



HAL
open science

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

Luis Lassaletta, Alberto Sanz-Cobena, Eduardo Aguilera, Miguel Quemada, Gilles Billen, Alberte Bondeau, Maria Luz Cayuela, Wolfgang Cramer, Joris P.C. Eekhout, Josette Garnier, et al.

► To cite this version:

Luis Lassaletta, Alberto Sanz-Cobena, Eduardo Aguilera, Miguel Quemada, Gilles Billen, et al.. Nitrogen dynamics in cropping systems under Mediterranean climate: a systemic analysis. *Environmental Research Letters*, 2021, 16 (7), pp.73002. 10.1088/1748-9326/ac002c . hal-03265203

HAL Id: hal-03265203

<https://amu.hal.science/hal-03265203v1>

Submitted on 19 Jun 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

ACCEPTED MANUSCRIPT • OPEN ACCESS

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

To cite this article before publication: Luis Lassaletta *et al* 2021 *Environ. Res. Lett.* in press <https://doi.org/10.1088/1748-9326/ac002c>

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is © 2021 The Author(s). Published by IOP Publishing Ltd.

As the Version of Record of this article is going to be / has been published on a gold open access basis under a CC BY 3.0 licence, this Accepted Manuscript is available for reuse under a CC BY 3.0 licence immediately.

Everyone is permitted to use all or part of the original content in this article, provided that they adhere to all the terms of the licence <https://creativecommons.org/licenses/by/3.0>

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions may be required. All third party content is fully copyright protected and is not published on a gold open access basis under a CC BY licence, unless that is specifically stated in the figure caption in the Version of Record.

View the [article online](#) for updates and enhancements.

1 Nitrogen dynamics in cropping systems under Mediterranean climate: a systemic 2 analysis

3
4 Luis Lassaletta^{1,*}, Alberto Sanz-Cobena¹, Eduardo Aguilera¹, Miguel Quemada¹, Gilles Billen²,
5 Alberte Bondeau³, Maria Luz Cayuela⁴, Wolfgang Cramer³, Joris P.C. Eekhout⁴, Josette Garnier⁵,
6 Bruna Grizzetti⁶, Diego S. Intrigliolo⁴, Margarita Ruiz Ramos¹, Estela Romero⁷, Antonio Vallejo¹,
7 Benjamín S. Gimeno⁸

8 * luis.lassaletta@upm.es

9 *1 ETSI Agronómica, Alimentaria y de Biosistemas, CEIGRAM, Universidad Politécnica de Madrid, Spain*

10 *2 UMR 7619 Metis, Sorbonne Université, Paris, Île-de-France, France*

11 *3 IMBE, Aix Marseille University, CNRS, IRD, Avignon University, Aix-en-Provence, France*

12 *4 Applied Biology and Soil Sciences Center (CEBAS), Spanish National Research Council (CSIC), Murcia, Spain*

13 *5 UMR 7619 Metis, CNRS, Paris, Île-de-France, FRANCE*

14 *6 European Commission Joint Research Centre (JRC), Ispra (VA), Italy*

15 *9 Dept. de Medio ambiente, Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA-INAGEA), Madrid, Spain*

16 Abstract

17 Worldwide, Mediterranean cropping systems face the complex challenge of producing enough
18 high-quality food while preserving the quantity and quality of scarce water for people and
19 agriculture in the context of climate change. While good management of nitrogen (N) is
20 paramount to achieving this objective, the efficient strategies developed for temperate systems
21 are often not adapted to the specificities of Mediterranean systems. In this work we combined
22 original data with a thorough literature review to highlight the most relevant drivers of N
23 dynamics in these semiarid systems. To do so, we provide an analysis at nested scales combining
24 a bottom–up approach from the field scale with a top–down approach considering the agro-food
25 system where cropping systems are inserted. We analyze the structural changes in the agro-food
26 systems affecting total N entering the territory; the contrasting response of yields to N availability
27 under rainfed and irrigated conditions in a precipitation gradient; the interaction between N
28 management and climate change adaptation; the main drivers affecting the release of Nr
29 compounds (NO₃⁻, NH₃, NO, N₂O) as compared with temperate systems; and finally, the behavior
30 of N once exported to highly regulated river networks. We conclude that a sustainable N
31 management in Mediterranean cropping systems requires the specific adaptation of practices to
32 the particular local agroenvironmental characteristics with special emphasis on water availability
33 for rainfed and irrigated systems. This approach should also include a systemic analysis of N inputs
34 into the territory that are 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 (Fig. 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 priority (Olson and Dinerstein, 2003). The total area covers 2.6 million km² and in 2010 had a population density of 95 inh/km² (i.e., 310 M inhabitants).

The land area of the Mediterranean Basin accounts for 66% of the world Mediterranean biome. The sustainability of this region for people and ecosystems is at stake due to: (1) scarcity of water (García-Ruiz *et al.*, 2011), (2) significant land-use changes, notably urbanization and abandonment of pastoralism (Malek *et al.*, 2018; Aguilera *et al.*, 2020), (3) increasing air and water pollution (Sanz-Cobena *et al.*, 2017), (4) biodiversity loss (Sala *et al.*, 2000), and (5) 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).

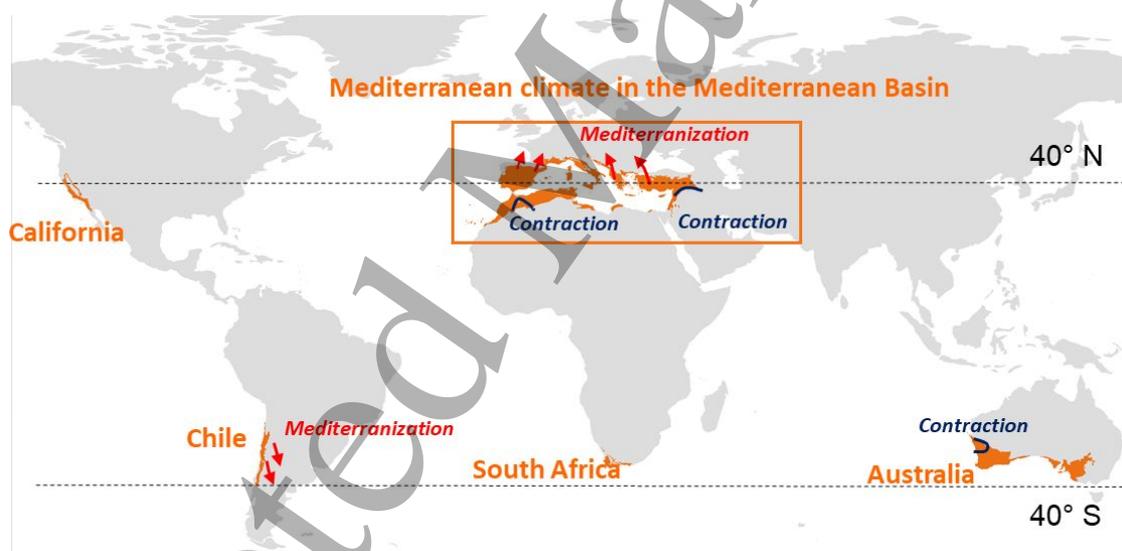


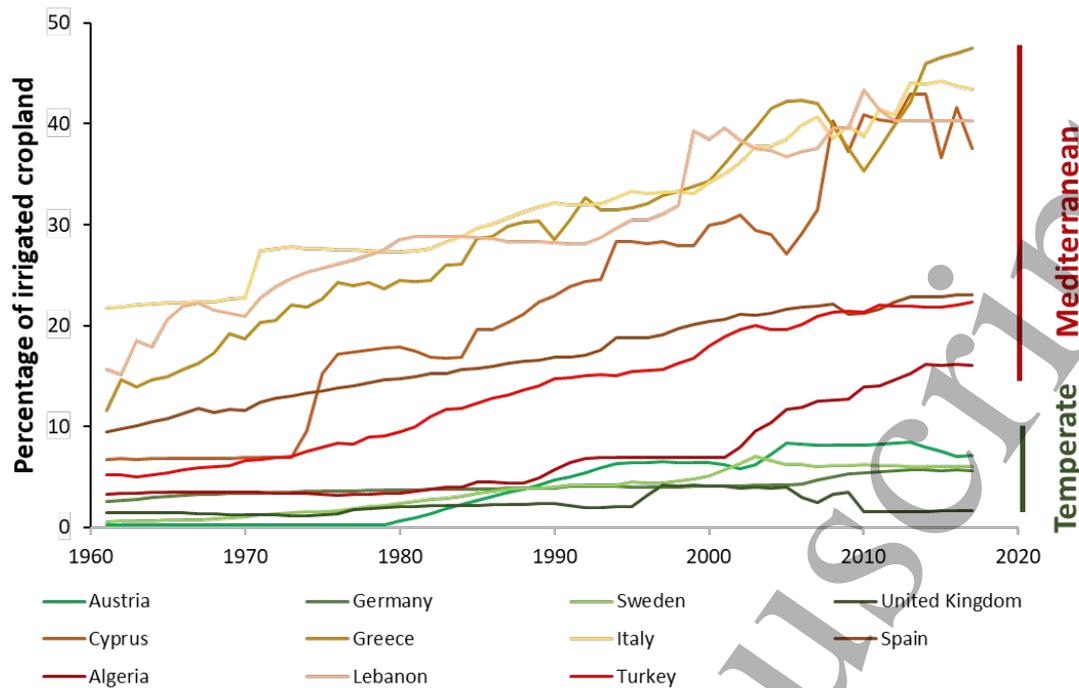
Figure 1. Global distribution of the Mediterranean biome (Olson *et al.* 2001) including potential areas of expansion (red arrows, “Mediterranization”) and contraction (blue lines). Adapted from Klausmeyer and Shaw (2009).

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). The 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

1
2
3 60 production. It is also characterized by flash floods and droughts, which are projected to be
4
5 61 exacerbated (Michaelides *et al.*, 2018).
6

7 62 During thousands of years of evolution, agriculture in the Mediterranean Basin has been adapted
8
9 63 to environmental conditions of relative instability, rainfall variability, and summer water stress
10
11 64 through the selection of crops, varieties and rotations, as well as hydraulic infrastructures and
12
13 65 management practices, resulting in diverse and unique agricultural systems (Blondel, 2006). This
14
15 66 diversification permits the cultivation of rainfed crops such as cereals, legumes, oilseeds, and
16
17 67 some vegetables in winter, as well as of drought-resistant permanent crops such as almonds,
18
19 68 grapes, and olives. Efficient irrigation can increase crop yields from 10% to 90%, depending on the
20
21 69 annual water stress and the technology (Wriedt *et al.*, 2009). Irrigation also allows for the
22
23 70 cultivation and expansion of horticultural crops, maize, tobacco, and citrus fruits in these semiarid
24
25 71 areas. As a result, irrigation is a common practice in traditional Mediterranean cropping systems,
26
27 72 and it has expanded more than in temperate areas in the past 20 years (Fig. 2).

28
29 73 Climate change is affecting the entire planet, and Mediterranean climate zones are no exception.
30
31 74 As occurring in the entire planet (Klausmeyer and Shaw, 2009) climate change impacts
32
33 75 Mediterranean biomes (Famiglietti *et al.*, 2011), where it is expected to increase water scarcity
34
35 76 via sustained warming and decreasing precipitation, consequently leading to an increase in
36
37 77 evaporative demand and in the intensity, duration, and frequency of droughts (García-Ruiz *et al.*,
38
39 78 2011; Spinoni *et al.*, 2018). Without adaptation crop yields will likely be impacted (Iglesias *et al.*,
40
41 79 2011), (Zampieri *et al.*, 2020). Irrigation requirements may increase substantially with climate
42
43 80 change (Fader *et al.*, 2016), and therefore irrigation techniques will have to be adapted as water
44
45 81 resources may turn out to be insufficient (Malek and Verburg, 2018).
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60



82
83 **Figure 2.** Evolution of cropland fraction equipped for irrigation in several Mediterranean countries (all of
84 them with than 50% of their agriculture under Mediterranean conditions) and a sample of temperate
85 countries in Europe (based on FAOSTAT, 2020).

86 Together with water, nitrogen (N) is the main limiting factor in agricultural production and must
87 be properly managed to sustain crop yields (Mueller *et al.*, 2012; Quemada *et al.*, 2020a).
88 Lassaletta *et al.* (2014a) showed that a robust hyperbolic relationship relates harvested yield,
89 expressed as N content and integrated over a whole crop rotation cycle, to average total annual
90 N inputs to soil, with a single parameter Y_{max} characterizing the pedo-climatic and technical and
91 agronomic context. This relationship implies that not all N applied to soil is recovered with the
92 harvested crop. Overall, N use efficiency (NUE) of the world cropping systems is less than 50%
93 (Bouwman *et al.*, 2013; Lassaletta *et al.*, 2014a; Bouwman *et al.*, 2017). Most of the N surplus, i.e.,
94 the amount of N input to soils not exported by harvested crops, is released to the environment),
95 where it undergoes a series of transformations, impacting different ecosystem compartments
96 through the so-called N cascade (Galloway *et al.*, 2003; Billen *et al.*, 2013). In agricultural systems,
97 reactive N (N_r , all nitrogen species except N_2) (Leach *et al.*, 2012) is preferentially emitted in the
98 form of: volatilized ammonia (NH_3), an aerosol precursor and soil-acidifying compound (Van
99 Damme *et al.*, 2018) that causes biodiversity losses when deposited (Ochoa-Hueso *et al.*, 2011);
100 nitrous oxide (N_2O), a potent greenhouse gas (Thompson *et al.*, 2019); and nitric oxide (NO), which
101 promotes the formation of tropospheric ozone (O_3) (Guardia *et al.*, 2017b). N can be also leached
102 as nitrate (NO_3^-), which is a threat to drinking water resources and freshwater biodiversity (van
103 Grinsven *et al.*, 2010) and promotes eutrophication of coastal waters (Garnier *et al.*, 2010). The
104 emission of these compounds imposes a high economic cost for society (Sutton *et al.*, 2013; Van

1
2
3 105 Grinsven *et al.*, 2013) and their adequate management has been linked to nine of the United
4
5 106 Nations Sustainable Development Goals (Morseletto, 2019).
6

7 107 The total N inputs to the world's Mediterranean cropping systems in 2010 were 5.9 Tg N, most of
8
9 108 them in the form of synthetic fertilizers. 75% of this N is applied in the crops of the Mediterranean
10
11 109 Basin under Mediterranean climate (see the Supplements for a complete N budget of
12
13 110 Mediterranean cropping systems). Adequate crop management in the Mediterranean biome
14
15 111 involves the simultaneous control of water and N inputs (Sadras, 2005; Sadras *et al.*, 2016). Two
16
17 112 contrasting situations are experienced: rainfed systems subject to important spatiotemporal
18
19 113 variability, which complicates the adjustment of optimal fertilization doses (Ryan, 2008; Ryan *et al.*,
20
21 114 *et al.*, 2009; Quemada and Gabriel, 2016); and irrigated systems dealing in many cases with water
22
23 115 supply limitations and high risk of nitrate leaching (Causape *et al.*, 2006; Barros *et al.*, 2012; Malik
24
25 116 and Dechmi, 2019). Other intrinsic characteristics of the Mediterranean systems such as the high
26
27 117 temperatures and the low carbon content of soil (Aguilera *et al.*, 2013a; Rodríguez Martín *et al.*,
28
29 118 2016; Aguilera *et al.*, 2018) have a strong impact on the microbial activity that drives the form in
30
31 119 which N is emitted and the magnitude of the flow from croplands to other compartments (Sanz-
32
33 120 Cobena *et al.*, 2017). N₂O emission factors, for example, are lower than those in temperate
34
35 121 systems (Cayuela *et al.*, 2017).
36

37 122 Sustainable N management, adapted to the particularities of the Mediterranean biome, depends
38
39 123 on knowledge of specific processes at the plot and farm scale (bottom-up approach), but also on
40
41 124 the understanding of the agro-food system that controls the new N entering a territory (top-down
42
43 125 approach). Organic manure may be efficiently recirculated at the regional scale, reducing the
44
45 126 demand for new fertilizers, while different agricultural commodities can be locally produced or
46
47 127 imported, all of which configure the structure of the N cycle (Billen *et al.*, 2014; Billen *et al.*, 2015;
48
49 128 Le Noë *et al.*, 2017; Mueller and Lassaletta, 2020). For example, in Spain, the input of new N into
50
51 129 the national territory (NANI, net anthropogenic N input) (Howarth *et al.*, 1996) has increased
52
53 130 fourfold during the past 60 years, contributing to important yield improvements but also to
54
55 131 significantly increased N pollution. Once N reaches the waterbodies, the high regulation of
56
57 132 freshwater resources for crop irrigation and drinking water supply can affect N dynamics in
58
59 133 Mediterranean watersheds. The fraction of runoff exported to coastal waters is lower than in
60
61 134 temperate watersheds, increasing the risk for pollution of aquifers, rivers, and lakes (Bartoli *et al.*,
62
63 135 2012; Romero *et al.*, 2016).
64

65 136 Worldwide, Mediterranean cropping systems face the complex challenge under the climate
66
67 137 change context of producing enough high-quality food for an often increasing population,
68

1
2
3 138 together with the need to preserve the quantity and quality of scarce water resources for people
4
5 139 and agriculture, while also reducing their impacts on air pollution. We present this review with
6
7 140 the overall aim of analyzing, from a systemic perspective, the particularities of N dynamics in
8
9 141 Mediterranean cropping systems associated with the emission of Nr compounds. Our approach
10
11 142 aims to extend from the plot or farm-scale to the agro-food systems that these cropping systems
12
13 143 are embedded in.

14 144 This study combines primary data with a literature review in order to provide an analysis at nested
15
16 145 scales of (1) the evolution of the N cycle in agro-food systems at the regional scale including crop
17
18 146 N budgets, (2) water and N interactions in contrasted irrigated and rainfed systems along a
19
20 147 precipitation gradient, (3) the implications of climate change adaptation for N management, (4)
21
22 148 the main drivers affecting the release of Nr compounds as compared with temperate systems, (5)
23
24 149 the behavior of N in Mediterranean watersheds, (6) the resulting policy recommendations for the
25
26 150 design of agro-environmental strategies tailored to Mediterranean conditions. The work mainly
27
28 151 focuses on the Mediterranean Basin, which forms a unique, conterminous and coherent territory,
29
30 152 suitable for developing a systemic analysis covering from the agro-food system to the river basin.
31
32 153 We postulate that the main lessons learnt for these semiarid systems managed under rainfed and
33
34 154 irrigated conditions are also relevant, not only for the rest of the world's Mediterranean areas but
35
36 155 also for the new areas undergoing "Mediterranization" due to climate change.

36 156 **2. Methods**

37
38 157 We analyzed the evolution of the N cycle in the agro-food system at the regional scale. Crop
39
40 158 production and pasture production are connected with livestock farming to supply food to the
41
42 159 local population, and also with the export or import of agricultural products to or from other
43
44 160 regions. Using N embedded in proteins or in N fertilizers as a marker, the structure of the agro-
45
46 161 food system is presented in a diagram showing N flows through the main transformation
47
48 162 compartments involved in the system, namely, crop and grass production, livestock breeding,
49
50 163 food processing, international trade, and final human consumption (General Representation of
51
52 164 Agro-Food Systems, GRAFS) (Billen *et al.*, 2014; Le Noë *et al.*, 2017; Billen *et al.*, 2018).

53
54 165 To construct the GRAFS diagrams, and since some statistics were available at the country scale
55
56 166 only, we considered 11 out of the 22 countries in the Mediterranean Basin. In these countries,
57
58 167 more than 50% of the crop and grassland area is under Mediterranean conditions: Portugal, Spain,
59
60 168 Italy, Albania, Greece, Turkey, Cyprus, Israel, Tunisia, Algeria, and Morocco (Supplements Table
169 S1). Countries presenting a marked temperate-to-Mediterranean gradient (France) or with
170 incomplete observations (Palestine), or those with relevant data missing for other reasons (Syria

1
2
3 171 and Libya), were not included. In total, the selected countries comprise 91% of crops and
4 172 grasslands under Mediterranean climate in the Mediterranean Basin and 61% of crops and
5 173 grasslands under Mediterranean climate worldwide. The crop mix at country level was estimated
6 174 by clustering crop data from FAOSTAT into generic groups, namely, cereals, legumes, roots,
7 175 oilseed, horticulture, permanent crops, and others. N budgets in cropping systems of the
8 176 Mediterranean biome were calculated by combining spatially-explicit, crop-specific datasets on
9 177 crop and livestock distribution, yields and N inputs with country-level data from FAOSTAT (see a
10 178 full description of the procedure in the Supplements).

11 179 Water–N interactions were analyzed in Spain as a putatively representative Mediterranean
12 180 country with a strong precipitation gradient with cereal crops under rainfed and irrigated
13 181 conditions. Data on yearly crop-specific yield and N fertilization rates (synthetic and organic) were
14 182 provided by the Spanish Ministry of Agriculture for wheat cultivation, split into rainfed and
15 183 irrigated systems at the province level (40 Spanish provinces with Mediterranean climate) for 26
16 184 years (1990–2015). Yield instability during that particular period was calculated separately for
17 185 rainfed and irrigated conditions at the province level by means of the coefficient of variation (CV)
18 186 of crop yield in each province. Yearly precipitation data were obtained from the CRU global
19 187 dataset (Seager *et al.*, 2019). Irrigation water application was estimated for each crop in each
20 188 province at monthly time steps based on crop evapotranspiration, which was calculated as
21 189 described in (Vila-Traver *et al.*, 2021). Crop water requirements were calculated by subtracting
22 190 effective precipitation from crop evapotranspiration. Irrigation water application was calculated
23 191 by dividing crop water requirement by the water efficiency of each irrigation technology (Wriedt
24 192 *et al.*, 2009).

25 193 Regional crop nutrient budgets at the Spanish province level include synthetic and organic N
26 194 fertilizers, and atmospheric deposition, as inputs (N_{in}), and N extracted in the main harvest as
27 195 outputs (NY). Nitrogen use efficiency (NUE) corresponds to NY/N_{in} and N surplus to $N_{in} - NY$
28 196 (Zhang *et al.*, 2020). Averaged NY vs. N_{in} response curves were estimated for each province and
29 197 fitted by the one-parameter hyperbolic curve :

30 198
$$NY = Y_{max} N_{in} / (N_{in} + Y_{max})$$

31 199 Where the parameter $Y_{max} = (N_{in} * NY) / (N_{in} - NY)$ represents the maximum yield at N saturation
32 200 conditions. This approach is commonly used in regional and large-scale approaches (Lassaletta *et*
33 201 *al.*, 2016; Mueller *et al.*, 2017; Mogollón *et al.*, 2018).

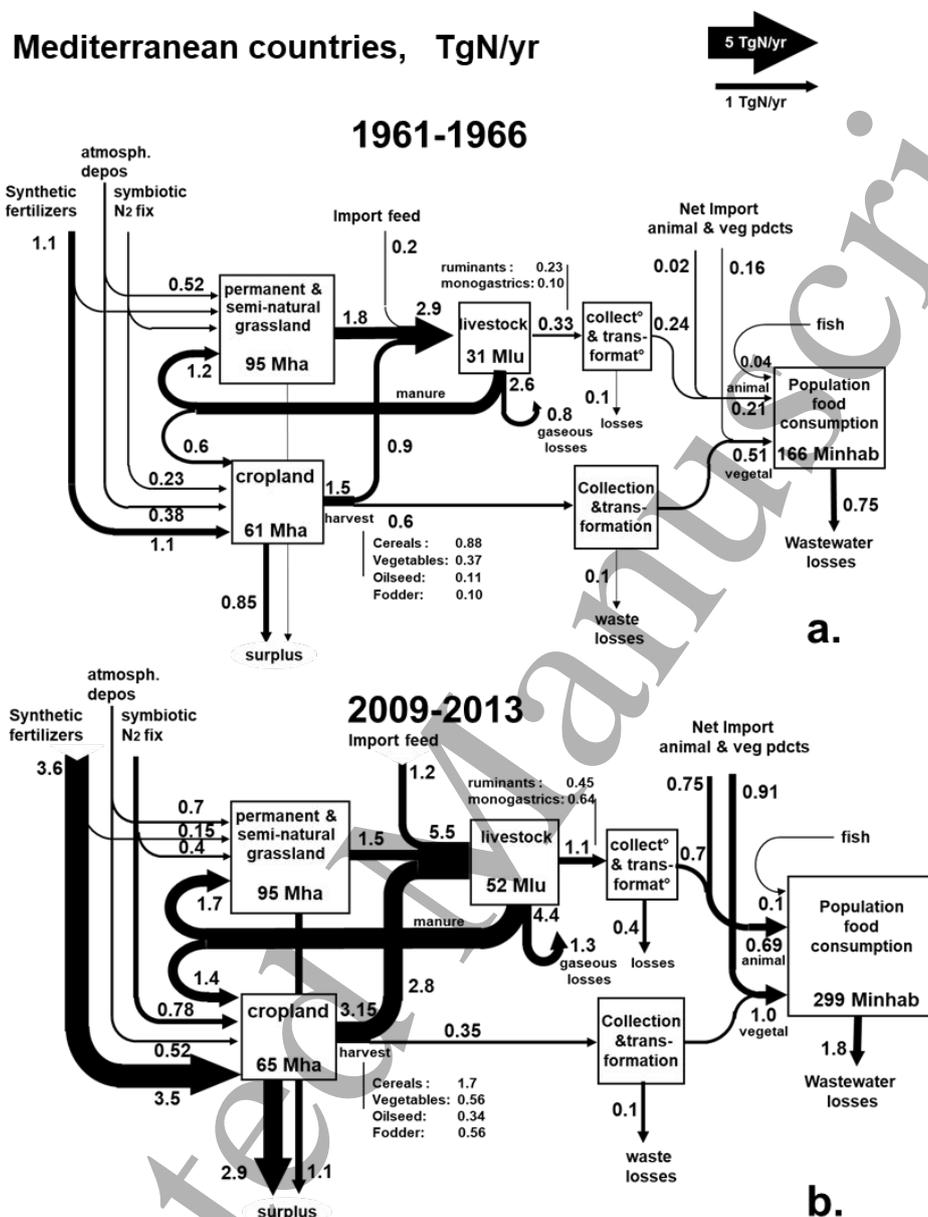
202 3. Trajectories of N use in the whole agro-food system in the Mediterranean Basin

203 The structure of the agro-food system for the periods 1961–1965 and 2009–2013 in the selected
204 Mediterranean countries is represented in diagrams showing N fluxes through the main
205 compartments. The components involved are crop and grass production, livestock breeding, food
206 transformation, international trade, and human consumption (Fig. 3). In the early 1960s,
207 Mediterranean countries as a whole (as defined in the Methods section) were close to self-
208 sufficiency for feeding their population of 166 million inhabitants, with a diet composed of 3.1
209 kg N/cap/yr of proteins from vegetal origin, and 1.5 kg N/cap/yr of animal proteins, including 0.2
210 kg N/cap/yr from fish. Livestock manure, together with symbiotic fixation of atmospheric N₂ and
211 atmospheric deposition of Nr, was the dominant form of N fertilizing input to cropland, even if
212 synthetic fertilizers already contributed significantly at that time. Livestock, dominated by
213 ruminants, thus played a major role by conveying N from permanent and seminatural grassland
214 to cropland soils. Imported feed was of limited significance, and approximately 60% of crop
215 production was dedicated to animal feeding. The remaining crop production was used for local
216 human nutrition together with animal production, such as meat and milk. Net imports of animal
217 and vegetable food products were minimal.

218 During the past 50 years, the population of the Mediterranean Basin countries increased by 80%
219 and changed its diet by increasing total protein ingestion by 30% (from 4.5 to 6.1 kg N/cap/yr),
220 while the share of animal proteins in this total rose from 32 to 43%. This transition has been more
221 evident in European Mediterranean countries and Israel than in the rest of the basin. On the one
222 hand, these changes made it possible that the protein consumption per capita did not fall below
223 WHO recommendations at any time. But these changes also indicate the gradual abandonment
224 of the so-called Mediterranean diet that was replaced by a “Western-type” diet that totally alters
225 the recommended relative proportions of each food group and negatively affects human health
226 (Blas *et al.*, 2019). This dietary change has profoundly impacted the structure of the entire agro-
227 food system, with a considerable intensification of animal breeding: livestock production
228 increased 3.5-fold, mostly in terms of monogastric animals feeding on grains.

229 Despite a concomitant intensification of cropping systems, increasing its use of synthetic N
230 fertilizers by a factor of 3, the production of forage and cereal was not enough to feed the
231 livestock. The rising demand for feed occurred in parallel to a change in the crop mix of the region.
232 The cultivation of cereals was reduced by 16% of the region’s total cropland area during the past
233 few decades. Only Morocco significantly increased cereal cropping areas. Legume crop surfaces
234 decreased in European countries but not in south and east Mediterranean countries. On the other

235 hand, cultivation of oilseed with potential allocation to animal consumption has almost doubled,
 236 although today its share is still too low to provide a sustained source of protein (5.2% of cropland).



237

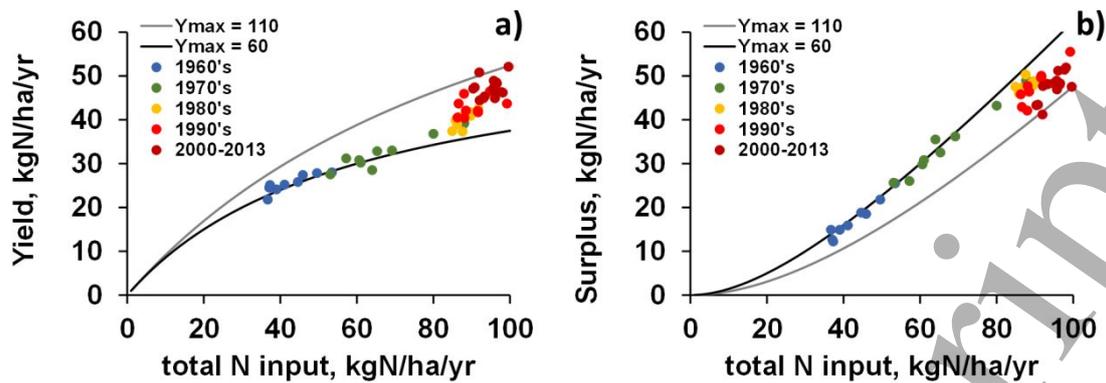
238 **Figure 3.** Generalized representation of the Agro-Food System (GRAFS) of countries in the Mediterranean
 239 Basin with more than 50% of their agricultural land under Mediterranean climate (11 selected countries,
 240 see Methods Section), in 1961–1965 (a) and 2009–2013 (b)

241 Massive imports of feed, namely, soybean and maize from the Americas, were required for
 242 livestock production (Lassaletta *et al.*, 2014b; Leip *et al.*, 2015; Billen *et al.*, 2019). Also,
 243 considerable net imports of animal food and cereals were needed to feed the human population.
 244 As a result, the external dependency of the agro-food system of Mediterranean countries, defined
 245 as the ratio of net import of food and feed proteins to the local animal and human ingestion, rose

1
2
3 246 from 6% in 1960 to 30% in 2013. This trend contributes to surpassing the carrying capacity of the
4
5 247 region by a factor of 2.5 (Galli *et al.*, 2015).
6

7 248 The trends in agro-food system components from both the demand side and the supply side
8
9 249 indicate massive temporal change (Fig. S2 Suppl.). The gradual increase of animal and human
10
11 250 consumption cannot be met by the increase of cropland yield and the stagnation of grassland
12
13 251 production, requiring recourse to increased importation. Thus, the level of external dependency
14
15 252 paralleled this gradual increment (Fig. S3 Suppl.).
16

17 253 Yield of arable land increased by a factor of two over the past 50 years. This is largely the result
18
19 254 of increased N fertilization. The trajectory of N yield versus soil N inputs follows the same distinct
20
21 255 hyperbolic relationship with a Y_{max} of approximately 60 kg N/ha/yr until the end of the 1970s (Fig.
22
23 256 4). From this time onward, improvements in yield were obtained with much lower increases in
24
25 257 fertilization than in the first decades. Consequently, the surplus, i.e., the excess of total N soil
26
27 258 inputs over N in harvested products, increased until the early 1980s and then levelled off until the
28
29 259 present period. Crop NUE decreased from 60% in the early 1960s to 44% in the 1980s, and then
30
31 260 increased again up to 50%. There are several reasons to explain the changes observed in the
32
33 261 aggregated N crop yield and NUE. On the one hand, the expansion of irrigated land (see Fig. 2)
34
35 262 and other agronomic improvements such as better fertilization and irrigation techniques, as well
36
37 263 as the development of improved crop varieties through breeding and selection, had a significant
38
39 264 effect on the observed yield increases. For example, wheat and tomato yields grew between two-
40
41 265 and threefold, and two- and fourfold, respectively. On the other hand, over-fertilization may have
42
43 266 moved the system to the inefficient part of the yield vs. N input response curve. In addition to
44
45 267 these agronomic factors, the aforementioned changes in the crop mix may have had an important
46
47 268 effect on the NUE of the system (Zhang *et al.*, 2015). High N input/N output systems such as
48
49 269 cereals were replaced by low N input/low N output systems such as permanent crops, systems
50
51 270 that have doubled in presence. This is linked to the specialization of Mediterranean agriculture in
52
53 271 vegetables, fruits, and olive oil for export to temperate European countries. Counterintuitively,
54
55 272 the cultivated area with high N input/low N output systems such as horticulture has been reduced
56
57 273 in European Mediterranean countries while their total production has increased, indicating high
58
59 274 intensification practices (e.g., greenhouses). By contrast, both the agricultural area and the
60
275 productivity of horticulture substantially increased in south and east Mediterranean countries.



276

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

280 Intensification of animal production, accompanied by an increase in the share of monogastric
 281 animals (representing 10% of the livestock units in 1961 and 27% in 2013), resulted in a limited
 282 improvement of aggregated protein conversion efficiency from 8% in the 1960s to 13% (at the
 283 herd level and considering edible protein only) in recent years. These NUE values aggregate many
 284 contrasting types of livestock systems. The most intensified systems have increased N efficiency
 285 significantly, gradually reducing the total demand for feed (expressed as dry matter) to produce
 286 1 kg of meat during the past decades and subsequently reducing the N excretion/kg meat during
 287 recent years (Lassaletta *et al.*, 2019; MAPA, 2020a, b). These systems strongly depend on
 288 imported feed, causing the externalization of N impacts (Bai *et al.*, 2014; Quemada *et al.*, 2020a)
 289 and increasing the input of new N embedded in the feed via international trade.

290 Alongside the intensification of both livestock and crop farming, environmental N losses increased
 291 considerably, as shown by the rise in Net Anthropogenic Nitrogen Input (NANI) from 620 to 1900
 292 kg N/km²/yr (Fig S3. Suppl.). While the input of synthetic N fertilizers was stabilized from 1985,
 293 the net import of food and feed steadily increased and today accounts for 2 Tg N/yr, i.e., 50% of
 294 synthetic fertilizers. This massive and increasing amount of feed largely transformed into manure
 295 represents a huge challenge for cropping and livestock systems. As a result of these changes,
 296 agricultural surplus and gaseous N emission from livestock breeding have also increased. Clearly,
 297 the trend toward losing self-sufficiency of the agro-food system was accompanied by the opening
 298 of nutrient cycles. The period from 1960 to the 1980s experienced the fastest increase in
 299 environmental losses, mostly from cropland. A stabilization of these losses was observed in the
 300 latest period in parallel to NUE increases.

301

302

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

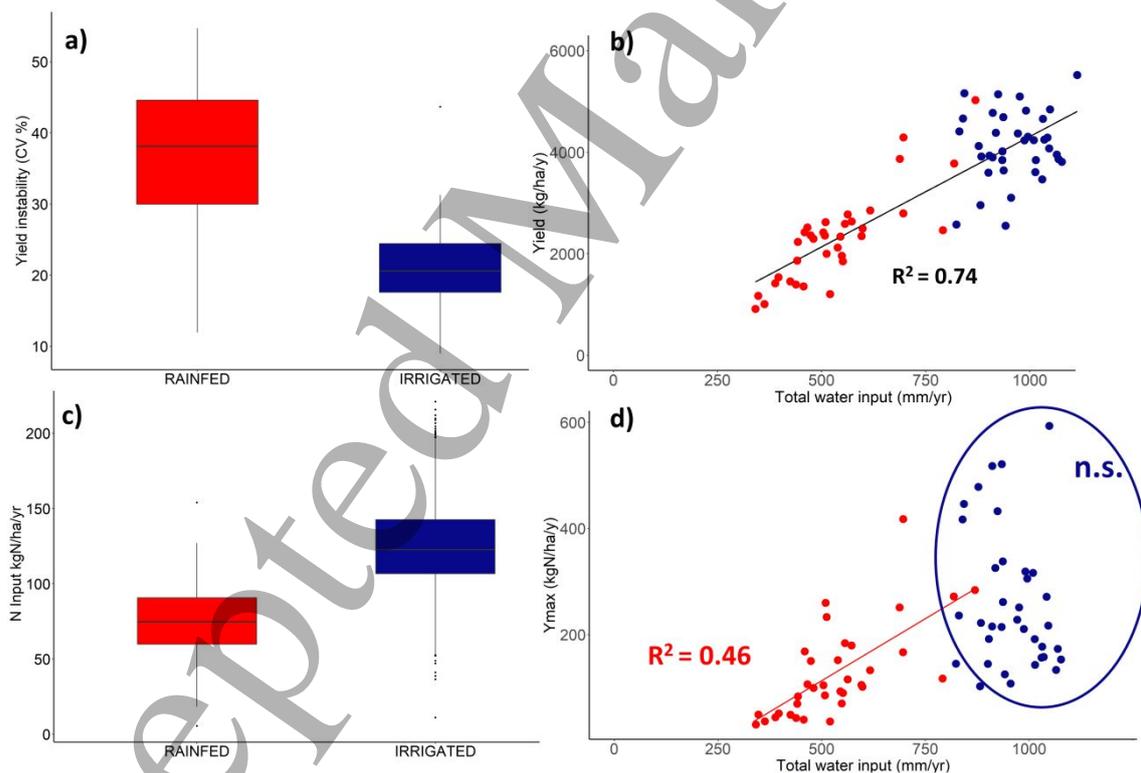
The crop yield response to water and N availability was stated as a paradigm of co-limitation, the simultaneous limitation of plant productivity by multiple resources. This co-limitation has been well studied in cereal crops of Mediterranean-type environments in Australia and Europe (Cossani and Sadras, 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 (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). Also, water is one of the main drivers of N losses at a cropping systems level, as excessive water input leads to leaching losses and favors denitrification, thereby enhancing N₂O emissions (Section 6). As a consequence, proper management of the interaction between NUE and water use efficiency (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 in Mediterranean areas that determines the pattern of land use (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, oak *dehesas*) or low-productivity rainfed arable crops (i.e., barley, wheat, sunflower, 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 also to crop diversification, providing the opportunity for more complex rotations including highly profitable crops (i.e., horticultural) usually characterized by a demand for large amounts of inputs 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 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 5000–20,000 km²) over 26 years (1990–2015). These provinces have

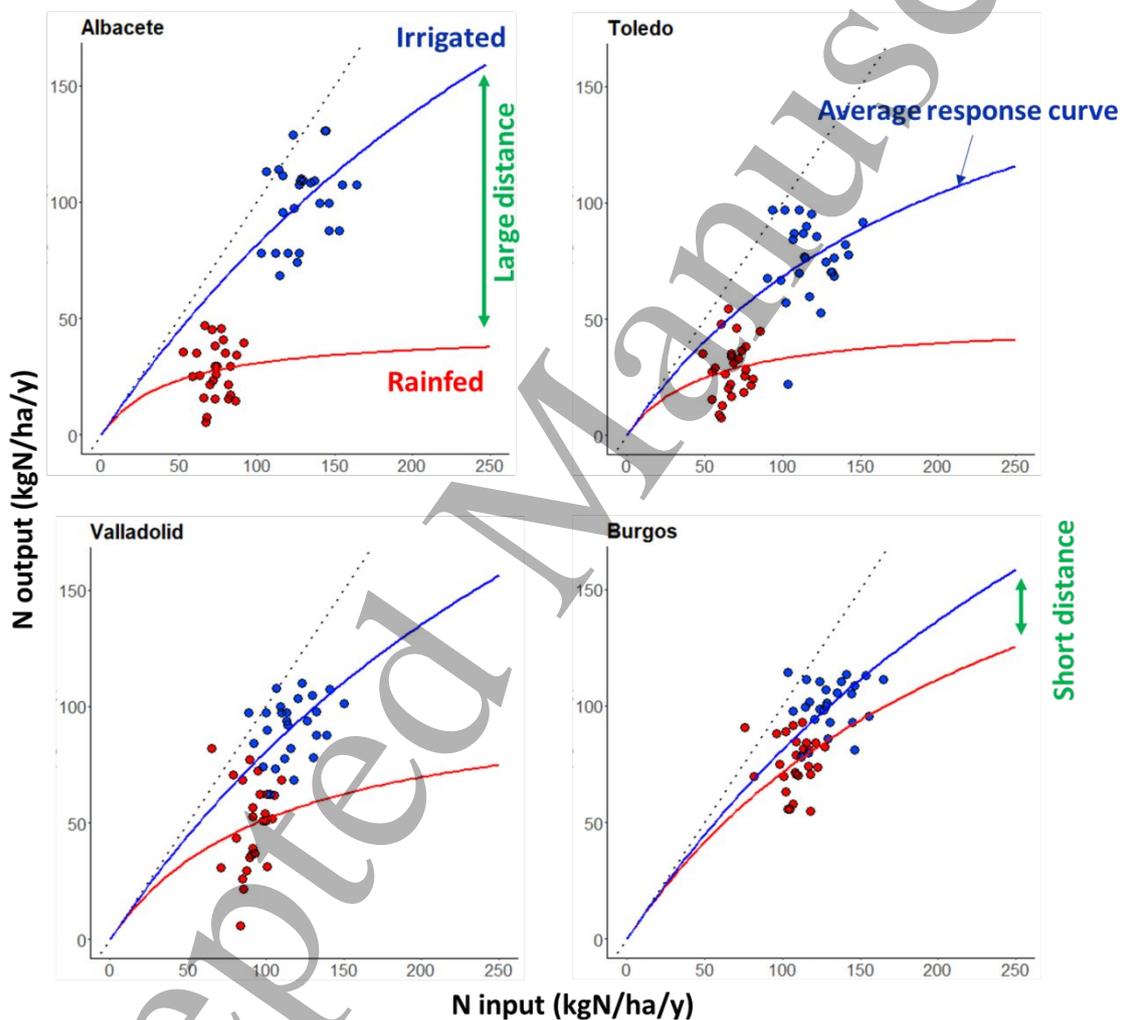
336 Mediterranean climate but different levels of annual precipitation (province range 341-869
 337 mm/yr), temperature (province annual mean temperature range 11-18 °C) and latitude (province
 338 range 36.5-42.8° latitude N). Average yield per province ranged from 0.9-2.5 t/ha/yr for rainfed
 339 systems and 2.6-5.5 t/ha/yr for irrigated systems.

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



350
 351 **Figure 5** Yield instability of wheat in rainfed and irrigated systems for the 40 Spanish provinces under
 352 Mediterranean conditions (1990-2015) (a); relationship between mean water input (precipitation +
 353 irrigation) and mean yield for each of the 40 provinces for rainfed and irrigated systems (b); mean N fertilizer
 354 input (1990-2015) of the 40 provinces for rainfed and irrigated systems (c); and relationship between total
 355 water input and Y_{\max} (the parameter of the hyperbolic response curve that relates yield and N inputs
 356 representing maximum yield at saturating N rates), $R^2 = 0.46$ for rainfed systems, and no significant (n.s.)
 357 relationship for irrigated crops (d).

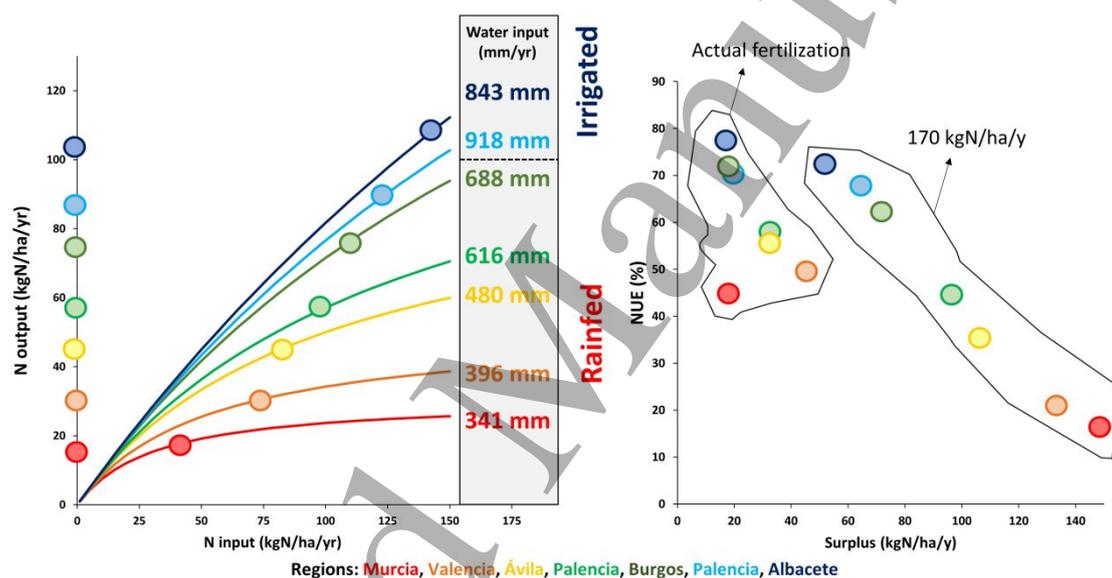
358 This relationship has important implications for agro-environmental management of fertilization
 359 in rainfed systems. In regions with water scarcity, crop N uptake is rapidly saturated and N
 360 surpluses accompanied by pollution (e.g., leaching during rainfall events) could occur at low
 361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



367
 368 **Figure 6** Yield vs. total N inputs (1990–2015) in four contrasting Spanish provinces. The curve is the mean
 369 yield fertilization response curve estimated by using the average input and yield during the study period
 370 (1990–2015) for rainfed (red) and irrigated (blue) systems. Annual mean precipitation: Albacete (388
 371 mm/yr), Toledo (426 mm/yr), Valladolid (465 mm/yr), Burgos (688 mm/yr).

372 In summary, for rainfed systems, farmers have the difficult task of adjusting fertilization in order
 373 to maximize yields while reducing N surpluses in a highly variable environment. Mean fertilization
 374 rates per province ranged from 42 to 150 kg N/ha/yr in rainfed systems and from 77 to 186

375 kg N/ha/yr in irrigated systems. In general, actual fertilization rates (estimated as the base for the
 376 national inventories of greenhouse gas emissions) are lower in the rainfed systems of those
 377 provinces with lower precipitation and faster N saturation (Fig. 7), and, with some exceptions,
 378 moderate N surplus (usually lower than 50 kg N/ha/yr). Poor planning with high fertilization rates
 379 in a very dry year entails a disproportionately low NUE and significantly high emissions of Nr to
 380 the environment. As described in Section 3, the increasing livestock production is generating a
 381 growing amount of manure that has to be properly managed and recirculated to crops. This
 382 manure application has to consider the distinct response of cropping systems to N applications.
 383 For example, the EU Nitrates Directive limits the application of N in manure to 170 kg N/ha/yr for
 384 areas considered as Nitrate Vulnerable Zones. These rates, albeit legal, would strongly reduce NUE
 385 in the drier regions, severely impairing the environment (Fig. 7).



386
 387 **Figure 7.** Yield vs. fertilization response curves, NUE and surplus under rainfed and irrigated conditions in
 388 several Spanish provinces in a precipitation gradient (period 1990-2015). Water input (mm/yr) is the mean
 389 annual water input including precipitation and irrigation. Averaged fertilization rates and yields (1990-2015
 390 averages) are provided by the Spanish Ministry of Agriculture as well as the result of a hypothetical
 391 fertilization rate of 170 kg N/ha/yr that is the limit of application of N in manure at the Nitrate Vulnerable
 392 Zones.

393

394 5. Interactions of N use with adaptation to climate change

395 As a summary of the climate change conditions in the Mediterranean described in Section 1,
 396 increases in maximum and minimum temperatures and in atmospheric CO₂ concentration are
 397 expected to be associated with decreased and more unpredictable precipitation. These changes
 398 combined will result in stronger fluctuations in water stress for crops (Fig. 4 Suppl.). Besides these
 399 climatic effects, “elevated atmospheric CO₂ concentration” (hereafter eCO₂) also affects plant N

1
2
3 400 dynamics. Therefore, under climate change scenarios with eCO₂, N dynamics with water and
4 401 temperature interactions have to be comprehensively studied. These effects are in general less
5 402 understood; however, in the past few decades, Free Air CO₂ Enrichment (FACE) experiments
6 403 (O'Leary *et al.*, 2015) and other laboratory or modeling studies indicate that CO₂ might enhance
7 404 photosynthesis in C₃ plant species such as wheat, rice, and barley (Ainsworth and Rogers, 2007),
8 405 especially under dry conditions (Bishop *et al.*, 2014), as well as N fixation by legumes (Parvin *et*
9 406 *al.*, 2018). This might increase total N crop requirements to build more biomass (Ainsworth and
10 407 Rogers, 2007). Under elevated CO₂ conditions, transpiration benefits from reduced stomata
11 408 opening to capture the same amount of CO₂. Therefore, low stomatal conductance, more
12 409 conservative water use, and higher transpiration efficiency may jointly increase WUE as well as
13 410 biomass and total water use (Houshmandfar *et al.*, 2018). On the negative side, a lower N content
14 411 in wheat grain has been reported under high CO₂ conditions (Tausz *et al.*, 2017). For legumes,
15 412 however, reduced N content in grain following a heatwave might be restored with eCO₂ (Parvin
16 413 *et al.*, 2020).

17
18
19
20
21
22
23
24
25
26
27 414 Adaptation to climate change in Mediterranean cropping systems needs to consider these
28 415 interactions and how they are modified by heat and water stress, as both of these adverse
29 416 conditions for crop growth are projected to occur more frequently in the future (Trnka *et al.*,
30 417 2014). Briefly, positive (crop growth stimulation and water saving) and negative (grain N dilution)
31 418 eCO₂ effects alike may be diminished under stressful conditions (Ainsworth *et al.*, 2008; van der
32 419 Kooi *et al.*, 2016). Also, stresses limit the crop response to N, as some part of the fertilizer cannot
33 420 be used while crop growth is water- or temperature-limited (Savin *et al.*, 2019). This implies low
34 421 NUE and high N surplus and greenhouse gas emissions (Quemada and Gabriel, 2016) (Section 4).
35 422 Under these conditions, adaptation of annual crops in Mediterranean environments usually
36 423 implies using varieties with high transpiration efficiency traits and early sowing dates (Porter *et*
37 424 *al.*, 2014). The aim of such strategies is to increase water accumulation over the crop cycle and to
38 425 restore the duration of the vegetation period shortened by warming, which accelerates crop
39 426 development. The target then is to identify the optimum combination of crop phenology and
40 427 sowing date, selecting the earliest possible sowing date ensuring that: (1) there is enough soil
41 428 water for successful germination, emergence, and canopy establishment, (2) the crop will flower
42 429 after the last spring frosts and before late spring–early summer heatwaves, and (3) most of grain
43 430 filling happens before the dry summer period (Kirkegaard and Hunt, 2010; Christy *et al.*, 2018;
44 431 Ruiz-Ramos *et al.*, 2018). These are already the goals of current strategies recommended in
45 432 Mediterranean systems, together with management for conserving soil moisture and reducing
46 433 soil and canopy temperature. For climate change adaptation, the main novelty is that the suitable
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 434 sowing window could become narrower in the future, as may the range of suitable varieties in
4
5 435 terms of phenology, potential yield, and resistance to stresses. Therefore, in these systems the
6
7 436 fulfilment of mitigation targets to reduce Nr emissions within the limits of effective adaptation
8
9 437 will require the combination of new or existing tailored varieties, optimized management for soil
10
11 438 and water conservation, and improved efficiencies, supported by knowledge and technological
12
13 439 solutions (Springmann *et al.*, 2018).

14 440 Farm-level management options such as agroforestry are currently studied in detail for their
15
16 441 potential to improve the sustainability of Mediterranean farming system, especially under climate
17
18 442 change (Arenas-Corraliza *et al.*, 2016; Mosquera-Losada *et al.*, 2018). Among others, they offer
19
20 443 access to deeper soil water tables (Cardinael *et al.*, 2015) and they reduce evaporation due to the
21
22 444 wind-break effect of trees (Campi *et al.*, 2012), thereby enhancing groundwater recharge (Kay *et*
23
24 445 *al.*, 2019), which are important issues regarding the climate projections for the Mediterranean.
25
26 446 While it has been shown that agroforestry can increase soil fertility and nutrient availability in
27
28 447 Europe (mostly Mediterranean cases) and North Africa (Torralba *et al.*, 2016; Zayani *et al.*, 2020),
29
30 448 and that tree–legume interactions maintain a sufficient level of N fixation under the shade of trees
31
32 449 in a Mediterranean agroforestry system (Querné *et al.*, 2017), the implications of agroforestry for
33
34 450 nutrient acquisition under water and heat stress are still poorly understood (Guillot *et al.*, 2019).
35
36 451 As stated by (Isaac and Borden, 2019), extensive research is needed on how agroforestry practices
37
38 452 stabilize key nutrient acquisition patterns in the face of environmental change.

39
40 453 Conservation agriculture (CA) – with no (or reduced) tillage, permanent organic soil cover, and
41
42 454 crop diversification – is another innovative agricultural system that has been suggested for climate
43
44 455 mitigation and adaptation in the Mediterranean due to its soil and water conservation capability
45
46 456 (Kassam *et al.*, 2012). The physical, chemical, and biological properties of soil are improved,
47
48 457 resulting in higher yields for dry conditions due to improved soil moisture availability (Mrabet,
49
50 458 2002). Although authors logically hypothesize on improved nutrient availability, studies indicate
51
52 459 that extractable N is not significantly greater under CA (López-Garrido *et al.*, 2011).
53
54 460 Measurements at all soil depths are needed to better understand the effect of CA on nutrient
55
56 461 distribution and its potential contribution to sustainable Mediterranean agriculture (Mrabet *et*
57
58 462 *al.*, 2012). Moreover, in an Italian dry environment, the limited amount of wheat crop residues
59
60 463 during the transition phase to CA required high N fertilization to maintain yields (Galieni *et al.*,
464
465 2016).

466
467

468 6. Emission of Nr compounds: drivers and adapted solutions

469 6.1 Ammonia

470 Similar to temperate agroecosystems, the main pathways of Nr loss from fertilized crops under
471 Mediterranean conditions are NH₃ volatilization to the atmosphere and NO₃⁻ leaching to
472 hydrosystems (Jarvis, 2011; Quemada *et al.*, 2013; Sanz-Cobena *et al.*, 2014). Ammonia (NH₃)
473 volatilization in cropping systems mainly occurs following NH₃ production through mineralization
474 or application of NH₄⁺-containing fertilizers, urea- or manure- and other organic-based N
475 fertilizers. The process of NH₃ volatilization is physicochemical (Walker *et al.*, 2013).
476 Meteorological conditions (air temperature, wind speed near the soil surface, atmospheric
477 stability, and rainfall), soil properties (e.g., texture, cation exchange capacity, and pH), and N
478 management options are the main drivers involved (Bouwman *et al.*, 1997). Most of these factors
479 are vastly determined by Mediterranean unique pedoclimatic conditions and management
480 practices, the latter being shaped by the dominant types of crop and livestock systems present in
481 these areas (Sanz-Cobena, 2010).

482 Atmospheric conditions greatly influence NH₃ volatilization rates (Cape *et al.*, 2009). Typical stable
483 atmospheric conditions with calm periods of wind (commonly associated with high pressures)
484 under Mediterranean conditions may lead to low volatilization rates following fertilization, mainly
485 in winter and during the night (Theobald *et al.*, 2015). Lower emission factors (EF: the percentage
486 of applied N that is lost as NH₃) are expected for winter crops as compared with irrigated summer
487 crops, even if similar agricultural practices are used. The rainfall regime is also critical for the
488 enhancement (or mitigation) of NH₃ losses. Sanz-Cobena *et al.* (2011) showed that more than 7-
489 14 mm water application immediately after fertilizer application is an effective strategy for
490 abating NH₃ volatilization due to enhanced solubilization and incorporation of the fertilizer into
491 the upper soil. By contrast, under low rainfall (i.e., 3 mm) conditions, NH₃ volatilization increases
492 because high concentrations of soluble N forms might be kept at the soil surface and hydrolysis
493 rates triggered following urea application (Sanz-Cobena *et al.*, 2011). Based on this, applying
494 water immediately after surface fertilization would be an efficient NH₃ abatement strategy in
495 irrigated Mediterranean agroecosystems. In rainfed crops, as the Mediterranean climate is
496 characterized by a limited number of rainfall events, the possibility of NH₃ mitigation due to
497 rainfall requires a good weather forecast.

498 Regarding fertilization practices, in Mediterranean cropping systems, even under conditions of
499 high atmospheric stability, the risk of NH₃ volatilization is greater if urea or liquid manure (i.e.,
500 slurries) is surface-applied (Marchetti *et al.*, 2004; Sanz *et al.*, 2010; Abalos *et al.*, 2012; Yagüe and

1
2
3 501 Bosch-Serra, 2013; Bosch-Serra *et al.*, 2014; Recio *et al.*, 2018; Sanz-Cobena *et al.*, 2019). The use
4
5 502 of urea as a synthetic N fertilizer has increased in the past decades in Mediterranean cropping
6
7 503 systems, as in the rest of the world (IFASTAT, 2020). However, the large NH₃ losses associated
8
9 504 with its application, triggered by the hydrolysis-mediated increase in soil pH, necessitate the
10
11 505 implementation of specific NH₃ abatement for this fertilizer (Bittman *et al.*, 2014). The most
12
13 506 common abatement practices are the incorporation of urea immediately following application,
14
15 507 mechanically or by means of water (Sanz-Cobena *et al.*, 2011; Rochette *et al.*, 2013), or the use of
16
17 508 urease inhibitors (Sanz-Cobena *et al.*, 2014; Recio *et al.*, 2020). These synthesized compounds
18
19 509 reduce the rate of urea hydrolysis thus allowing for its incorporation into the soil (Sanz-Cobena *et*
20
21 510 *al.*, 2008; Turner *et al.*, 2010; Sanz-Cobena *et al.*, 2017; Fu *et al.*, 2020). Pollution swapping (such
22
23 511 as N leaching) might also occur if these strategies are improperly managed (Sanz-Cobena *et al.*,
24
25 512 2017). On the contrary, due to the predominant nitrifying conditions in rainfed systems under
26
27 513 Mediterranean conditions, the decreased NH₄⁺ pool induced by urease inhibitors can have a co-
28
29 514 benefit due to mitigated N₂O emissions from this microbiological process (Sanz-Cobena *et al.*,
30
31 515 2016). The incorporation of urea by water in irrigated systems is facilitated (Sanz-Cobena *et al.*,
32
33 516 2011), thus avoiding excessive soil compaction as well as greenhouse gas emissions from
34
35 517 machinery. Increasing generation of animal manures in certain Mediterranean areas (e.g. Italy
36
37 518 and Spain) has triggered ammonia emissions due to surface application of slurries. Although less
38
39 519 effective than injection (Sanz-Cobena *et al.*, 2019), the possibility of adapting existing on-farm
40
41 520 equipment to mix the slurry with the soil makes this option technically suitable and cost-effective
42
43 521 (Bittman *et al.*, 2014).

44 522 6.2 Nitrous oxide

45
46 523 Studies on N₂O emissions in Mediterranean cropping systems are underrepresented compared to
47
48 524 other temperate areas. (Aguilera *et al.*, 2013b), and studies deciphering N₂O formation pathways
49
50 525 are conspicuously low. The few published studies to date point at nitrification and nitrifier-
51
52 526 denitrification as particularly relevant mechanisms in Mediterranean soils (Zhu *et al.*, 2013). The
53
54 527 prevalence of distinct formation pathways in Mediterranean soils, driven by the specific climatic
55
56 528 conditions and agronomic practices, will ultimately determine the best N₂O mitigation strategies.
57
58 529 There is ample evidence that N₂O emission factors (EF: the percentage of applied N that is lost as
59
60 530 N₂O) in Mediterranean rainfed cropping systems (EF: 0.27% according to Cayuela *et al.*, 2017) are
531
532 531 significantly lower than in other temperate areas (0.9% according to Stehfest and Bouwman
533
534 532 2006). However, as irrigation is a common practice in Mediterranean cropping systems in
535
536 533 summer, it changes the moisture pattern and substantially increases the total amount of water in

1
2
3 534 soil. As a consequence, EFs in irrigated crops (0.63%) are significantly higher than in rainfed crops
4
5 535 (0.27%) (Aguilera *et al.*, 2013b; Cayuela *et al.*, 2017).

6
7 536 In both rainfed and irrigated systems, the adjustment of N application to crop needs is one of the
8
9 537 best recommended strategies to mitigate N₂O emission (Guardia *et al.*, 2018). Additionally, the
10
11 538 use of nitrification inhibitors with both synthetic and organic N fertilizers (Sanz-Cobena *et al.*,
12
13 539 2012; Abalos *et al.*, 2014; Gilsanz *et al.*, 2016; Guardia *et al.*, 2017b) is also an effective mitigation
14
15 540 strategy.

16
17 541 The type of irrigation directly determines N₂O emissions (Cayuela *et al.*, 2017). Localized irrigation
18
19 542 systems such as drip irrigation significantly abate N₂O losses due to a highly localized moist area.
20
21 543 On the contrary, sprinkler-irrigated fertilized systems are an important source of N₂O emissions
22
23 544 due to the increased soil moisture in large surface areas (Guardia *et al.*, 2017b). Nevertheless,
24
25 545 recent studies show how optimized sprinkler irrigation systems can considerably reduce N₂O
26
27 546 emissions in intensive maize crops (Franco-Luesma *et al.*, 2019; Franco-Luesma *et al.*, 2020).

28
29 547 Precipitation following long drought periods promotes high N₂O emissions. This is very common
30
31 548 in Mediterranean soils in summer or following the first rainfall in autumn (Cárdenas *et al.*, 1993).
32
33 549 A recent meta-analysis demonstrates that flooding the soil after extended periods of drought
34
35 550 produces a larger pulse in N₂O emissions, compared with soils that were already moderately wet
36
37 551 before the flood event (Barrat *et al.*, 2020). These pulses are likely more common under
38
39 552 Mediterranean conditions than in temperate agroecosystems where pulses are usually due to
40
41 553 freeze–thaw events (Sanchez-Martin *et al.*, 2010).

42
43 554 Another important factor modulating N₂O emissions in Mediterranean cropping systems is soil
44
45 555 pH. Mediterranean soils are predominantly neutral or alkaline (Slessarev *et al.*, 2016) and this has
46
47 556 important implications for the final ratio of denitrification products. (Cayuela *et al.*, 2013) found
48
49 557 an average N₂O/(N₂+ N₂O) ratio of 0.4 in five Mediterranean high-pH soils, whereas the average
50
51 558 value for other temperate soils was 0.8. This implies that the last step of denitrification (the
52
53 559 transformation of N₂O to N₂) was enhanced in Mediterranean soils. A recent global meta-analysis
54
55 560 of 1104 field measurements found soil pH to be the most relevant parameter defining regional
56
57 561 N₂O emissions, with significantly lower EFs for soils with increasing pH (Wang *et al.*, 2018).

562 6.3 Nitric oxide

56
57 563 Together with N₂O, nitric oxide (NO) is a by-product of nitrification (Medinets *et al.*, 2015), thus
58
59 564 particularly common in Mediterranean rainfed systems (Vallejo *et al.*, 2005; Meijide *et al.*, 2007;
60

1
2
3 565 Meijide *et al.*, 2009; Sanchez-Martín *et al.*, 2010; Sanz-Cobena *et al.*, 2012; Guardia *et al.*, 2017a;
4 566 Guardia *et al.*, 2017b; Recio *et al.*, 2019). Significant emissions of NO, a precursor of tropospheric
5 567 ozone (O₃), have been reported after N fertilization with either organic or synthetic N fertilizers
6 568 and in both rainfed and irrigated systems, particularly if drip-irrigation is performed (Guardia *et al.*
7 569 *et al.*, 2017a). These authors associated increased NO fluxes with enhanced nitrification in the
8 570 proximity of the wet front that surrounds the irrigation bulb. There is evidence that NO_x (both NO
9 571 and NO₂) emission exponentially increases with temperature and that, after soil rewetting, strong
10 572 pulses of NO_x emission are produced in high-temperature regions (Garrido *et al.*, 2002). In the
11 573 Mediterranean region, as mentioned earlier, the pulses that occur after rewetting result in high
12 574 contributions to the total NO budget. Analyzing the different agroecosystems, irrigated crops are
13 575 also important contributors of NO, because the importance of nitrification and the temporal
14 576 pattern of soil moisture occurred when the soil temperature is high, with frequent irrigation–
15 577 drying cycles. Abating soil NO_x emissions should be considered in future efforts to improve
16 578 regional air quality in the surrounding of irrigated crops, because these emissions contribute to
17 579 the high concentration of O₃ found in many rural areas in the Mediterranean region (Calvete-Sogo
18 580 *et al.*, 2014).

31 581 *6.4 Nitrate and losses to the hydrosphere*

32 582 In Mediterranean irrigated agriculture, nitrate leaching is strongly dependent on water
33 583 application. Intensive irrigation together with over-fertilization is the main cause of nitrate
34 584 leaching (Isidoro *et al.*, 2006; Caverro *et al.*, 2012; Laspidou and Samantzi, 2014; Lasagna and De
35 585 Luca, 2019). Excessive water is often applied either to avoid salt accumulation in soil or to
36 586 compensate for the heterogeneity of the water-delivery system, enhancing nitrate leaching
37 587 during crop growth (Díez *et al.*, 2000). Low crop N availability is then compensated by increasing
38 588 fertilizer rates leading to a vicious circle characterized by low WUE and NUE. Therefore, the two
39 589 main drivers of nitrate leaching are water percolation and soil inorganic N accumulation, and
40 590 strategies to mitigate losses are oriented toward keeping these processes under sustainable
41 591 thresholds.

42 592 Strategies to improve water management rely on adapting water application to crop
43 593 requirements and are mainly based on improving irrigation schedules or technologies. Irrigation
44 594 should be scheduled to avoid over-irrigation and limit water percolation (Zinkernagel *et al.*, 2020).
45 595 Additionally, the water delivery technology may have a major impact on the main N processes
46 596 governing N losses. Drip and sprinkle irrigation have the potential to localize water in the root
47 597 zone and limit percolation and nitrate leaching (Causape *et al.*, 2006; Vazquez *et al.*, 2006; Caverro

1
2
3 598 *et al.*, 2012; Garcia-Garizabal *et al.*, 2014; Malik *et al.*, 2019), whereas with flood irrigation it is
4
5 599 difficult to achieve a high water efficiency and control leaching losses (Garcia-Garizabal *et al.*,
6
7 600 2012).

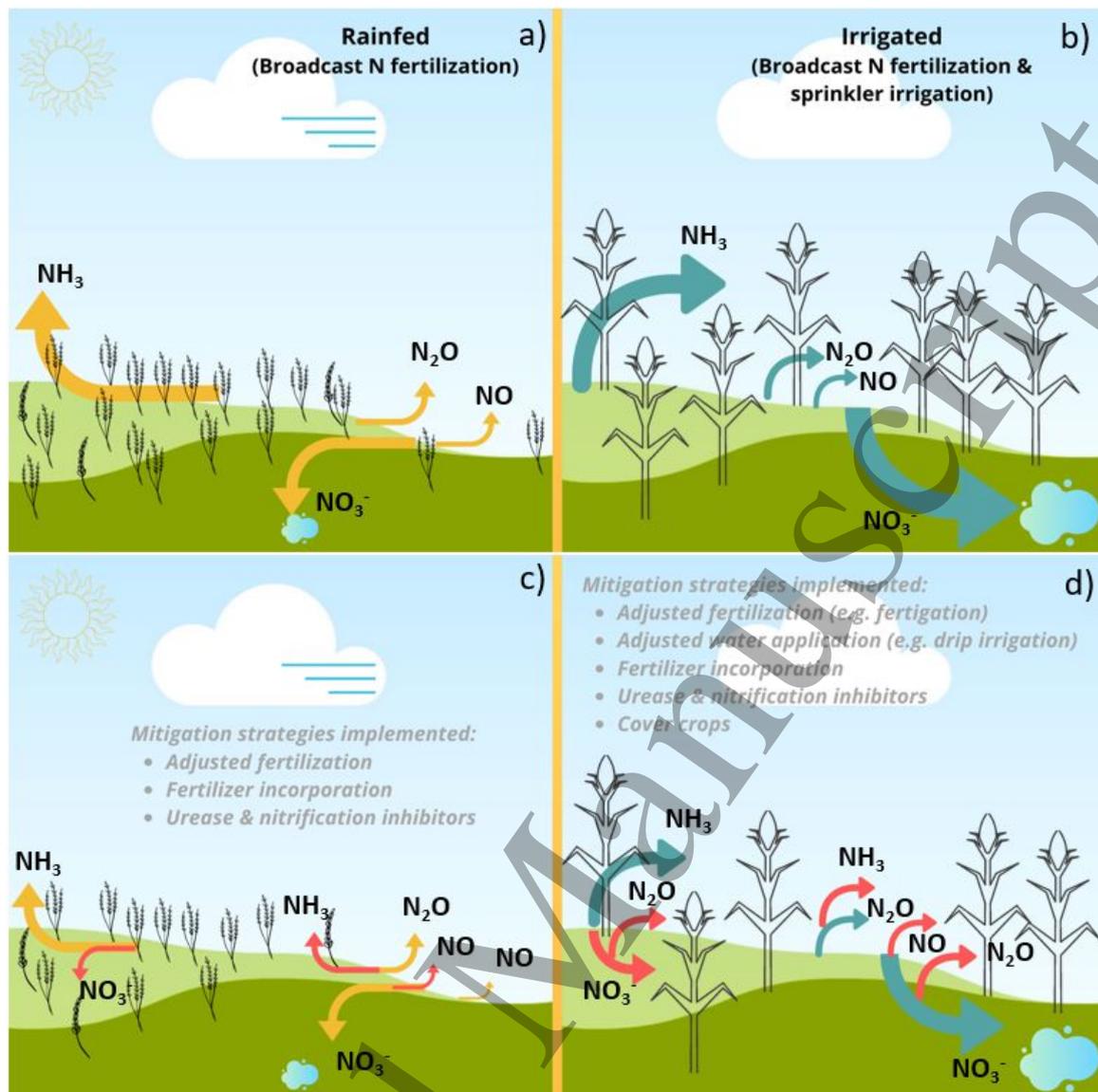
8
9 601 Adjusting N fertilization, both synthetic and organic, to crop requirements remains crucial in order
10
11 602 to avoid soil N accumulation and mitigate nitrate leaching (Quemada *et al.*, 2013). Intensive
12
13 603 livestock associated with irrigated land is common in Mediterranean areas and avoiding excessive
14
15 604 application of manure to cropland is highly recommended (Mantovi *et al.*, 2006; Nikolaidis *et al.*,
16
17 605 2009; Yague and Quilez, 2010). In the Po valley, establishing a N balance to minimize N surplus
18
19 606 was identified as the first step toward mitigating the effect of high livestock concentration that
20
21 607 leads to poor water quality (Perego *et al.*, 2012).

22 608 Replacing the traditional fall–winter fallow by cover crops in irrigated areas reduced nitrate
23
24 609 leaching by 35% on average in a meta-analysis of irrigated land (Quemada *et al.*, 2013). Compare
25
26 610 to fallow soils, cover crops minimize the risk of N leaching by reducing water percolation due to
27
28 611 an increase in evaporation, assimilating the soil residual N after harvesting the summer crop thus
29
30 612 reducing nitrate concentration in the leachate, and enhancing microbial N immobilization
31
32 613 associated to C inputs from cover crops roots (Gabriel *et al.*, 2012; Benoit *et al.*, 2016; Thapa *et al.*,
33
34 614 2018). Replacing the fallow with a non-legume is more efficient than with a legume in reducing
35
36 615 leaching, and mixes of grass/legume greatly reduce leaching with respect to the fallow (Tosti *et al.*,
37
38 616 2014). Additionally, the combination of N recycling and the boost of soil N mineralization in
39
40 617 the short and long term after cover crops may allow to reduce fertilization rates without affecting
41
42 618 yields. Indeed, the increase in N₂O emissions caused by legume cover crops could be offset by the
43
44 619 N fertilizer savings and its associated indirect CO₂ emissions (Guardia *et al.*, 2019; Quemada *et al.*,
45
46 620 2020b). In general, Mediterranean irrigated soils are prone to high mineralization rates, and
47
48 621 strategies that enhance soil stable organic compounds, allow for the recovery of soil physical
49
50 622 properties and fertility in the long term and contribute toward mitigating nitrate leaching losses
51
52 623 (Diacono and Montemurro, 2010; García-González *et al.*, 2018).

53
54 624 An additional pathway of N losses that is influenced by practices such as irrigation and cover
55
56 625 cropping is leaching of dissolved organic N (DON). Soil water content regulates the ratio of DON
57
58 626 and inorganic N forms in Mediterranean soils, being DON dominant under various plant
59
60 627 communities during wet periods (Delgado-Baquerizo *et al.*, 2011). In an irrigated maize field of
61
62 628 central Chile, DON leaching under a grass cover crop was twice the rate of nitrate leaching, even
63
64 629 if the total N losses were reduced compared with the fallow (Salazar *et al.*, 2019). Although the
65
66 630 full ecological significance of DON loss remains unclear, it may represent a large part of the total

1
2
3 631 dissolved N, and monitoring DON leaching may contribute toward mitigating diffuse pollution
4
5 632 from agricultural systems.
6

7 633 Losses to hydrosystems from rainfed agriculture in the Mediterranean basin are mainly associated
8
9 634 with dissolved N in runoff or attached to soil-eroded particles (Section 7). In rainfed cropland,
10
11 635 nitrate leaching showed to be relevant after intense rainfall events or wet periods that are
12
13 636 common in semi-arid (Ruiz-Ramos *et al.*, 2011) or humid (Arregui and Quemada, 2006)
14
15 637 Mediterranean areas. High winter nitrate flows from upland cereals are very common when
16
17 638 winter fertilization is applied (Lassaletta *et al.*, 2009, 2010). Finally, transformation of rainfed into
18
19 639 irrigated fields may greatly enhance nitrate leaching and become a major risk for water pollution
20
21 640 if it concerns large areas (Merchan *et al.*, 2015). During the transition period, N mineralization
22
23 641 may release a large amount of nitrate until the soil organic matter content reaches a new
24
25 642 equilibrium (Quemada and Gabriel, 2016). Promoting temporary soil mining by minimizing N
26
27 643 fertilizer application may help mitigate the risk of nitrate pollution (Vazquez *et al.*, 2006). The
28
29 644 main pathways of environmental N losses from rainfed and irrigated cropland are summarized in
30
31 645 Figure 8.
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60



646

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

655

656 7. From the croplands to the aquatic continuum

657 7.1 Soil erosion and N flows

658 Mediterranean soils are particularly vulnerable to water erosion, due to frequent intense rainfall
 659 events (Cortesi *et al.*, 2012; Merheb *et al.*, 2016), the typical steep slopes (Tarolli *et al.*, 2012) and
 660 the climatic conditions that make Mediterranean regions prone to wildfire, often associated with

1
2
3 661 soil erosion (Shakesby, 2011). While annual precipitation in many Mediterranean regions is
4
5 662 expected to decrease under climate change (Cramer *et al.*, 2018; Brogli *et al.*, 2019), several
6
7 663 studies highlight an expected increase in extreme precipitation events (Hagos *et al.*, 2016; Polade
8
9 664 *et al.*, 2017; Trambly and Somot, 2018) which could lead to increased soil erosion (Morán-
10
11 665 Ordóñez *et al.*, 2020).

12 666 It has been estimated that globally 23–42 Tg N is moved by soil erosion each year, which is in the
13
14 667 same order of magnitude as N applied as chemical fertilizer and N removed by harvested crops
15
16 668 (Quinton *et al.*, 2010). In spite of this, the transport of N has been largely neglected in soil erosion
17
18 669 studies, which mostly focus on the impact of erosion on the redistribution of soil organic matter
19
20 670 (SOM) and associated phosphorus (Garnier *et al.*, 2015). N is a structural component of SOM
21
22 671 (Tipping *et al.*, 2016), hence, the transport of SOM after extreme rainfall events affects soil N
23
24 672 stocks. The redistribution of SOM is associated with the dynamics of sediment transport and
25
26 673 deposition (Boix-Fayos *et al.*, 2015). As such, SOM may be deposited in common depositional
27
28 674 landscape units, including river bars, floodplains, and reservoirs (Fissore *et al.*, 2017) (see also
29
30 675 Section 7.2). The impact of soil erosion on SOM dynamics is still open to debate. Eroded SOM may
31
32 676 be subject to mineralization during transport, potentially leading to increased SOM
33
34 677 decomposition (Lal, 2004), depending on the travel time and distance (Quinton *et al.*, 2010). On
35
36 678 the contrary, the deep burial of SOM-rich sediments may lead to reduced SOM decomposition
37
38 679 rates (Berhe *et al.*, 2007). Due to heterogeneous land use configurations, the transport of
39
40 680 sediment and SOM in Mediterranean catchments is highly complex (Boix-Fayos *et al.*, 2015),
41
42 681 making it more difficult to assess how SOM, and consequently N, is redistributed in Mediterranean
43
44 682 environments.

42 683 *7.2 N retention in Mediterranean river basins*

45 684 Nitrogen losses from agricultural land reach water bodies by surface runoff and leaching to
46
47 685 groundwater, as well as by soil erosion and atmospheric deposition. Once in the aquatic system,
48
49 686 N undergoes different processes of transport, storage, transformation and elimination to gaseous
50
51 687 forms, and part of it is finally exported to coastal areas.

52
53 688 Mediterranean climatic features, including high temperatures and low rainfall, often
54
55 689 concentrated in a few large precipitation events, favor N retention in the watersheds –i.e.
56
57 690 considering retention as the sum of storage, transformation and elimination processes–. High
58
59 691 temperatures are accompanied by high evapotranspiration rates, so runoff mainly occurs after
60
61 692 intense events. Moreover, the irregular precipitation patterns and the recurrence of summer

1
2
3 693 droughts have driven intensive hydraulic management to secure water availability (Castaldelli *et*
4 694 *al.*, 2013; Soana *et al.*, 2017; Soana *et al.*, 2019; Romero *et al.*, 2021), and most rivers comprise a
5
6 695 large number of dams, reservoirs and irrigation channels (Sadaoui *et al.*, 2018). Reservoirs and
7
8 696 channels increase land-water contact surface and residence time in the watersheds, and allows
9
10 697 for enhanced nutrient processing via denitrification, uptake by riparian vegetation and freshwater
11 698 macrophytes, infiltration and leaching to groundwater (Bartoli *et al.*, 2012; Lassaletta *et al.*, 2012;
12 699 Romero *et al.*, 2016). Besides, reservoirs are built to contend with water scarcity and buffer great
13
14 700 episodes of rain and flooding, which means that they also decrease the transport of N to coastal
15
16 701 areas during flashy rainfall events.
17
18

19 702 All these waterwork developments contribute to increasing N retention in the river basin with
20 703 potentially higher pressure on inland waters (including groundwater) and less export to coastal
21 704 systems. Higher retention percentages in the Mediterranean with respect to other climatic
22 705 conditions –and especially in arid and semiarid Mediterranean basins– have been reported in
23 706 several recent studies that include different geographical scales (the Iberian Peninsula, European
24 707 Mediterranean basins, and the entire Mediterranean basin) and different modeling approaches
25 708 (Romero *et al.*, 2016; Grizzetti *et al.*, 2021; Romero *et al.*, 2021).
26
27
28
29
30
31

32 709 Despite high retention and hence high elimination rates, N concentration in water bodies might
33 710 be increased in regions affected by water scarcity due to the low dilution capacity by water flow,
34 711 as has been observed in southern Europe, mainly in Spain, Italy and Greece (Grizzetti *et al.*, 2017).
35 712 In addition, as N retention includes permanent and temporal components, high values of
36 713 retention might hide an accumulation of N in soils and groundwater in the river basin, and a delay
37 714 between sources and impacts in aquatic ecosystems (Grizzetti *et al.*, 2015).
38
39
40
41
42
43
44

45 715

46 716 **8. Lessons learned and policy dimensions**

47 717 The climatic and agronomic specificities of the Mediterranean region worldwide demand N
48 718 management techniques specifically suited for this region. Agronomic practices (rainfed vs.
49 719 irrigated crops; annual crops vs. permanent crops) or soil characteristics (acidic vs. calcareous; soil
50 720 carbon content) could limit the beneficial effects of sustainable practices successfully developed
51 721 and implemented in other regions, and even prevent their implementation. In any case, they
52 722 should be adapted considering the climate change context and potential adverse side effects, such
53 723 as pollution swapping. The definition of the most suited management practices at the local level
54
55
56
57
58
59
60

1
2
3 724 should be defined under a co-creation process considering the end-users' needs and constraints
4
5 725 with the support of researchers and the various implicated agents.
6

7 726 The systemic approach considering the overall N budget within the agro-food system in the
8
9 727 Mediterranean Basin has highlighted those processes demanding urgent action. Anyhow,
10
11 728 accounting, surveillance, and control of the different elements of the agro-food system need to
12
13 729 be implemented. Although measures taken at the farm level eventually impact the overall system,
14
15 730 multilateral, subregional, and national actions are needed to control N surpluses and their
16
17 731 environmental impacts. This study has identified important differences in the agro-food system
18
19 732 across the Mediterranean Basin, mostly related to climatic factors (coastal vs. in-land areas;
20
21 733 subarid vs. arid areas). The study of these systems at the national and province level has identified
22
23 734 where governmental actions via incentives or regulations are needed, considering the geopolitical
24
25 735 angle in the degree of intensification or import–export of feed and food.

26
27 736 In the Mediterranean biome, management of water and N should be jointly appraised developing
28
29 737 N fertilization schemes tailored not only to the potential N crop demand but also to water
30
31 738 availability (quantity) and quality, the soil chemical and physical characteristics, as well as the
32
33 739 fertilizer resources locally available. The case of the agro-food system transformation observed in
34
35 740 the countries of the Mediterranean Basin is paradigmatic. The increasing manure production and
36
37 741 the associated crop–livestock disconnection are critical in other regions of the world (Garnier *et*
38
39 742 *al.*, 2016; Jin *et al.*, 2020; Mueller and Lassaletta, 2020), but they are of particular concern in the
40
41 743 Mediterranean Basin. The best use of the available local manure has to consider the much lower
42
43 744 response of rainfed systems and the high leaching potential of irrigated systems. Thus, the
44
45 745 consideration not only of the two contrasting worlds –namely, rainfed and irrigated systems – but
46
47 746 also of the precipitation gradient to rainfed systems is important. Analysis of potential maximum
48
49 747 yields and yield vs. fertilization relationships, adapted to local conditions, should be made to set
50
51 748 sustainable N application rates.

52
53 749 In conclusion, bottom–up and top–down approaches should go hand in hand, combining (1) local
54
55 750 assessments of the most suited farming systems that jointly improve N and water use efficiency
56
57 751 considering the crop specificities, water availability for irrigation, and the edapho-climatic
58
59 752 conditions up-scaled to national and continental level, and (2) a systemic analysis of N inputs into
60
753 the systems fueled by food demand. Indicators for monitoring should be derived in order to
754 suggest policies and governance systems tailored to the local specificities. In addition, structural
755 measures promoting the reconnection of crop and livestock farming, including the relocation of
756 feed production, the reduction of food waste, and the consideration of the key effect of human
757 consumption patterns (diet, reconnection of production and consumption in time and space) have

1
2
3 758 to be considered (Billen *et al.*, 2019). This integrated vision is aligned with the spirit of the recent
4
5 759 Farm to Fork Strategy (and Biodiversity Strategy) of the European Union that aims to halve N
6
7 760 pollution in agricultural systems and also considers recommendations at the consumption level..

8
9 761 Markets are not currently considering N-related environmental externalities in the region, which
10
11 762 also have socio-economic implications. However, the lack of proper connection of our scientific
12
13 763 findings with socio-economic indicators prevents defining relevant guidelines integrating
14
15 764 agronomic, environmental and social aspects of the Mediterranean farming systems.
16
17 765 Nevertheless, farmers' adoption of locally suited best sustainable practices could very likely result
18
19 766 in yield losses compared to "business as usual" practices, demanding the implementation of
20
21 767 compensating schemes to account for the environmental services they provide.

22
23 768 As a whole, the implementation of these practices also demands modifications in rural planning,
24
25 769 considering the local biophysical, climatic, and socioeconomic conditions but also the
26
27 770 heterogeneity of different land uses at the landscape and catchment levels. The integration of
28
29 771 sustainable practices at the regional scale may help address coexisting environmental challenges
30
31 772 such as land degradation, biodiversity loss, food security, climate change mitigation and
32
33 773 adaptation, and water scarcity (Ruiz *et al.*, 2020). These features should be taken into account
34
35 774 when developing future policies by integrating top-down system analysis with bottom-up
36
37 775 initiatives aiming to identify the most urgent problems and feasible solutions, based on the
38
39 776 quantification of ecosystem services as well as sustainable economic issues and the well-being of
40
41 777 farmers (van Leeuwen *et al.*, 2019).

42
43 778

44 779 **Acknowledgments**

45 780 This work was partly supported by 7th Framework Programmes funded by the European Union
46
47 781 through the LUC4C project (grant agreement 603542). A. Bondeau and W. Cramer acknowledge
48
49 782 Labex OT-Med (ANR-11-LABX-0061) funded by the French Government Investissements d'Avenir
50
51 783 program of the French National Research Agency (ANR) through the A*MIDEX project (ANR-11-
52
53 784 IDEX-0001-02)., We are grateful to the Spanish Ministry of Economy and Competitiveness
54
55 785 (AgroSceNA-UP, PID2019-107972RB-I00), the Comunidad de Madrid, Spain (AGRISOST-CM
56
57 786 S2018/BAA-4330 project). L. Lassaletta is supported by Spanish Ministry of Economy and
58
59 787 Competitiveness (MINECO) and European Commission ERDF Ramón y Cajal grant
60
788 (RYC-2016-20269), Programa Propio from UPM, and acknowledges the Comunidad de Madrid
789 (Spain) and structural funds 2014-2020 (ERDF and ESF). E. Aguilera is supported by a Juan de la
790 Cierva research contract from the Spanish Ministry of Economy and Competitiveness (FJCI-2017-
791 34077). A. Sanz-Cobena thanks to the Autonomous Community of Madrid and UPM for their
792 economic support through the research project APOYO-JOVENES-NFW8ZQ-42-XE8B5K. We are
793 very grateful to the two anonymous reviewers for their constructive and useful suggestions.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

794

Accepted Manuscript

795 **References**

- 796 Abalos, D, Jeffery, S, Sanz-Cobena, A, Guardia, G, Vallejo, A, 2014. Meta-analysis of the effect of
797 urease and nitrification inhibitors on crop productivity and nitrogen use efficiency.
798 *Agriculture, Ecosystems & Environment* 189, 136-
799 144.<http://dx.doi.org/10.1016/j.agee.2014.03.036>
- 800 Abalos, D, Sanz-Cobena, A, Misselbrook, T, Vallejo, A, 2012. Effectiveness of urease inhibition on
801 the abatement of ammonia, nitrous oxide and nitric oxide emissions in a non-irrigated
802 Mediterranean barley field. *Chemosphere* 89, 310-318.10.1016/j.chemosphere.2012.04.043
- 803 Aguilera, E, Díaz-Gaona, C, García-Laureano, R, Reyes-Palomo, C, Guzmán, GI, Ortolani, L, Sánchez-
804 Rodríguez, M, Rodríguez-Estévez, V, 2020. Agroecology for adaptation to climate change and
805 resource depletion in the Mediterranean region. A review. *Agricultural Systems* 181,
806 102809.<https://doi.org/10.1016/j.agsy.2020.102809>
- 807 Aguilera, E, Guzmán, GI, Álvaro-Fuentes, J, Infante-Amate, J, García-Ruiz, R, Carranza-Gallego, G,
808 Soto, D, González de Molina, M, 2018. A historical perspective on soil organic carbon in
809 Mediterranean cropland (Spain, 1900–2008). *Science of The Total Environment* 621, 634-
810 648.10.1016/J.SCITOTENV.2017.11.243
- 811 Aguilera, E, Lassaletta, L, Gattinger, A, Gimeno, BSBS, 2013a. Managing soil carbon for climate
812 change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis.
813 *Agriculture, Ecosystems & Environment* 168, 25-
814 36.<http://dx.doi.org/10.1016/j.agee.2013.02.003>
- 815 Aguilera, E, Lassaletta, L, Sanz-Cobena, A, Garnier, J, Vallejo, A, 2013b. The potential of organic
816 fertilizers and water management to reduce N₂O emissions in Mediterranean climate
817 cropping systems. A review. *Agriculture, Ecosystems and Environment* 164, 32-
818 52.10.1016/j.agee.2012.09.006
- 819 Ainsworth, EA, Leakey, ADB, Ort, DR, Long, SP, 2008. FACE-ing the facts: inconsistencies and
820 interdependence among field, chamber and modeling studies of elevated [CO₂] impacts on
821 crop yield and food supply. *New Phytologist* 179, 5-9.10.1111/j.1469-8137.2008.02500.x
- 822 Ainsworth, EA, Rogers, A, 2007. The response of photosynthesis and stomatal conductance to
823 rising [CO₂]: mechanisms and environmental interactions. *Plant, Cell & Environment* 30, 258-
824 270.10.1111/j.1365-3040.2007.01641.x
- 825 Arenas-Corraliza, G, Mantino, A, López-Díaz, M, Moreno, G, 2016. Cropping among trees to cope
826 with climate change. 3rd European Agroforestry Conference. EURAF, Montpellier, pp. 23-25
- 827 Arregui, LM, Quemada, M, 2006. Drainage and nitrate leaching in a crop rotation under different
828 N-fertilizer strategies: application of capacitance probes. *Plant and Soil* 288, 57-
829 69.10.1007/s11104-006-9064-9
- 830 Aschmann, H, 1973. Distribution and Peculiarity of Mediterranean Ecosystems. Berlin.
- 831 Bai, ZH, Ma, L, Qin, W, Chen, Q, Oenema, O, Zhang, FS, 2014. Changes in Pig Production in China
832 and Their Effects on Nitrogen and Phosphorus Use and Losses. *Environmental Science &*
833 *Technology* 48, 12742-12749.10.1021/es502160v
- 834 Barrat, HA, Evans, J, Chadwick, DR, Clark, IM, Le Cocq, K, M. Cardenas, L, 2020. The impact of
835 drought and rewetting on N₂O emissions from soil in temperate and Mediterranean climates.
836 *European Journal of Soil Science* n/a.10.1111/ejss.13015
- 837 Barros, R, Isidoro, D, Aragues, R, 2012. Irrigation management, nitrogen fertilization and nitrogen
838 losses in the return flows of La Violada irrigation district (Spain). *Agriculture Ecosystems &*
839 *Environment* 155, 161-171.10.1016/j.agee.2012.04.004

- 1
2
3 840 Bartoli, M, Racchetti, E, Delconte, CA, Sacchi, E, Soana, E, Laini, A, Longhi, D, Viaroli, P, 2012.
4 841 Nitrogen balance and fate in a heavily impacted watershed (Oglio River, Northern Italy): in
5 842 quest of the missing sources and sinks. *Biogeosciences* 9, 361-373.10.5194/bg-9-361-2012
- 7 843 Benoit, M, Garnier, J, Beaudoin, N, Billen, G, 2016. A participative network of organic and
8 844 conventional crop farms in the Seine Basin (France) for evaluating nitrate leaching and yield
9 845 performance. *Agricultural Systems* 148, 105-113.10.1016/j.agsy.2016.07.005
- 11 846 Berhe, AA, Harte, J, Harden, JW, Torn, MS, 2007. The Significance of the Erosion-induced
12 847 Terrestrial Carbon Sink. *BioScience* 57, 337-346.10.1641/b570408
- 13 848 Billen, G, Garnier, J, Lassaletta, L, 2013. The nitrogen cascade from agricultural soils to the sea:
14 849 modelling nitrogen transfers at regional watershed and global scales. *Philosophical*
15 850 *Transactions of the Royal Society B: Biological Sciences* 368.10.1098/rstb.2013.0123
- 17 851 Billen, G, Lassaletta, L, Garnier, J, 2014. A biogeochemical view of the global agro-food system:
18 852 Nitrogen flows associated with protein production, consumption and trade. *Global Food*
19 853 *Security* 3.10.1016/j.gfs.2014.08.003
- 21 854 Billen, G, Lassaletta, L, Garnier, J, 2015. A vast range of opportunities for feeding the world in
22 855 2050: trade-off between diet, N contamination and international trade. *Environmental*
23 856 *Research Letters* 10, 25001-25001.10.1088/1748-9326/10/2/025001
- 25 857 Billen, G, Lassaletta, L, Garnier, J, Le Noë, J, Aguilera, E, Sanz-Cobeña, A, 2019. Opening to Distant
26 858 Markets or Local Reconnection of Agro-Food Systems? Environmental Consequences at
27 859 Regional and Global Scales. *Agroecosystem Diversity*, 391-413.10.1016/B978-0-12-811050-
28 860 8.00025-X
- 29 861 Billen, G, Le Noë, J, Garnier, J, 2018. Two contrasted future scenarios for the French agro-food
30 862 system. *Science of the Total Environment* 637-638, 695-
31 863 705.<https://doi.org/10.1016/j.scitotenv.2018.05.043>
- 33 864 Bishop, KA, Leakey, ADB, Ainsworth, EA, 2014. How seasonal temperature or water inputs affect
34 865 the relative response of C3 crops to elevated [CO2]: a global analysis of open top chamber
35 866 and free air CO2 enrichment studies. *Food and Energy Security* 3, 33-45.10.1002/fes3.44
- 37 867 Bittman, S, Dědina, M, Howard, C, Oenema, O, Sutton, M, 2014. Options for Ammonia Mitigation:
38 868 Guidance from the UNECE Task Force on Reactive Nitrogen. Centre for Ecology and
39 869 Hydrology, Edinburgh, UK
- 41 870 Blas, A, Garrido, A, Unver, O, Willaarts, B, 2019. A comparison of the Mediterranean diet and
42 871 current food consumption patterns in Spain from a nutritional and water perspective. *Science*
43 872 *of The Total Environment* 664, 1020-1029.10.1016/J.SCITOTENV.2019.02.111
- 45 873 Blondel, J, 2006. The 'Design' of mediterranean landscapes: A millennial story of humans and
46 874 ecological systems during the historic period. *Human Ecology* 34, 713-729.10.1007/s10745-
47 875 006-9030-4
- 48 876 Boix-Fayos, C, Nadeu, E, Quiñonero, JM, Martínez-Mena, M, Almagro, M, de Vente, J, 2015.
49 877 Sediment flow paths and associated organic carbon dynamics across a Mediterranean
50 878 catchment. *Hydrol. Earth Syst. Sci.* 19, 1209-1223.10.5194/hess-19-1209-2015
- 52 879 Bosch-Serra, AD, Yagüe, MR, Teira-Esmatges, MR, 2014. Ammonia emissions from different
53 880 fertilizing strategies in Mediterranean rainfed winter cereals. *Atmospheric Environment* 84,
54 881 204-212.<https://doi.org/10.1016/j.atmosenv.2013.11.044>
- 56 882 Bouwman, AF, Lee, DS, Asman, WAH, Dentener, FJ, Van Der Hoek, KW, Olivier, JGJ, 1997. A global
57 883 high-resolution emission inventory for ammonia. *Global Biogeochemical Cycles* 11, 561-
58 884 587.10.1029/97gb02266

- 1
2
3 885 Bouwman, AFF, Beusen, AHWHW, Lassaletta, L, van Apeldoorn, DFF, van Grinsven, HJMJM, Zhang,
4 886 J, Ittersum Van, MKK, 2017. Lessons from temporal and spatial patterns in global use of N
5 887 and P fertilizer on cropland. *Scientific Reports* 7, 40366-40366.10.1038/srep40366
6 888 <http://www.nature.com/articles/srep40366#supplementary-information>
- 8 889 Bouwman, L, Goldewijk, KK, Van Der Hoek, KW, Beusen, AHW, Van Vuuren, DP, Willems, J, Rufino,
9 890 MC, Stehfest, E, 2013. Exploring global changes in nitrogen and phosphorus cycles in
10 891 agriculture induced by livestock production over the 1900–2050 period. *Proceedings of the*
11 892 *National Academy of Sciences* 110, 20882-20887.10.1073/pnas.1012878108
- 13 893 Brogli, R, Sørland, SL, Kröner, N, Schär, C, 2019. Causes of future Mediterranean precipitation
14 894 decline depend on the season. *Environmental Research Letters* 14, 114017.10.1088/1748-
15 895 9326/ab4438
- 16 896 Calvete-Sogo, H, Elvira, S, Sanz, J, González-Fernández, I, García-Gómez, H, Sánchez-Martín, L,
17 897 Alonso, R, Bermejo-Bermejo, V, 2014. Current ozone levels threaten gross primary
18 898 production and yield of Mediterranean annual pastures and nitrogen modulates the
19 899 response. *Atmospheric Environment* 95, 197-
20 900 206. <https://doi.org/10.1016/j.atmosenv.2014.05.073>
- 22 901 Campi, P, Palumbo, AD, Mastroilli, M, 2012. Evapotranspiration estimation of crops protected by
23 902 windbreak in a Mediterranean region. *Agricultural Water Management* 104, 153-
24 903 162. <https://doi.org/10.1016/j.agwat.2011.12.010>
- 26 904 Cape, JN, van der Eerden, LJ, Sheppard, LJ, Leith, ID, Sutton, MA, 2009. Reassessment of Critical
27 905 Levels for Atmospheric Ammonia. In: Sutton, M.A., Reis, S., Baker, S.M.H. (Eds.), *Atmospheric*
28 906 *Ammonia: Detecting emission changes and environmental impacts*. Springer Netherlands,
29 907 Dordrecht, pp. 15-40.
- 31 908 Cárdenas, L, Rondón, A, Johansson, C, Sanhueza, E, 1993. Effects of soil moisture, temperature,
32 909 and inorganic nitrogen on nitric oxide emissions from acidic tropical savannah soils. *Journal*
33 910 *of Geophysical Research: Atmospheres* 98, 14783-14790.10.1029/93jd01020
- 35 911 Cardinael, R, Mao, Z, Prieto, I, Stokes, A, Dupraz, C, Kim, JH, Jourdan, C, 2015. Competition with
36 912 winter crops induces deeper rooting of walnut trees in a Mediterranean alley cropping
37 913 agroforestry system. *Plant and Soil* 391, 219-235.10.1007/s11104-015-2422-8
- 39 914 Castaldelli, G, Soana, E, Racchetti, E, Pierobon, E, Mastrocicco, M, Tesini, E, Fano, E, Bartoli, M,
40 915 2013. Nitrogen Budget in a Lowland Coastal Area Within the Po River Basin (Northern Italy):
41 916 Multiple Evidences of Equilibrium Between Sources and Internal Sinks. *Environmental*
42 917 *Management* 52, 567-580.10.1007/s00267-013-0052-6
- 44 918 Causape, J, Quilez, D, Aragues, R, 2006. Irrigation efficiency and quality of irrigation return flows
45 919 in the Ebro River Basin: An overview. *Environmental Monitoring and Assessment* 117, 451-
46 920 461.10.1007/s10661-006-0763-8
- 47 921 Caverro, J, Barros, R, Sellam, F, Topcu, S, Isidoro, D, Hartani, T, Lounis, A, Ibrikci, H, Cetin, M,
48 922 Williams, JR, Aragues, R, 2012. APEX simulation of best irrigation and N management
49 923 strategies for off-site N pollution control in three Mediterranean irrigated watersheds.
50 924 *Agricultural Water Management* 103, 88-99.10.1016/j.agwat.2011.10.021
- 52 925 Cayuela, ML, Sánchez-Monedero, MA, Roig, A, Hanley, K, Enders, A, Lehmann, J, 2013. Biochar
53 926 and denitrification in soils: when, how much and why does biochar reduce N₂O emissions?
54 927 *Scientific Reports* 3, 1732.10.1038/srep01732
- 56 928 Cayuela, MLML, Aguilera, E, Sanz-Cobena, A, Adams, DCDC, Abalos, D, Barton, L, Ryals, R, Silver,
57 929 WLWL, Alfaro, MAMA, Pappa, VAVA, Smith, P, Garnier, J, Billen, G, Bouwman, L, Bondeau, A,
58 930 Lassaletta, L, 2017. Direct nitrous oxide emissions in Mediterranean climate cropping
59 931 systems: Emission factors based on a meta-analysis of available measurement data.

- 1
2
3 932 *Agriculture, Ecosystems & Environment* 238, 25-
4 933 35.<https://doi.org/10.1016/j.agee.2016.10.006>
5
6 934 Christy, B, Tausz-Posch, S, Tausz, M, Richards, R, Rebetzke, G, Condon, A, McLean, T, Fitzgerald,
7 935 G, Bourgault, M, O'Leary, G, 2018. Benefits of increasing transpiration efficiency in wheat
8 936 under elevated CO₂ for rainfed regions. *Global Change Biology* 24, 1965-
9 937 1977.10.1111/gcb.14052
10
11 938 Cortesi, N, Gonzalez-Hidalgo, JC, Brunetti, M, Martin-Vide, J, 2012. Daily precipitation
12 939 concentration across Europe 1971–2010. *Nat. Hazards Earth Syst. Sci.* 12, 2799-
13 940 2810.10.5194/nhess-12-2799-2012
14
15 941 Cossani, CM, Sadras, VO, 2018. Water-Nitrogen Colimitation in Grain Crops. In: Sparks, D.L. (Ed.),
16 942 *Advances in Agronomy*, Vol 150. Elsevier Academic Press Inc, San Diego, pp. 231-274.
17
18 943 Cramer, W, Guiot, J, Fader, M, Garrabou, J, Gattuso, J-P, Iglesias, A, Lange, MA, Lionello, P, Llasat,
19 944 MC, Paz, S, Peñuelas, J, Snoussi, M, Toreti, A, Tsimplis, MN, Xoplaki, E, 2018. Climate change
20 945 and interconnected risks to sustainable development in the Mediterranean. *Nature Climate*
21 946 *Change*.10.1038/s41558-018-0299-2
22
23 947 Delgado-Baquerizo, M, Covelo, F, Gallardo, A, 2011. Dissolved Organic Nitrogen in Mediterranean
24 948 Ecosystems. *Pedosphere* 21, 309-318.[https://doi.org/10.1016/S1002-0160\(11\)60131-8](https://doi.org/10.1016/S1002-0160(11)60131-8)
25
26 949 Diacono, M, Montemurro, F, 2010. Long-term effects of organic amendments on soil fertility. A
27 950 review. *Agronomy for Sustainable Development* 30, 401-422.10.1051/agro/2009040
28
29 951 Díez, JA, Caballero, R, Roman, R, Tarquis, A, Cartagena, MC, Vallejo, A, 2000. Integrated fertilizer
30 952 and irrigation management to reduce nitrate leaching in Central Spain. *Journal of*
31 953 *Environmental Quality* 29
32
33 954 Fader, M, Shi, S, von Bloh, W, Bondeau, A, Cramer, W, 2016. Mediterranean irrigation under
34 955 climate change: more efficient irrigation needed to compensate for increases in irrigation
35 956 water requirements. *Hydrol. Earth Syst. Sci.* 20, 953-973.10.5194/hess-20-953-2016
36
37 957 Famiglietti, JS, Lo, M, Ho, SL, Bethune, J, Anderson, KJ, Syed, TH, Swenson, SC, de Linage, CR,
38 958 Rodell, M, 2011. Satellites measure recent rates of groundwater depletion in California's
39 959 Central Valley. *Geophysical Research Letters* 38.10.1029/2010gl046442
40
41 960 Fissore, C, Dalzell, BJ, Berhe, AA, Voegtli, M, Evans, M, Wu, A, 2017. Influence of topography on
42 961 soil organic carbon dynamics in a Southern California grassland. *CATENA* 149, 140-
43 962 149.<https://doi.org/10.1016/j.catena.2016.09.016>
44
45 963 Franco-Luesma, S, Alvaro-Fuentes, J, Plaza-Bonilla, D, Arrue, JL, Cantero-Martínez, C, Caverro, J,
46 964 2019. Influence of irrigation time and frequency on greenhouse gas emissions in a solid-set
47 965 sprinkler-irrigated maize under Mediterranean conditions. *Agricultural Water Management*
48 966 221, 303-311.10.1016/j.agwat.2019.03.042
49
50 967 Franco-Luesma, S, Caverro, J, Plaza-Bonilla, D, Cantero-Martínez, C, Tortosa, G, Bedmar, E, Alvaro-
51 968 Fuentes, J, 2020. Irrigation and tillage effects on soil nitrous oxide emissions in maize
52 969 monoculture. *Agronomy Journal*.10.1002/agj2.20057
53
54 970 Fu, Q, Abadie, M, Blaud, A, Carswell, A, Misselbrook, TH, Clark, IM, Hirsch, PR, 2020. Effects of
55 971 urease and nitrification inhibitors on soil N, nitrifier abundance and activity in a sandy loam
56 972 soil. *Biology and Fertility of Soils* 56, 185-194.10.1007/s00374-019-01411-5
57
58 973 Gabriel, JL, Muñoz-Carpena, R, Quemada, M, 2012. The role of cover crops in irrigated systems:
59 974 Water balance, nitrate leaching and soil mineral nitrogen accumulation. *Agriculture,*
60 975 *Ecosystems & Environment* 155, 50-61.10.1016/j.agee.2012.03.021

- 1
2
3 976 Galieni, A, Stagnari, F, Visioli, G, Marmiroli, N, Specca, S, Angelozzi, G, D'Egidio, S, Pisante, M, 2016.
4 977 Nitrogen fertilisation of durum wheat: a case study in Mediterranean area during transition
5 978 to conservation agriculture. *Italian Journal of Agronomy* 11, 12-23.10.4081/ija.2016.662
6
7 979 Galli, A, Halle, M, Grunewald, N, 2015. Physical limits to resource access and utilisation and their
8 980 economic implications in Mediterranean economies. *Environmental Science & Policy* 51, 125-
9 981 136.<http://dx.doi.org/10.1016/j.envsci.2015.04.002>
10
11 982 Galloway, JN, Aber, JD, Erisman, JW, Seitzinger, SP, Howarth, RW, Cowling, EB, Cosby, BJ, 2003.
12 983 The nitrogen cascade. *BioScience* 53, 341-356.10.1641/0006-
13 984 3568(2003)053[0341:tnc]2.0.co;2
14
15 985 Garcia-Garizabal, I, Abrahao, R, Causape, J, 2012. Irrigation management and pollution by salts
16 986 and nitrate: flood vs. pressurized system. *Itea-Informacion Tecnica Economica Agraria* 108,
17 987 482-500
18
19 988 Garcia-Garizabal, I, Causape, J, Abrahao, R, 2014. Changes in irrigation management and quantity
20 989 and quality of drainage water in a traditional irrigated land. *Environmental Earth Sciences* 72,
21 990 233-242.10.1007/s12665-013-2949-z
22
23 991 García-González, I, Hontoria, C, Gabriel, JL, Alonso-Ayuso, M, Quemada, M, 2018. Cover crops to
24 992 mitigate soil degradation and enhance soil functionality in irrigated land. *Geoderma* 322, 81-
25 993 88.<https://doi.org/10.1016/j.geoderma.2018.02.024>
26
27 994 García-Ruiz, JM, López-Moreno, JI, Vicente-Serrano, SM, Lasanta-Martínez, T, Beguería, S, 2011.
28 995 Mediterranean water resources in a global change scenario. *Earth-Science Reviews* 105, 121-
29 996 139.10.1016/j.earscirev.2011.01.006
30
31 997 Garnier, J, Anglade, J, Benoit, M, Billen, G, Puech, T, Ramarson, A, Passy, P, Silvestre, M, Lassaletta,
32 998 L, Trommenschlager, MJM, Schott, C, Tallec, G, 2016. Reconnecting crop and cattle farming
33 999 to reduce nitrogen losses to river water of an intensive agricultural catchment (Seine basin,
34 1000 France): past, present and future. *Environmental Science & Policy* 63, 76-
35 1001 90.<http://dx.doi.org/10.1016/j.envsci.2016.04.019>
36
37 1002 Garnier, J, Beusen, A, Thieu, V, Billen, G, Bouwman, L, 2010. N:P:Si nutrient export ratios and
38 1003 ecological consequences in coastal seas evaluated by the ICEP approach. *Global*
39 1004 *Biogeochemical Cycles* 24.10.1029/2009gb003583
40
41 1005 Garnier, J, Lassaletta, L, Billen, G, Romero, E, Grizzetti, B, Némery, J, Le, TPQTPQ, Pistocchi, C,
42 1006 Aissa-Grouz, N, Luu, TNMTNM, Vilmin, L, Dorioz, J-MJM, 2015. Phosphorus budget in the
43 1007 water-agro-food system at nested scales in two contrasted regions of the world (ASEAN-8
44 1008 and EU-27). *Global Biogeochemical Cycles* 29, 2015GB005147-
45 1009 002015GB005147.10.1002/2015gb005147
46
47 1010 Garrido, F, Hénault, C, Gaillard, H, Pérez, S, Germon, JC, 2002. N₂O and NO emissions by
48 1011 agricultural soils with low hydraulic potentials. *Soil Biology and Biochemistry* 34, 559-
49 1012 575.[https://doi.org/10.1016/S0038-0717\(01\)00172-9](https://doi.org/10.1016/S0038-0717(01)00172-9)
50
51 1013 Gilsanz, C, Báez, D, Misselbrook, TH, Dhanoa, MS, Cárdenas, LM, 2016. Development of emission
52 1014 factors and efficiency of two nitrification inhibitors, DCD and DMPP. *Agriculture, Ecosystems*
53 1015 *& Environment* 216, 1-8.<https://doi.org/10.1016/j.agee.2015.09.030>
54
55 1016 Giorgi, F, 2006. Climate change hot-spots. *Geophysical Research Letters*
56 1017 33.10.1029/2006gl025734
57
58 1018 Grizzetti, B, Passy, P, Billen, G, Bouraoui, F, Garnier, J, Lassaletta, L, 2015. The role of water
59 1019 nitrogen retention in integrated nutrient management: assessment in a large basin using
60 1020 different modelling approaches. *Environmental Research Letters* 10.10.1088/1748-
1021 9326/10/6/065008

- 1
2
3 1022 Grizzetti, B, Pistocchi, A, Liqueste, C, Udias, A, Bouraoui, F, van de Bund, W, 2017. Human pressures
4 1023 and ecological status of European rivers. *Scientific Reports* 7, 205-205.10.1038/s41598-017-
5 1024 00324-3
- 7 1025 Grizzetti, B, Vigiak, O, Udias, A, Aloe, A, Zanni, M, Bouraoui, F, Pistocchi, A, Dorati, C, Friedland, R,
8 1026 De Roo, A, Benitez Sanz, C, Leip, A, Bielza, M, 2021. How EU policies could reduce nutrient
9 1027 pollution in European inland and coastal waters? *EarthArXiv*
10 1028 <https://doi.org/10.31223/X5CC91>
- 12 1029 Guardia, G, Aguilera, E, Vallejo, A, Sanz-Cobena, A, Alonso-Ayuso, M, Quemada, M, 2019. Effective
13 1030 climate change mitigation through cover cropping and integrated fertilization: A global
14 1031 warming potential assessment from a 10-year field experiment. *Journal of Cleaner Production*
15 1032 241.10.1016/j.jclepro.2019.118307
- 17 1033 Guardia, G, Cangani, MT, Andreu, G, Sanz-Cobena, A, Garcia-Marco, S, Manuel Alvarez, J, Recio-
18 1034 Huetos, J, Vallejo, A, 2017a. Effect of inhibitors and fertigation strategies on GHG emissions,
19 1035 NO fluxes and yield in irrigated maize. *Field Crops Research* 204, 135-
20 1036 145.10.1016/j.fcr.2017.01.009
- 22 1037 Guardia, G, Cangani, MT, Sanz-Cobena, A, Junior, JL, Vallejo, A, 2017b. Management of pig manure
23 1038 to mitigate NO and yield-scaled N₂O emissions in an irrigated Mediterranean crop.
24 1039 *Agriculture, Ecosystems & Environment* 238, 55-
25 1040 66.<https://doi.org/10.1016/j.agee.2016.09.022>
- 27 1041 Guardia, G, Sanz-Cobena, A, Sanchez-Martín, L, Fuertes-Mendizábal, T, González-Murua, C,
28 1042 Álvarez, JM, Chadwick, D, Vallejo, A, 2018. Urea-based fertilization strategies to reduce yield-
29 1043 scaled N oxides and enhance bread-making quality in a rainfed Mediterranean wheat crop.
30 1044 *Agriculture, Ecosystems & Environment* 265, 421-
31 1045 431.<https://doi.org/10.1016/j.agee.2018.06.033>
- 33 1046 Guillot, E, Hinsinger, P, Dufour, L, Roy, J, Bertrand, I, 2019. With or without trees: Resistance and
34 1047 resilience of soil microbial communities to drought and heat stress in a Mediterranean
35 1048 agroforestry system. *Soil Biology and Biochemistry* 129, 122-
36 1049 135.<https://doi.org/10.1016/j.soilbio.2018.11.011>
- 38 1050 Hagos, SM, Leung, LR, Yoon, J-H, Lu, J, Gao, Y, 2016. A projection of changes in landfalling
39 1051 atmospheric river frequency and extreme precipitation over western North America from the
40 1052 Large Ensemble CESM simulations. *Geophysical Research Letters* 43, 1357-
41 1053 1363.<https://doi.org/10.1002/2015GL067392>
- 43 1054 Hernández, L, 2017. Exploring range shifts of contrasting tree species across a bioclimatic
44 1055 transition zone. *European journal of forest research* v. 136, pp. 481-492-2017 v.2136
45 1056 no.2013.10.1007/s10342-017-1047-2
- 47 1057 Hochman, Z, Horan, H, 2018. Causes of wheat yield gaps and opportunities to advance the water-
48 1058 limited yield frontier in Australia. *Field Crops Research* 228, 20-
49 1059 30.<https://doi.org/10.1016/j.fcr.2018.08.023>
- 51 1060 Houshmandfar, A, Fitzgerald, GJ, O'Leary, G, Tausz-Posch, S, Fletcher, A, Tausz, M, 2018. The
52 1061 relationship between transpiration and nutrient uptake in wheat changes under elevated
53 1062 atmospheric CO₂. *Physiologia Plantarum* 163, 516-529.10.1111/ppl.12676
- 55 1063 Howarth, RW, Billen, G, Swaney, D, Townsend, A, Jaworski, N, Lajth, K, Downing, JA, Elmgren, R,
56 1064 Caraco, N, Jordan, T, Berendso, E, Freney, J, Kudryarov, V, Murdoch, P, Zhao-Liang, Z, 1996.
57 1065 Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic
58 1066 Ocean: Natural and human influences. *Biogeochemistry* 35, 75-139

- 1
2
3 1067 Iglesias, A, Mougou, R, Moneo, M, Quiroga, S, 2011. Towards adaptation of agriculture to climate
4 1068 change in the Mediterranean. *Regional Environmental Change* 11, S159-
5 1069 S166.10.1007/s10113-010-0187-4
6
7 1070 Isaac, ME, Borden, KA, 2019. Nutrient acquisition strategies in agroforestry systems. *Plant and Soil*
8 1071 444, 1-19.10.1007/s11104-019-04232-5
9
10 1072 Isidoro, D, Quílez, D, Aragüés, R, 2006. Environmental impact of irrigation in La Violada District
11 1073 (Spain): II. Nitrogen fertilization and nitrate export patterns in drainage water. *Journal of*
12 1074 *Environmental Quality* 35, 776-785
13
14 1075 Jarvis, S, Nitrogen flows in farming systems across Europe. In *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives*, M. A. Sutton and others, eds. Cambridge, United
15 1076 Kingdom: Cambridge University Press, pp. 211–228., 2011. Nitrogen flows in farming systems
16 1077 across Europe. In *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives*. In: Sutton, M.A.a.o. (Ed.), *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives*. Cambridge University Press, Cambridge, pp. 211–228.
17 1078
18 1079
19 1080
20 1081 Jin, S, Zhang, B, Wu, B, Han, D, Hu, Y, Ren, C, Zhang, C, Wei, X, Wu, Y, Mol, APJ, Reis, S, Gu, B, Chen,
21 1082 J, 2020. Decoupling livestock and crop production at the household level in China. *Nature*
22 1083 *Sustainability*.10.1038/s41893-020-00596-0
23
24 1084 Kassam, A, Friedrich, T, Derpsch, R, Lahmar, R, Mrabet, R, Basch, G, González-Sánchez, EJ, 2012.
25 1085 Conservation agriculture in the dry Mediterranean climate. *Field Crops Research* 132, 7-
26 1086 17.10.1016/J.FCR.2012.02.023
27
28 1087 Kay, S, Graves, A, Palma, JHN, Moreno, G, Roces-Díaz, JV, Aviron, S, Chouvardas, D, Crous-Duran,
29 1088 J, Ferreiro-Domínguez, N, García de Jalón, S, Măcișan, V, Mosquera-Losada, MR, Pantera,
30 1089 A, Santiago-Freijanes, JJ, Szerencsits, E, Torralba, M, Burgess, PJ, Herzog, F, 2019.
31 1090 Agroforestry is paying off – Economic evaluation of ecosystem services in European
32 1091 landscapes with and without agroforestry systems. *Ecosystem Services* 36,
33 1092 100896.<https://doi.org/10.1016/j.ecoser.2019.100896>
34
35 1093 Kirkegaard, J, Hunt, J, 2010. Increasing productivity by matching farming system management and
36 1094 genotype in water-limited environments. *Journal of experimental botany* 61, 4129-
37 1095 4143.10.1093/jxb/erq245
38
39 1096 Klausmeyer, KR, Shaw, MR, 2009. Climate Change, Habitat Loss, Protected Areas and the Climate
40 1097 Adaptation Potential of Species in Mediterranean Ecosystems Worldwide. *PLOS ONE* 4,
41 1098 e6392.10.1371/journal.pone.0006392
42
43 1099 Lal, R, 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*
44 1100 304, 1623-1627
45
46 1101 Lasagna, M, De Luca, DA, 2019. Evaluation of sources and fate of nitrates in the western Po plain
47 1102 groundwater (Italy) using nitrogen and boron isotopes. *Environmental Science and Pollution*
48 1103 *Research* 26, 2089-2104.10.1007/s11356-017-0792-6
49
50 1104 Laspidou, C, Samantzi, V, 2014. Identifying and quantifying nitrogen and phosphorus loadings
51 1105 from agriculture and livestock waste in the Penios River Basin District. *Toxicological and*
52 1106 *Environmental Chemistry* 97, 90.10.1080/02772248.2014.942312
53
54 1107 Lassaletta, L, Billen, G, Garnier, J, Bouwman, L, Velazquez, E, Mueller, ND, Gerber, JS, 2016.
55 1108 Nitrogen use in the global food system: past trends and future trajectories of agronomic
56 1109 performance, pollution, trade, and dietary demand. *Environmental Research Letters* 11,
57 1110 95007-95007.10.1088/1748-9326/11/9/095007
58
59 1111 Lassaletta, L, Billen, G, Grizzetti, B, Anglade, J, Garnier, J, 2014a. 50 year trends in nitrogen use
60 1112 efficiency of world cropping systems: the relationship between yield and nitrogen input to

- 1
2
3 1113 cropland. *Environmental Research Letters* 9, 105011-105011.10.1088/1748-
4 1114 9326/9/10/105011
- 5
6 1115 Lassaletta, L, Billen, G, Grizzetti, B, Garnier, J, Leach, AM, Galloway, JN, 2014b. Food and feed
7 1116 trade as a driver in the global nitrogen cycle: 50-year trends. *Biogeochemistry* 118, 225-
8 1117 241.10.1007/s10533-013-9923-4
- 9
10 1118 Lassaletta, L, Estellés, F, Beusen, AHW, Bouwman, L, Calvet, S, van Grinsven, HJM, Doelman, JC,
11 1119 Stehfest, E, Uwizeye, A, Westhoek, H, 2019. Future global pig production systems according
12 1120 to the Shared Socioeconomic Pathways. *Science of The Total Environment* 665, 739-
13 1121 751.10.1016/J.SCITOTENV.2019.02.079
- 14 1122 Lassaletta, L, García-Gómez, H, Gimeno, BS, Rovira, JV, 2009. Agriculture-induced increase in
15 1123 nitrate concentrations in stream waters of a large Mediterranean catchment over 25 years
16 1124 (1981-2005). *Science of the Total Environment* 407.10.1016/j.scitotenv.2009.08.002
- 17
18 1125 Lassaletta, L, García-Gómez, H, Gimeno, BS, Rovira, JV, 2010. Headwater streams: Neglected
19 1126 ecosystems in the EU Water Framework Directive. Implications for nitrogen pollution control.
20 1127 *Environmental Science and Policy* 13.10.1016/j.envsci.2010.04.005
- 21
22 1128 Lassaletta, L, Romero, E, Billen, G, Garnier, J, García-Gómez, H, Rovira, JVV, 2012. Spatialized N
23 1129 budgets in a large agricultural Mediterranean watershed: high loading and low transfer.
24 1130 *Biogeosciences* 9, 8723-8759.10.5194/bg-9-57-2012
- 25
26 1131 Le Noë, J, Billen, G, Garnier, J, 2017. How the structure of agro-food systems shapes nitrogen,
27 1132 phosphorus, and carbon fluxes: The generalized representation of agro-food system applied
28 1133 at the regional scale in France. *Science of the Total Environment* 586, 42-
29 1134 55.<https://doi.org/10.1016/j.scitotenv.2017.02.040>
- 30
31 1135 Leach, AM, Galloway, JN, Bleeker, A, Erisman, JW, Kohn, R, Kitzes, J, 2012. A nitrogen footprint
32 1136 model to help consumers understand their role in nitrogen losses to the environment.
33 1137 *Environmental Development* 1, 40-66.10.1016/j.envdev.2011.12.005
- 34
35 1138 Leip, A, Billen, G, Garnier, J, Grizzetti, B, Lassaletta, L, Reis, S, Simpson, D, Sutton, MA, de Vries, W,
36 1139 Weiss, F, Westhoek, H, 2015. Impacts of European livestock production: nitrogen, sulphur,
37 1140 phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity.
38 1141 *Environmental Research Letters* 10.10.1088/1748-9326/10/11/115004
- 39
40 1142 López-Bellido, L, 1992. Mediterranean cropping systems. In: Pearson, C.J. (Ed.), *Ecosystems of the*
41 1143 *World. Field Crop Ecosystems*. Elsevier, Netherlands, pp. 311–356.
- 42
43 1144 López-Garrido, R, Madejón, E, Murillo, JM, Moreno, F, 2011. Short and long-term distribution with
44 1145 depth of soil organic carbon and nutrients under traditional and conservation tillage in a
45 1146 Mediterranean environment (southwest Spain). *Soil Use and Management* 27, 177-
46 1147 185.<https://doi.org/10.1111/j.1475-2743.2011.00329.x>
- 47
48 1148 Malek, Ž, Verburg, PH, 2018. Adaptation of land management in the Mediterranean under
49 1149 scenarios of irrigation water use and availability. *Mitigation and Adaptation Strategies for*
50 1150 *Global Change* 23, 821-837.10.1007/s11027-017-9761-0
- 51
52 1151 Malek, Ž, Verburg, PH, R Geijzendorffer, I, Bondeau, A, Cramer, W, 2018. Global change effects on
53 1152 land management in the Mediterranean region. *Global Environmental Change* 50, 238-
54 1153 254.10.1016/J.GLOENVCHA.2018.04.007
- 55
56 1154 Malik, W, Dechmi, F, 2019. DSSAT modelling for best irrigation management practices assessment
57 1155 under Mediterranean conditions. *Agricultural Water Management* 216, 27-
58 1156 43.<https://doi.org/10.1016/j.agwat.2019.01.017>
- 59
60 1157 Malik, W, Isla, R, Dechmi, F, 2019. DSSAT-CERES-maize modelling to improve irrigation and
1158 nitrogen management practices under Mediterranean conditions. *Agricultural Water*
1159 *Management* 213, 298-308.10.1016/j.agwat.2018.10.022

- 1
2
3 1160 Mantovi, P, Fumagalli, L, Beretta, GP, Guermandi, M, 2006. Nitrate leaching through the
4 1161 unsaturated zone following pig slurry applications. *Journal of Hydrology* 316, 195-
5 1162 212.10.1016/j.jhydrol.2005.04.026
- 7 1163 MAPA, 2020a. Bovino. Bases zootécnicas para el cálculo del balance alimentario de nitrógeno y
8 1164 de fósforo. In: Ministerio de Agricultura, P.y.A.E. (Ed.), Madrid, p. 906
- 10 1165 MAPA, 2020b. Procino blanco. Bases zootécnicas para el cálculo del balance alimentario de
11 1166 nitrógeno y de fósforo. In: Ministerio de Agricultura, P.y.A.E. (Ed.), Madrid, p. 164
- 13 1167 Marchetti, R, Ponzoni, G, Spallacci, P, 2004. Simulating nitrogen dynamics in agricultural soils
14 1168 fertilized with pig slurry and urea. *Journal of Environmental Quality* 33, 1217-
15 1169 1229.10.2134/jeq2004.1217
- 17 1170 Medinets, S, Skiba, U, Rennenberg, H, Butterbach-Bahl, K, 2015. A review of soil NO
18 1171 transformation: Associated processes and possible physiological significance on organisms.
19 1172 *Soil Biology and Biochemistry* 80, 92-117. <http://dx.doi.org/10.1016/j.soilbio.2014.09.025>
- 21 1173 Meijide, A, Díez, JA, Sánchez-Martín, L, López-Fernández, S, Vallejo, A, 2007. Nitrogen oxide
22 1174 emissions from an irrigated maize crop amended with treated pig slurries and composts in a
23 1175 Mediterranean climate. *Agriculture, Ecosystems & Environment* 121, 383-
24 1176 394.10.1016/j.agee.2006.11.020
- 26 1177 Meijide, A, Garcia-Torres, L, Arce, A, Vallejo, A, 2009. Nitrogen oxide emissions affected by organic
27 1178 fertilization in a non-irrigated Mediterranean barley field. *Agriculture Ecosystems &
28 1179 Environment* 132, 106-115.10.1016/j.agee.2009.03.005
- 30 1180 Merchan, D, Causape, J, Abrahao, R, Garcia-Garizabal, I, 2015. Assessment of a newly
31 1181 implemented irrigated area (Lerma Basin, Spain) over a 10-year period. II: Salts and nitrate
32 1182 exported. *Agricultural Water Management* 158, 288-296.10.1016/j.agwat.2015.04.019
- 34 1183 Merheb, M, Moussa, R, Abdallah, C, Colin, F, Perrin, C, Baghdadi, N, 2016. Hydrological response
35 1184 characteristics of Mediterranean catchments at different time scales: a meta-analysis.
36 1185 *Hydrological Sciences Journal* 61, 2520-2539.10.1080/02626667.2016.1140174
- 38 1186 Michaelides, S, Karacostas, T, Sánchez, JL, Retalis, A, Pytharoulis, I, Homar, V, Romero, R, Zanis, P,
39 1187 Giannakopoulos, C, Bühl, J, Ansmann, A, Merino, A, Melcón, P, Lagouvardos, K, Kotroni, V,
40 1188 Bruggeman, A, López-Moreno, JJ, Berthet, C, Katragkou, E, Tymvios, F, Hadjimitsis, DG,
41 1189 Mamouri, R-E, Nisantzi, A, 2018. Reviews and perspectives of high impact atmospheric
42 1190 processes in the Mediterranean. *Atmospheric Research* 208, 4-
43 1191 44. <https://doi.org/10.1016/j.atmosres.2017.11.022>
- 45 1192 Mogollón, JMM, Lassaletta, L, Beusen, AHWHW, Grinsven, HJMv, Westhoek, H, Bouwman, AFF,
46 1193 Van Grinsven, HJM, Westhoek, H, Bouwman, AFF, 2018. Assessing future reactive nitrogen
47 1194 inputs into global croplands based on the shared socioeconomic pathways. *Environmental
48 1195 Research Letters* 13, 44008-44008.10.1088/1748-9326/aab212
- 50 1196 Morán-Ordóñez, A, Duane, A, Gil-Tena, A, De Cáceres, M, Aquilué, N, Guerra, CA, Geijzendorffer,
51 1197 IR, Fortin, M-J, Brotons, L, 2020. Future impact of climate extremes in the Mediterranean:
52 1198 Soil erosion projections when fire and extreme rainfall meet. *Land Degradation &
53 1199 Development* n/a.10.1002/ldr.3694
- 55 1200 Morseletto, P, 2019. Confronting the nitrogen challenge: Options for governance and target
56 1201 setting. *Global Environmental Change* 54, 40-49.10.1016/J.GLOENVCHA.2018.10.010
- 58 1202 Mosquera-Losada, MR, Santiago-Freijanes, JJ, Rois-Díaz, M, Moreno, G, den Herder, M, Aldrey-
59 1203 Vázquez, JA, Ferreiro-Domínguez, N, Pantera, A, Pisanelli, A, Rigueiro-Rodríguez, A, 2018.
60 1204 Agroforestry in Europe: A land management policy tool to combat climate change. *Land Use
61 1205 Policy* 78, 603-613. <https://doi.org/10.1016/j.landusepol.2018.06.052>

- 1
2
3 1206 Mrabet, R, 2002. WHEAT YIELD AND WATER USE EFFICIENCY UNDER CONTRASTING RESIDUE AND
4 1207 TILLAGE MANAGEMENT SYSTEMS IN A SEMIARID AREA OF MOROCCO. *Experimental*
5 1208 *Agriculture* 38, 237-248.10.1017/S0014479702000285
- 7 1209 Mrabet, R, Moussadek, R, Fadlaoui, A, van Ranst, E, 2012. Conservation agriculture in dry areas of
8 1210 Morocco. *Field Crops Research* 132, 84-94.<https://doi.org/10.1016/j.fcr.2011.11.017>
- 10 1211 Mueller, ND, Gerber, JS, Johnston, M, Ray, DK, Ramankutty, N, Foley, JA, 2012. Closing yield gaps
11 1212 through nutrient and water management. *Nature* 490, 254-
12 1213 257.[http://www.nature.com/nature/journal/v490/n7419/abs/nature11420.html#suppleme](http://www.nature.com/nature/journal/v490/n7419/abs/nature11420.html#supplementary-information)
13 1214 [ntary-information](http://www.nature.com/nature/journal/v490/n7419/abs/nature11420.html#supplementary-information)
- 14 1215 Mueller, ND, Lassaletta, L, 2020. Nitrogen challenges in global livestock systems. *Nature Food* 1,
15 1216 400-401.10.1038/s43016-020-0117-7
- 17 1217 Mueller, ND, Lassaletta, L, Runck, BCB, Billen, G, Garnier, J, Gerber, JS, 2017. Declining spatial
18 1218 efficiency of global cropland nitrogen allocation. *Global Biogeochemical Cycles* 31, 245-
19 1219 257.10.1002/2016GB005515
- 21 1220 Myers, N, Mittermeier, RA, Mittermeier, CG, da Fonseca, GAB, Kent, J, 2000. Biodiversity hotspots
22 1221 for conservation priorities. *Nature* 403, 853-858.10.1038/35002501
- 23 1222 Nikolaidis, NP, Karageorgis, AP, Kapsimalis, V, Drakopoulou, P, Skoulikidis, N, Behrendt, H, Levkov,
24 1223 Z, 2009. Management of nutrient emissions of Axios River catchment: Their effect in the
25 1224 coastal zone of Thermaikos Gulf, Greece. *Ecological Modelling* 220, 383-
26 1225 396.<https://doi.org/10.1016/j.ecolmodel.2008.10.003>
- 28 1226 O'Leary, GJ, Christy, B, Nuttall, J, Huth, N, Cammarano, D, Stöckle, C, Basso, B, Shcherbak, I,
29 1227 Fitzgerald, G, Luo, Q, Farre-Codina, I, Palta, J, Asseng, S, 2015. Response of wheat growth,
30 1228 grain yield and water use to elevated CO₂ under a Free-Air CO₂ Enrichment (FACE)
31 1229 experiment and modelling in a semi-arid environment. *Global Change Biology* 21, 2670-
32 1230 2686.10.1111/gcb.12830
- 34 1231 Ochoa-Hueso, R, Allen, EB, Branquinho, C, Cruz, C, Dias, T, Fenn, ME, Manrique, E, Pérez-Corona,
35 1232 ME, Sheppard, LJ, Stock, WD, 2011. Nitrogen deposition effects on Mediterranean-type
36 1233 ecosystems: An ecological assessment. *Environmental Pollution* 159, 2265-2279.DOI:
37 1234 10.1016/j.envpol.2010.12.019
- 39 1235 Olson, D, Dinerstein, E, 2003. The Global 200: Priority Ecoregions for Global Conservation. *Annals*
40 1236 *of the Missouri Botanical Garden* 89.10.2307/3298564
- 42 1237 Parvin, S, Uddin, S, Bourgault, M, Delahunty, A, Nuttall, J, Brand, J, O'Leary, G, Fitzgerald, GJ,
43 1238 Armstrong, R, Tausz, M, 2020. Effect of heat wave on N₂ fixation and N remobilisation of
44 1239 lentil (*Lens culinaris* MEDIK) grown under free air CO₂ enrichment in a mediterranean-type
45 1240 environment. *Plant Biology* 22, 123-132.10.1111/plb.13047
- 46 1241 Parvin, S, Uddin, S, Bourgault, M, Roessner, U, Tausz-Posch, S, Armstrong, R, O'Leary, G, Fitzgerald,
47 1242 G, Tausz, M, 2018. Water availability moderates N₂ fixation benefit from elevated [CO₂]: A
48 1243 2-year FACE study on lentil (*Lens culinaris* MEDIK.) in a water limited agro-ecosystem. *Plant,*
49 1244 *Cell & Environment* 41.10.1111/pce.13360
- 51 1245 Perego, A, Basile, A, Bonfante, A, De Mascellis, R, Terribile, F, Brenna, S, Acutis, M, 2012. Nitrate
52 1246 leaching under maize cropping systems in Po Valley (Italy). *Agriculture, Ecosystems &*
53 1247 *Environment* 147, 57-65.10.1016/j.agee.2011.06.014
- 55 1248 Polade, SD, Gershunov, A, Cayan, DR, Dettinger, MD, Pierce, DW, 2017. Precipitation in a warming
56 1249 world: Assessing projected hydro-climate changes in California and other Mediterranean
57 1250 climate regions. *Scientific Reports* 7, 10783.10.1038/s41598-017-11285-y
- 59 1251 Porter, J, Xie L, Challinor AJ, Cochrane K, Howden SM, Iqbal MM, Lobell DB, 2014. Food security
60 1252 and food production systems. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD,

- 1
2
3 1253 Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken
4 1254 S, Mastrandrea PR, LL, W. (Eds.), *Climate Change 2014: Impacts, Adaptation, and*
5 1255 *Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the*
6 1256 *Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge
7 1257 University Press, NY, pp. 485-453.
- 9 1258 Quemada, M, Baranski, M, Nobel-de Lange, MNJ, Vallejo, A, Cooper, JM, 2013. Meta-analysis of
10 1259 strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop
11 1260 yield. *Agriculture, Ecosystems & Environment* 174, 1-
12 1261 10.<http://dx.doi.org/10.1016/j.agee.2013.04.018>
- 14 1262 Quemada, M, Gabriel, JL, 2016. Approaches for increasing nitrogen and water use efficiency
15 1263 simultaneously. *Global Food Security* 9, 29-35.<http://dx.doi.org/10.1016/j.gfs.2016.05.004>
- 17 1264 Quemada, M, Lassaletta, L, Jensen, LS, Godinot, O, Brentrup, F, Buckley, C, Foray, S, Hvid, SK,
18 1265 Oenema, J, Richards, KG, Oenema, O, 2020a. Exploring nitrogen indicators of farm
19 1266 performance among farm types across several European case studies. *Agricultural Systems*
20 1267 177, 102689.<https://doi.org/10.1016/j.agry.2019.102689>
- 22 1268 Quemada, M, Lassaletta, L, Leip, A, Jones, A, Lugato, E, 2020b. Integrated management for
23 1269 sustainable cropping systems: Looking beyond the greenhouse balance at the field scale.
24 1270 *Global Change Biology* 26, 2584-2598.<https://doi.org/10.1111/gcb.14989>
- 26 1271 Querné, A, Battie-laclau, P, Dufour, L, Wery, J, Dupraz, C, 2017. Effects of walnut trees on
27 1272 biological nitrogen fixation and yield of intercropped alfalfa in a Mediterranean agroforestry
28 1273 system. *European Journal of Agronomy* 84, 35-46.<https://doi.org/10.1016/j.eja.2016.12.001>
- 29 1274 Quinton, JN, Govers, G, Van Oost, K, Bardgett, RD, 2010. The impact of agricultural soil erosion on
30 1275 biogeochemical cycling. *Nature Geoscience* 3, 311-314.10.1038/ngeo838
- 32 1276 Recio, J, Alvarez, JM, Rodriguez-Quijano, M, Vallejo, A, 2019. Nitrification inhibitor DMPSA
33 1277 mitigated N₂O emission and promoted NO sink in rainfed wheat. *Environmental Pollution*
34 1278 245, 199-207.10.1016/J.ENVPOL.2018.10.135
- 36 1279 Recio, J, Montoya, M, Ginés, C, Sanz-Cobena, A, Vallejo, A, Alvarez, JM, 2020. Joint mitigation of
37 1280 NH₃ and N₂O emissions by using two synthetic inhibitors in an irrigated cropping soil.
38 1281 *Geoderma* 373, 114423.<https://doi.org/10.1016/j.geoderma.2020.114423>
- 40 1282 Recio, J, Vallejo, A, Le-Noë, J, Garnier, J, García-Marco, S, Álvarez, JM, Sanz-Cobena, A, 2018. The
41 1283 effect of nitrification inhibitors on NH₃ and N₂O emissions in highly N fertilized irrigated
42 1284 Mediterranean cropping systems. *Science of the Total Environment* 636, 427-
43 1285 436.<https://doi.org/10.1016/j.scitotenv.2018.04.294>
- 45 1286 Rochette, P, Angers, DA, Chantigny, MH, Gasser, MO, MacDonald, JD, Pelster, DE, Bertrand, N,
46 1287 2013. Ammonia Volatilization and Nitrogen Retention: How Deep to Incorporate Urea?
47 1288 *Journal of Environmental Quality* 42, 1635-1642.10.2134/jeq2013.05.0192
- 49 1289 Rodríguez Martín, JA, Álvaro-Fuentes, J, Gonzalo, J, Gil, C, Ramos-Miras, JJ, Grau Corbí, JM, Boluda,
50 1290 R, 2016. Assessment of the soil organic carbon stock in Spain. *Geoderma* 264, Part, 117-
51 1291 125.<https://doi.org/10.1016/j.geoderma.2015.10.010>
- 53 1292 Romero, E, Garnier, J, Billen, G, Peters, F, Lassaletta, L, 2016. Water management practices
54 1293 exacerbate nitrogen retention in Mediterranean catchments. *Science of the Total*
55 1294 *Environment* 573, 420-432.<http://dx.doi.org/10.1016/j.scitotenv.2016.08.007>
- 57 1295 Romero, E, Ludwig, W, Sadaoui, M, Lassaletta, L, Bouwman, AF, Beusen, AHW, van Apeldoorn, D,
58 1296 Sardans, J, Janssens, IA, Ciais, P, Obersteiner, M, Peñuelas, J, 2021. The Mediterranean region
59 1297 as a paradigm of the global decoupling of N and P between soils and freshwaters. *Global*
60 1298 *Biogeochemical Cycles* n/a, e2020GB006874.<https://doi.org/10.1029/2020GB006874>

- 1
2
3 1299 Ruiz-Ramos, M, Ferrise, R, Rodríguez, A, Lorite, IJ, Bindi, M, Carter, TR, Fronzek, S, Palosuo, T,
4 1300 Pirttioja, N, Baranowski, P, Buis, S, Cammarano, D, Chen, Y, Dumont, B, Ewert, F, Gaiser, T,
5 1301 Hlavinka, P, Hoffmann, H, Höhn, JG, Jurecka, F, Kersebaum, KC, Krzyszczak, J, Lana, M,
6 1302 Mechiche-Alami, A, Minet, J, Montesino, M, Nendel, C, Porter, JR, Ruget, F, Semenov, MA,
7 1303 Steinmetz, Z, Stratonovitch, P, Supit, I, Tao, F, Trnka, M, de Wit, A, Rötter, RP, 2018.
8 1304 Adaptation response surfaces for managing wheat under perturbed climate and CO₂ in a
9 1305 Mediterranean environment. *Agricultural Systems* 159, 260-
10 1306 274.10.1016/J.AGSY.2017.01.009
- 11
12 1307 Ruiz-Ramos, M, Gabriel, JL, Vazquez, N, Quemada, M, 2011. Evaluation of nitrate leaching in a
13 1308 vulnerable zone: effect of irrigation water and organic manure application. *Spanish Journal*
14 1309 *of Agricultural Research* 9, 924-937
- 15
16 1310 Ruiz, I, Almagro, M, García de Jalón, S, Solà, MdM, Sanz, MJ, 2020. Assessment of sustainable land
17 1311 management practices in Mediterranean rural regions. *Journal of Environmental*
18 1312 *Management* 276, 111293. <https://doi.org/10.1016/j.jenvman.2020.111293>
- 19
20 1313 Ryan, J, 2008. A perspective on balanced fertilization in the Mediterranean region. *Turkish Journal*
21 1314 *of Agriculture and Forestry* 32, 79-89
- 22
23 1315 Ryan, J, Ibrikci, H, Sommer, R, McNeill, A, 2009. NITROGEN IN RAINFED AND IRRIGATED CROPPING
24 1316 SYSTEMS IN THE MEDITERRANEAN REGION. In: Sparks, D.L. (Ed.), *Advances in Agronomy*, Vol
25 1317 104, pp. 53-136.
- 26
27 1318 Sadaoui, M, Ludwig, W, Bourrin, F, Romero, E, 2018. The impact of reservoir construction on
28 1319 riverine sediment and carbon fluxes to the Mediterranean Sea. *Progress in Oceanography*
29 1320 163, 94-111. <https://doi.org/10.1016/j.pocean.2017.08.003>
- 30
31 1321 Sadras, Vc, Roget, D, Krause, M, 2003. Dynamic cropping strategies for risk management in dry-
32 1322 land farming systems. *Agricultural Systems* 76, 929-948. [https://doi.org/10.1016/S0308-](https://doi.org/10.1016/S0308-521X(02)00010-0)
33 1323 [521X\(02\)00010-0](https://doi.org/10.1016/S0308-521X(02)00010-0)
- 34
35 1324 Sadras, VO, 2005. A quantitative top-down view of interactions between stresses: theory and
36 1325 analysis of nitrogenwater co-limitation in Mediterranean agro-ecosystems. *Australian*
37 1326 *Journal of Agricultural Research* 56, 1151-1157. <https://doi.org/10.1071/AR05073>
- 38
39 1327 Sadras, VO, Hayman, PT, Rodriguez, D, Monjardino, M, Bielich, M, Unkovich, M, Mudge, B, Wang,
40 1328 E, 2016. Interactions between water and nitrogen in Australian cropping systems:
41 1329 physiological, agronomic, economic, breeding and modelling perspectives. *Crop & Pasture*
42 1330 *Science* 67, 1019-1053.10.1071/cp16027
- 43
44 1331 Sala, OE, Chapin, FS, Armesto, JJ, Berlow, E, Bloomfield, J, Dirzo, R, Huber-Sanwald, E, Huenneke,
45 1332 LF, Jackson, RB, Kinzig, A, Leemans, R, Lodge, DM, Mooney, HA, Oesterheld, M, Poff, NL,
46 1333 Sykes, MT, Walker, BH, Walker, M, Wall, DH, 2000. Biodiversity - Global biodiversity scenarios
47 1334 for the year 2100. *Science* 287, 1770-1774.10.1126/science.287.5459.1770
- 48
49 1335 Salazar, O, Balboa, L, Peralta, K, Rossi, M, Casanova, M, Tapia, Y, Singh, R, Quemada, M, 2019.
50 1336 Effect of cover crops on leaching of dissolved organic nitrogen and carbon in a maize-cover
51 1337 crop rotation in Mediterranean Central Chile. *Agricultural Water Management* 212, 399-
52 1338 406. <https://doi.org/10.1016/j.agwat.2018.07.031>
- 53
54 1339 Sanchez-Martín, L, Meijide, A, Garcia-Torres, L, Vallejo, A, 2010. Combination of drip irrigation and
55 1340 organic fertilizer for mitigating emissions of nitrogen oxides in semiarid climate. *Agriculture,*
56 1341 *Ecosystems & Environment* 137, 99-107. <https://doi.org/10.1016/j.agee.2010.01.006>
- 57
58 1342 Sanchez-Martin, L, Sanz-Cobena, A, Meijide, A, Quemada, M, Vallejo, A, 2010. The importance of
59 1343 the fallow period for N₂O and CH₄ fluxes and nitrate leaching in a Mediterranean irrigated
60 1344 agroecosystem. *European Journal of Soil Science* 61, 710-720.10.1111/j.1365-
1345 2389.2010.01278.x

- 1
2
3 1346 Sanz-Cobena, A, 2010. Ammonia emissions from fertiliser application: Quantification techniques
4 1347 and mitigation strategies. . Universidad Politécnica de Madrid
- 5
6 1348 Sanz-Cobena, A, Abalos, D, Meijide, A, Sanchez-Martin, L, Vallejo, A, 2016. Soil moisture
7 1349 determines the effectiveness of two urease inhibitors to decrease N₂O emission. *Mitigation
8 1350 and Adaptation Strategies for Global Change* 21, 1131-1144.10.1007/s11027-014-9548-5
- 9
10 1351 Sanz-Cobena, A, Lassaletta, L, Aguilera, E, del Prado, A, Garnier, J, Billen, G, Iglesias, A, Sanchez, B,
11 1352 Guardia, G, Abalos, D, Plaza-Bonilla, D, Puigdueta-Bartolome, I, Moral, R, Galan, E, Arriaga, H,
12 1353 Merino, P, Infante-Amate, J, Meijide, A, Pardo, G, Alvaro-Fuentes, J, Gilsanz, C, Baez, D,
13 1354 Doltra, J, Gonzalez-Ubierna, S, Cayuela, ML, Menendez, S, Diaz-Pines, E, Le-Noe, J, Quemada,
14 1355 M, Estelles, F, Calvet, S, van Grinsven, HJM, Westhoek, H, Sanz, MJ, Gimeno, BS, Vallejo, A,
15 1356 Smith, P, 2017. Strategies for greenhouse gas emissions mitigation in Mediterranean
16 1357 agriculture: A review. *Agriculture Ecosystems & Environment* 238, 5-
17 1358 24.10.1016/j.agee.2016.09.038
- 18
19 1359 Sanz-Cobena, A, Lassaletta, L, Estelles, F, Del Prado, A, Guardia, G, Abalos, D, Aguilera, E, Pardo,
20 1360 G, Vallejo, A, Sutton, MA, Garnier, J, Billen, G, 2014. Yield-scaled mitigation of ammonia
21 1361 emission from N fertilization: the Spanish case. *Environmental Research Letters*
22 1362 9.10.1088/1748-9326/9/12/125005
- 23
24 1363 Sanz-Cobena, A, Misselbrook, T, Camp, V, Vallejo, A, 2011. Effect of water addition and the urease
25 1364 inhibitor NBPT on the abatement of ammonia emission from surface applied urea.
26 1365 *Atmospheric Environment* 45, 1517-1524.<https://doi.org/10.1016/j.atmosenv.2010.12.051>
- 27
28 1366 Sanz-Cobena, A, Misselbrook, TH, Arce, A, Mingot, JI, Diez, JA, Vallejo, A, 2008. An inhibitor of
29 1367 urease activity effectively reduces ammonia emissions from soil treated with urea under
30 1368 Mediterranean conditions. *Agriculture, Ecosystems & Environment* 126, 243-
31 1369 249.10.1016/j.agee.2008.02.001
- 32
33 1370 Sanz-Cobena, A, Misselbrook, TH, Hernáiz, P, Vallejo, A, 2019. Impact of rainfall to the
34 1371 effectiveness of pig slurry shallow injection method for NH₃ mitigation in a Mediterranean
35 1372 soil. *Atmospheric Environment* 216,
36 1373 116913.<https://doi.org/10.1016/j.atmosenv.2019.116913>
- 37
38 1374 Sanz-Cobena, A, Sınchez-Martın, L, Garcıa-Torres, L, Vallejo, A, 2012. Gaseous emissions of
39 1375 N₂O and NO and NO₃⁻ leaching from urea applied with urease and nitrification inhibitors
40 1376 to a maize (*Zea mays*) crop. *Agriculture, Ecosystems & Environment* 149, 64-
41 1377 73.10.1016/j.agee.2011.12.016
- 42
43 1378 Sanz, A, Misselbrook, T, Sanz, MJ, Vallejo, A, 2010. Use of an inverse dispersion technique for
44 1379 estimating ammonia emission from surface-applied slurry. *Atmospheric Environment* 44,
45 1380 999-1002.<https://doi.org/10.1016/j.atmosenv.2009.08.044>
- 46
47 1381 Savin, R, Sadras, VO, Slafer, GA, 2019. Benchmarking nitrogen utilisation efficiency in wheat for
48 1382 Mediterranean and non-Mediterranean European regions. *Field Crops Research* 241,
49 1383 107573.<https://doi.org/10.1016/j.fcr.2019.107573>
- 50
51 1384 Seager, R, Osborn, TJ, Kushnir, Y, Simpson, IR, Nakamura, J, Liu, H, 2019. Climate Variability and
52 1385 Change of Mediterranean-Type Climates. *Journal of Climate* 32, 2887-2915.10.1175/jcli-d-
53 1386 18-0472.1
- 54
55 1387 Shakesby, RA, 2011. Post-wildfire soil erosion in the Mediterranean: Review and future research
56 1388 directions. *Earth-Science Reviews* 105, 71-
57 1389 100.<https://doi.org/10.1016/j.earscirev.2011.01.001>
- 58
59 1390 Slessarev, EW, Lin, Y, Bingham, NL, Johnson, JE, Dai, Y, Schimel, JP, Chadwick, OA, 2016. Water
60 1391 balance creates a threshold in soil pH at the global scale. *Nature* 540, 567-
1392 569.10.1038/nature20139

- 1
2
3 1393 Soana, E, Balestrini, R, Vincenzi, F, Bartoli, M, Castaldelli, G, 2017. Mitigation of nitrogen pollution
4 1394 in vegetated ditches fed by nitrate-rich spring waters. *Agriculture Ecosystems & Environment*
5 1395 243, 74-82.10.1016/j.agee.2017.04.004
6
7 1396 Soana, E, Bartoli, M, Milardi, M, Fano, EA, Castaldelli, G, 2019. An ounce of prevention is worth a
8 1397 pound of cure: Managing macrophytes for nitrate mitigation in irrigated agricultural
9 1398 watersheds. *Science of the Total Environment* 647, 301-312.10.1016/j.scitotenv.2018.07.385
10
11 1399 Spinoni, J, Vogt, JV, Naumann, G, Barbosa, P, Dosio, A, 2018. Will drought events become more
12 1400 frequent and severe in Europe? *International Journal of Climatology* 38, 1718-
13 1401 1736.10.1002/joc.5291
14
15 1402 Springmann, M, Clark, M, Mason-D'Croz, D, Wiebe, K, Bodirsky, BL, Lassaletta, L, de Vries, W,
16 1403 Vermeulen, SJ, Herrero, M, Carlson, KM, Jonell, M, Troell, M, DeClerck, F, Gordon, LJ, Zurayk,
17 1404 R, Scarborough, P, Rayner, M, Loken, B, Fanzo, J, Godfray, HCJ, Tilman, D, Rockström, J,
18 1405 Willett, W, 2018. Options for keeping the food system within environmental limits. *Nature*
19 1406 562, 519–525.10.1038/s41586-018-0594-0
20
21 1407 Stehfest, E, Bouwman, L, 2006. N₂O and NO emission from agricultural fields and soils under
22 1408 natural vegetation: summarizing available measurement data and modeling of global annual
23 1409 emissions. *Nutrient Cycling in Agroecosystems* 74, 207-228.10.1007/s10705-006-9000-7
24
25 1410 Sutton, MA, Bleeker, A, Howard, CM, Bekunda, M, Grizzetti, B, de Vries, W, van Grinsven, HJM,
26 1411 Abrol, YP, Adhya, TK, Billen, G, Davidson, EA, Datta, A, Diaz, R, Erisman, JW, Liu X, J, Oenema,
27 1412 O, Palm, C, Raghuram, N, Reis, S, Scholz, RW, Sims, T, Westhoek, H, F.S, Z, 2013. Our nutrient
28 1413 world. The challenge to produce more food and energy with less pollution. UNEP, Edinburgh.
29
30 1414 Tarolli, P, Borga, M, Morin, E, Delrieu, G, 2012. Analysis of flash flood regimes in the North-
31 1415 Western and South-Eastern Mediterranean regions. *Nat. Hazards Earth Syst. Sci.* 12, 1255-
32 1416 1265.10.5194/nhess-12-1255-2012
33
34 1417 Tausz, M, Norton, RM, Tausz-Posch, S, Löw, M, Seneweera, S, O'Leary, G, Armstrong, R, Fitzgerald,
35 1418 GJ, 2017. Can additional N fertiliser ameliorate the elevated CO₂-induced depression in grain
36 1419 and tissue N concentrations of wheat on a high soil N background? *Journal of Agronomy and*
37 1420 *Crop Science* 203, 574-583.10.1111/jac.12209
38
39 1421 Thapa, R, Mirsky, SB, Tully, KL, 2018. Cover Crops Reduce Nitrate Leaching in Agroecosystems:A
40 1422 Global Meta-Analysis. *Journal of Environmental Quality* 47, 1400-
41 1423 1411.<https://doi.org/10.2134/jeq2018.03.0107>
42
43 1424 Theobald, MR, Sanz-Cobena, A, Vallejo, A, Sutton, MA, 2015. Suitability and uncertainty of two
44 1425 models for the simulation of ammonia dispersion from a pig farm located in an area with
45 1426 frequent calm conditions. *Atmospheric Environment* 102, 167-
46 1427 175.<https://doi.org/10.1016/j.atmosenv.2014.11.056>
47
48 1428 Thompson, RL, Lassaletta, L, Patra, PK, Wilson, C, Wells, KC, Gressent, A, Koffi, EN, Chipperfield,
49 1429 MP, Winiwarter, W, Davidson, EA, Tian, H, Canadell, JG, 2019. Acceleration of global N₂O
50 1430 emissions seen from two decades of atmospheric inversion. *Nature Climate Change* 9, 993-
51 1431 998.10.1038/s41558-019-0613-7
52
53 1432 Tipping, E, Somerville, CJ, Luster, J, 2016. The C:N:P:S stoichiometry of soil organic matter.
54 1433 *Biogeochemistry* 130, 117-131.10.1007/s10533-016-0247-z
55
56 1434 Torralba, M, Fagerholm, N, Burgess, PJ, Moreno, G, Plieninger, T, 2016. Do European agroforestry
57 1435 systems enhance biodiversity and ecosystem services? A meta-analysis. *Agriculture,*
58 1436 *Ecosystems & Environment* 230, 150-161.<https://doi.org/10.1016/j.agee.2016.06.002>
59
60 1437 Tosti, G, Benincasa, P, Farneselli, M, Tei, F, Guiducci, M, 2014. Barley-hairy vetch mixture as cover
1438 crop for green manuring and the mitigation of N leaching risk. *European Journal of Agronomy*
1439 54, 34-39.10.1016/j.eja.2013.11.012

- 1
2
3 1440 Trambly, Y, Somot, S, 2018. Future evolution of extreme precipitation in the Mediterranean.
4 1441 *Climatic Change* 151, 289-302.10.1007/s10584-018-2300-5
- 5
6 1442 Trnka, M, Rotter, RP, Ruiz-Ramos, M, Kersebaum, KC, Olesen, JE, Zalud, Z, Semenov, MA, 2014.
7 1443 Adverse weather conditions for European wheat production will become more frequent with
8 1444 climate change. *Nature Clim. Change* advance on.10.1038/nclimate2242
9 1445 [http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate2242.html#supplem](http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate2242.html#supplementary-information)
10 1446 [entary-information](http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate2242.html#supplementary-information)
- 11
12 1447 Turner, DA, Edis, RB, Chen, D, Freney, JR, Denmead, OT, Christie, R, 2010. Determination and
13 1448 mitigation of ammonia loss from urea applied to winter wheat with N-(n-butyl)
14 1449 thiophosphorictriamide. *Agriculture Ecosystems & Environment* 137, 261-
15 1450 266.10.1016/j.agee.2010.02.011
- 16
17 1451 Vallejo, A, Garcia-Torres, L, Diez, JA, Arce, A, Lopez-Fernandez, S, 2005. Comparison of N losses
18 1452 (NO₃⁻, N₂O, NO) from surface applied, injected or amended (DCD) pig slurry of an irrigated
19 1453 soil in a Mediterranean climate. *Plant and Soil* 272, 313-325.10.1007/s11104-004-5754-3
- 20
21 1454 Van Damme, M, Clarisse, L, Whitburn, S, Hadji-Lazaro, J, Hurtmans, D, Clerbaux, C, Coheur, P-F,
22 1455 2018. Industrial and agricultural ammonia point sources exposed. *Nature* 564, 99-
23 1456 103.10.1038/s41586-018-0747-1
- 24
25 1457 van der Kooi, CJ, Reich, M, Löw, M, De Kok, LJ, Tausz, M, 2016. Growth and yield stimulation under
26 1458 elevated CO₂ and drought: A meta-analysis on crops. *Environmental and Experimental*
27 1459 *Botany* 122, 150-157.<https://doi.org/10.1016/j.envexpbot.2015.10.004>
- 28
29 1460 Van Grinsven, HJM, Holland, M, Jacobsen, BH, Klimont, Z, Sutton, MA, Willems, WJ, 2013. Costs
30 1461 and Benefits of Nitrogen for Europe and Implications for Mitigation. *Environmental Science*
31 1462 *& Technology* 47, 3571-3579.10.1021/es303804g
- 32
33 1463 van Grinsven, HJM, Rabl, A, de Kok, TM, 2010. Estimation of incidence and social cost of colon
34 1464 cancer due to nitrate in drinking water in the EU: a tentative cost-benefit assessment.
35 1465 *Environmental Health* 9.58 10.1186/1476-069x-9-58
- 36
37 1466 van Leeuwen, CCE, Cammeraat, ELH, de Vente, J, Boix-Fayos, C, 2019. The evolution of soil
38 1467 conservation policies targeting land abandonment and soil erosion in Spain: A review. *Land*
39 1468 *Use Policy* 83, 174-186.<https://doi.org/10.1016/j.landusepol.2019.01.018>
- 40
41 1469 Vazquez, N, Pardo, A, Suso, ML, Quemada, M, 2006. Drainage and nitrate leaching under
42 1470 processing tomato growth with drip irrigation and plastic mulching. *Agriculture Ecosystems*
43 1471 *& Environment* 112, 313-323.10.1016/j.agee.2005.07.009
- 44
45 1472 Vila-Traver, J, Aguilera, E, Infante-Amate, J, González de Molina, M, 2021. Climate change and
46 1473 industrialization as the main drivers of Spanish agriculture water stress. *Science of The Total*
47 1474 *Environment* 760, 143399.<https://doi.org/10.1016/j.scitotenv.2020.143399>
- 48
49 1475 Vogiatzakis, IN, Mannion, AM, Griffiths, GH, 2006. Mediterranean ecosystems: problems and tools
50 1476 for conservation. *Progress in Physical Geography* 30, 175-200.10.1191/0309133306pp472ra
- 51
52 1477 Walker, JT, Jones, MR, Bash, JO, Myles, L, Meyers, T, Schwede, D, Herrick, J, Nemitz, E, Robarge,
53 1478 W, 2013. Processes of ammonia air-surface exchange in a fertilized *Zea mays* canopy.
54 1479 *Biogeosciences* 10, 981-998.10.5194/bg-10-981-2013
- 55
56 1480 Wang, Y, Guo, J, Vogt, RD, Mulder, J, Wang, J, Zhang, X, 2018. Soil pH as the chief modifier for
57 1481 regional nitrous oxide emissions: New evidence and implications for global estimates and
58 1482 mitigation. *Global Change Biology* 24, e617-e626.10.1111/gcb.13966
- 59
60 1483 Wriedt, G, Van der Velde, M, Aloe, A, Bouraoui, F, 2009. Estimating irrigation water requirements
1484 in Europe. *Journal of Hydrology* 373, 527-544.10.1016/j.jhydrol.2009.05.018

- 1
2
3 1485 Yagüe, MR, Bosch-Serra, AD, 2013. Slurry field management and ammonia emissions under
4 1486 Mediterranean conditions. *Soil Use and Management* 29, 397-400.10.1111/sum.12061
5
6 1487 Yague, MR, Quilez, D, 2010. Cumulative and Residual Effects of Swine Slurry and Mineral Nitrogen
7 1488 in Irrigated Maize. *Agronomy Journal* 102, 1682-1691.10.2134/agronj2010.0282
8
9 1489 Zampieri, M, Toreti, A, Ceglar, A, Naumann, G, Turco, M, Tebaldi, C, 2020. Climate resilience of
10 1490 the top ten wheat producers in the Mediterranean and the Middle East. *Regional*
11 1491 *Environmental Change* 20, 41.10.1007/s10113-020-01622-9
12
13 1492 Zayani, I, Bouhafa, K, Ammari, M, Ben Allal, L, 2020. Agroforestry: Smart Practice for Sustainable
14 1493 Agricultural Development. *Advanced Intelligent Systems for Sustainable Development*
15 1494 (AI2SD'2019). Springer International Publishing,, Cham, pp. 36-47.
16
17 1495 Zhang, X, Davidson, EA, Mauzerall, DL, Searchinger, TD, Dumas, P, Shen, Y, 2015. Managing
18 1496 nitrogen for sustainable development. *Nature* 528, 51.10.1038/nature15743
19 1497 <https://www.nature.com/articles/nature15743#supplementary-information>
20
21 1498 Zhang, X, Davidson, EA, Zou, T, Lassaletta, L, Quan, Z, Li, T, Zhang, W, 2020. Quantifying Nutrient
22 1499 Budgets for Sustainable Nutrient Management. *Global Biogeochemical Cycles* 34,
23 1500 e2018GB006060.<https://doi.org/10.1029/2018GB006060>
24
25 1501 Zhu, X, Burger, M, Doane, TA, Horwath, WR, 2013. Ammonia oxidation pathways and nitrifier
26 1502 denitrification are significant sources of N₂O and NO under low oxygen
27 1503 availability. *Proceedings of the National Academy of Sciences* 110, 6328-
28 1504 6333.10.1073/pnas.1219993110
29
30 1505 Zinkernagel, J, Maestre-Valero, JF, Seresti, SY, Intrigliolo, DS, 2020. New technologies and practical
31 1506 approaches to improve irrigation management of open field vegetable crops. *Agricultural*
32 1507 *Water Management* 242, 106404.<https://doi.org/10.1016/j.agwat.2020.106404>
33 1508
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60