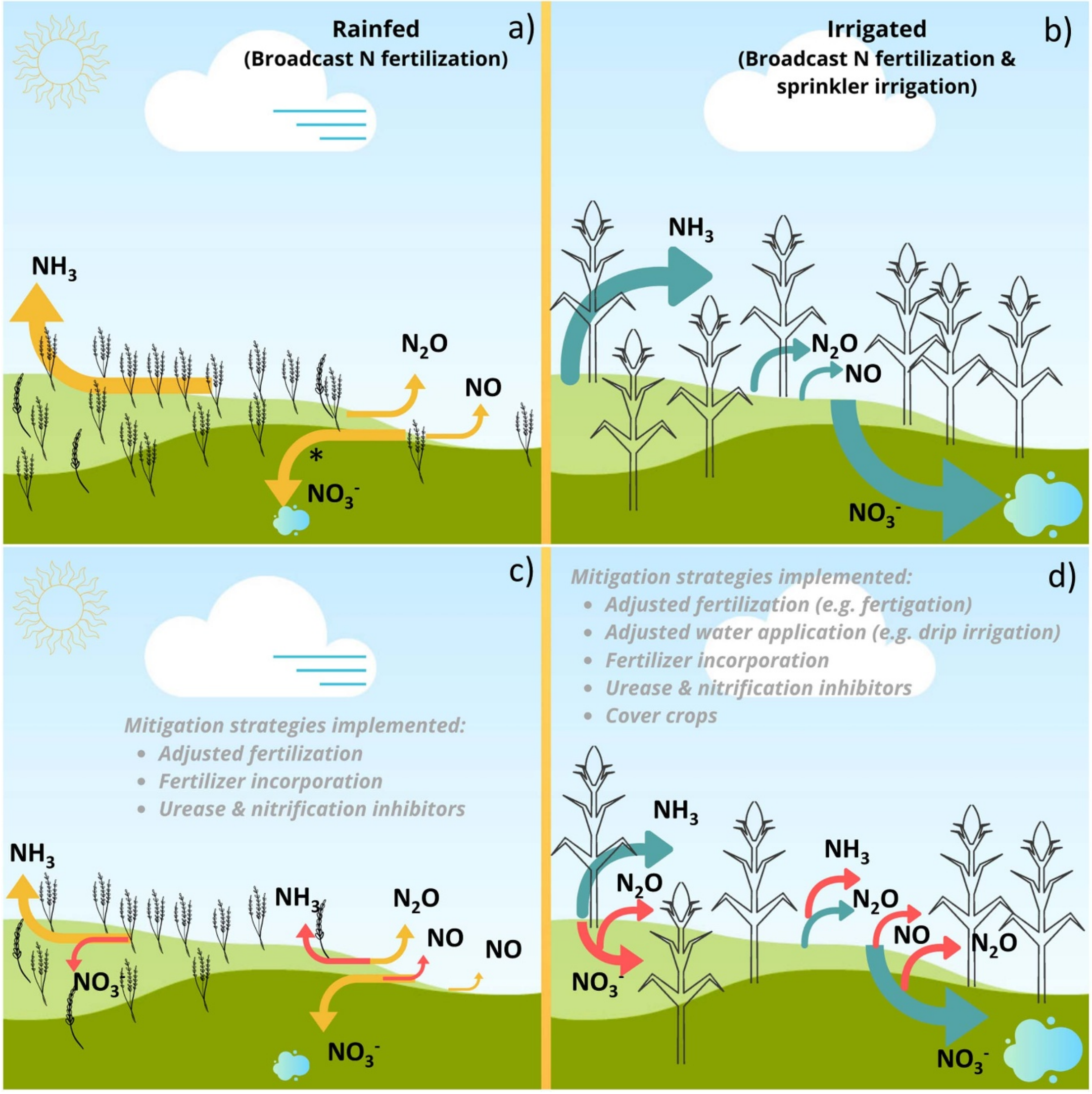

Figure 8. Schematic representation of the main pathways of reactive N loss in Mediterranean agroecosystems, both rainfed (a), (c) and irrigated (b), (d) under broadcast N fertilization. Size of the arrow is proportional to the net amount of N being lost to both the atmosphere and water bodies. Bottom figures (c) and (d) show the impact of the most recognized Nr abatement strategies in the area focusing on N fertilizer management, irrigation (e.g. drop or well-planned sprinkler irrigation) and cover cropping. Red arrows indicate the potential pathways of pollution swapping. * Similar to temperate areas, high NO_3^- leaching can occur in upland cereal croplands during intensive precipitation in winter. Our own elaboration based on the scientific literature referred to in the text.

and irrigation channels (Sadaoui *et al* 2018). Reservoirs and channels increase the land–water contact surface and residence time in the watersheds, and allow for enhanced nutrient processing via denitrification, uptake by riparian vegetation and freshwater macrophytes, infiltration and leaching to groundwater (Bartoli *et al* 2012, Lassaletta *et al* 2012, Romero *et al* 2016). In addition, reservoirs are built to contend with water scarcity and buffer great episodes of rain and flooding, which means that they also decrease the transport of N to coastal areas during flashy rainfall events.

All these waterwork developments contribute to increasing N retention in the river basin with potentially higher pressure on inland waters (including groundwater) and less export to coastal systems. Higher retention percentages in the Mediterranean with respect to other climatic conditions—and especially in arid and semi-arid Mediterranean basins—have been reported in several recent studies that include different geographical scales (the Iberian Peninsula, European Mediterranean basins and the entire Mediterranean basin) and different modeling approaches (Romero *et al* 2016, 2021, Grizzetti *et al* 2021).

Despite high retention and hence high elimination rates, N concentration in water bodies might be increased in regions affected by water scarcity due to the low dilution capacity by water flow, as has been observed in southern Europe, mainly in Spain, Italy and Greece (Grizzetti *et al* 2017). In addition, as N retention includes permanent and temporal components, high values of retention might hide an accumulation of N in soils and groundwater in the river basin, and a delay between sources and impacts in aquatic ecosystems (Grizzetti *et al* 2015).

8. Lessons learned and policy dimensions

The climatic and agronomic specificities of the Mediterranean region worldwide demand N management techniques specifically suited to this region. Agronomic practices (rainfed versus irrigated crops; annual crops versus permanent crops) or soil characteristics (acidic versus calcareous; soil carbon content) could limit the beneficial effects of sustainable practices successfully developed and implemented in other regions, and even prevent their implementation. In any case, they should be adapted considering the climate change context and potential adverse side effects, such as pollution swapping. The definition of the most suited management practices at the local level should be defined under a co-creation process considering the end-users' needs and constraints with the support of researchers and various implicated agents.

The systemic approach considering the overall N budget within the agro-food system in the Mediterranean Basin has highlighted those processes demanding urgent action. Anyhow, accounting, surveillance and control of the different elements of the agro-food system need to be implemented. Although measures taken at the farm level eventually impact the overall system, multilateral, subregional and national action is needed to control N surplus and its environmental impact. This study has identified important differences in the agro-food system across the Mediterranean Basin, mostly related to climatic factors (coastal versus in-land areas; subarid versus arid areas). The study of these systems at the national and provincial level has identified where governmental actions via incentives or regulations are needed, considering the geopolitical angle in the degree of intensification or import–export of feed and food.

In the Mediterranean biome, the management of water and N should be jointly appraised, developing N fertilization schemes tailored not only to potential N crop demand, but to water availability (quantity) and quality, the soil chemical and physical characteristics, as well as the fertilizer resources locally available. The case of agro-food system transformation observed in the countries of the Mediterranean Basin is paradigmatic. The increasing manure production and associated crop-livestock disconnection are critical in other regions of the world (Garnier *et al* 2016, Jin *et al* 2020, Mueller and Lassaletta 2020), but they are of particular concern in the Mediterranean Basin. The best use of the available local manure has to consider the much lower response of rainfed systems and the high leaching potential of the irrigated systems. Thus, the consideration not only of the two contrasting worlds—namely, rainfed and irrigated systems—but of the precipitation gradient to rainfed systems is important. The analysis of potential maximum yields and yield versus fertilization relationships, adapted to local conditions, should be done to set sustainable N application rates.

We conclude that bottom-up and top-down approaches should go hand in hand, combining (a) local assessment of the most suited farming systems that jointly improve N and WUE considering the crop specificities, water availability for irrigation and edapho-climatic conditions up-scaled to national and continental level, and (b) a systemic analysis of N input into the systems fueled by food demand. Indicators for monitoring should be derived in order to suggest policies and governance systems tailored to the local specificities. In addition, structural measures promoting the reconnection of crop and livestock farming, including the relocation of feed production, reduction of food waste and consideration of the key effect of human consumption patterns (diet, reconnection of production and consumption in time and space) have to be considered (Billen *et al* 2019). This integrated vision is aligned with the spirit of the recent Farm to Fork Strategy (and Biodiversity Strategy) of the European Union that aims to halve N pollution in agricultural systems and also considers recommendations at the consumption level.

Markets are not currently considering N-related environmental externalities in the region, which also have socio-economic implications. However, the lack of proper connection of our scientific findings with socio-economic indicators prevents defining relevant guidelines integrating agronomic, environmental and social aspects of Mediterranean farming systems. Nevertheless, farmers' adoption of locally suited best sustainable practices could very likely result in yield losses compared to 'business as usual' practices, demanding the implementation of compensating schemes to account for the environmental services they provide.

As a whole, the implementation of these practices also demands modifications in rural planning, considering not only the local biophysical, climatic and socio-economic conditions, but the heterogeneity of different land use at the landscape and catchment levels. The integration of sustainable practices at the regional scale may help address coexisting environmental challenges, such as land degradation, biodiversity loss, food security, climate change mitigation and adaptation, and water scarcity (Ruiz *et al* 2020). These features should be taken into account when developing future policies by integrating top-down system analysis with bottom-up initiatives aiming to identify the most urgent problems and feasible solutions, based on the quantification of ecosystem services as well as sustainable economic issues and the well-being of farmers (van Leeuwen *et al* 2019).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgment

This work was partly supported by 7th Framework Programmes funded by the European Union through the LUC4C project (Grant Agreement 603542). A Bondeau and W Cramer acknowledge Labex OTMed (ANR-11-LABX-0061) funded by the French Government Investissements d'Avenir program of the French National Research Agency (ANR) through the A∗MIDEX project (ANR-11-IDEX-0001-02). The authors are grateful to the Spanish Ministry of Economy and Competitiveness (AgroSceNA-UP, PID2019-107972RB-I00), the Comunidad de Madrid, Spain (AGRISOST-CM S2018/BAA-4330 project). L Lassaletta is supported by Spanish Ministry of Economy and Competitiveness (MINECO) and European Commission ERDF Ramón y Cajal grant (RYC-2016-20269), Programa Propio from UPM, and acknowledges the Comunidad de Madrid (Spain) and structural funds 2014-2020 (ERDF and ESF). L Lassaletta is extremely grateful to Rafael Lassaletta (Nano) for permanent support and care. E Aguilera is supported by a Juan de la Cierva research contract from the Spanish Ministry of Economy and Competitiveness (FJCI-2017-34077). A Sanz-Cobena gratefully acknowledges the Autonomous Community of Madrid and UPM for their economic support through the research project APOYOJOVENES-NFW8ZQ-42-XE8B5K. We are also grateful to Patrick Durand and the organizers of the 20th Nitrogen Workshop (Rennes, France) where a first version of this work was presented as a keynote. The authors are most grateful to the two anonymous reviewers for their constructive and useful suggestions.

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