ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Fertilization strategies for abating N pollution at the scale of a highly vulnerable and diverse semi-arid agricultural region (Murcia, Spain)

To cite this article: Alberto Sanz-Cobena *et al* 2023 *Environ. Res. Lett.* **18** 064030

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
21 January 2023

REVISED
16 May 2023

ACCEPTED FOR PUBLICATION
19 May 2023

PUBLISHED
1 June 2023

LETTER

Fertilization strategies for abating N pollution at the scale of a highly vulnerable and diverse semi-arid agricultural region (Murcia, Spain)

Alberto Sanz-Cobena[1,*], Luis Lassaletta[1], Alfredo Rodríguez[2], Eduardo Aguilera[1], Pablo Piñero[1], Marta Moro[1], Josette Garnier[3], Gilles Billen[3], Rasmus Einarsson[4], Zhaohai Bai[5], Lin Ma[5], Ivanka Puigdueta[6], Margarita Ruíz-Ramos[1], Antonio Vallejo[1], Mohammad Zaman[7], Juan Infante-Amate[8] and Benjamín S Gimeno[9,*]

[1] CEIGRAM, Universidad Politécnica de Madrid, Madrid, Spain
[2] Department of Economic Analysis and Finances, Universidad de Castilla-La Mancha, 45071 Toledo, Spain
[3] SU CNRS EPHE, Umr Metis, Paris, France
[4] Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden
[5] Hebei Key Laboratory of Soil Ecology, Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang, Hebei, People's Republic of China
[6] Universitat Politècnica de València, Valencia, Spain
[7] Soil and Water Management and Crop Nutrition, Joint FAO, IAEA Division of Nuclear Techniques in Food and Agriculture, Vienna, Austria
[8] Department of Economic Theory and History, University of Granada, Granada, Spain
[9] Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA), CSIC, Madrid, Spain
[*] Authors to whom any correspondence should be addressed.

E-mail: a.sanz@upm.es and sanchez.benjamin@inia.csic.es

Keywords: nitrogen, ammonia, nitrous oxide, mediterranean region, fertilizing practices

Supplementary material for this article is available online

Abstract

Overuse of N fertilizers in crops has induced the disruption of the N cycle, triggering the release of reactive N (Nr) to the environment. Several EU policies have been developed to address this challenge, establishing targets to reduce agricultural Nr losses. Their achievement could be materialized through the introduction of fertilizing innovations such as incorporating fertilizer into soils, using urease inhibitors, or by adjusting N inputs to crop needs that could impact in both yields and environment. The Murcia region (southeastern Spain) was selected as a paradigmatic case study, since overfertilization has induced severe environmental problems in the region in the last decade, to assess the impact of a set of 8 N fertilizing alternatives on crop yields and environmental Nr losses. Some of these practices imply the reduction of N entering in crops. We followed an integrated approach analyzing the evolution of the region in the long-term (1860–2018) and considering nested spatial- (from grid to region) and systems scales (from crops to the full agro-food system). We hypothesized that, even despite reduction of N inputs, suitable solutions for the abatement of Nr can be identified without compromising crop yields. The most effective option to reduce Nr losses was removing synthetic N fertilizers, leading to 75% reductions in N surpluses mainly due to a reduction of 64% of N inputs, but with associated yield penalties (31%–35%). The most feasible alternative was the removal of urea, resulting in 19% reductions of N inputs, 15%–21% declines in N surplus, and negligible yield losses. While these measures are applied at the field scale, their potential to produce a valuable change can only be assessed at regional scale. Because of this, a spatial analysis was performed showing that largest Nr losses occurred in irrigated horticultural crops. The policy implications of the results are discussed.

1. Introduction

As a component of proteins and nucleic acids, nitrogen (N) is an essential element for producing vegetal and animal food (Galloway *et al* 2008, Sutton *et al* 2013). However, only 22% of the new N entering the global agrifood system reaches our plates (Sutton *et al* 2021). The rest is largely released to the environment as reactive N (Nr) in the form of (i) ammonia (NH_3) (Bittman *et al* 2014) and oxides of N (NO_x) (Guardia *et al* 2018), which pollute the air, (ii) nitrate (NO_3^-), which pollutes drinking water and contributes to eutrophication (Quemada *et al* 2013), and (iii) nitrous oxide (N_2O) (Thompson *et al* 2019), which promotes global warming (Smith *et al* 2021) and stratospheric ozone depletion (Zeng *et al* 2022). Overuse of N fertilizers in croplands, both synthetic and organic, is one of the main drivers of this alteration (Lassaletta *et al* 2016). Mitigation of Nr losses is urgently needed to achieve the challenge of reducing N waste by 50% by 2030 (European Commission COM 2020, Sutton *et al* 2021).

In Europe, the severe problems associated with Nr pollution and their social costs have been described in detail (Sutton *et al* 2011, van Grinsven *et al* 2013). Several policies and strategies have been developed to address these problems, including the Nitrates Directive and the Water Framework Directive, the recent reform of the Common Agricultural Policy, and the Organic Farming Action Plan. In addition, the EU's Farm to Fork strategy (F2f, European Commission COM 2020) establishes the target of reducing nutrient losses from agriculture by at least 50% by 2030, estimating that it would induce at least a 20% reduction in fertilizer use. These ambitious goals should be based on the adoption of specific measures considering regional and local particularities to avoid potential trade-offs (Sanz-Cobena *et al* 2017, Billen *et al* 2021, Aguilera *et al* 2021a). The reduction of the use of synthetic and organic N fertilizers, the better use of local organic resources (Spiegal *et al* 2020, Zhang and Lassaletta 2022), and the conversion of conventional areas to organic management are also highlighted in the recent EU communication for fertilizer availability (European Commission COM 2022). Strategies promoting better N fertilization include the use of technological innovations aiming to reduce N losses, such as fertilizer incorporation in soils or the application of slow-release fertilizer or both urease and nitrification inhibitors (Sanz-Cobena *et al* 2014, 2019, Sutton *et al* 2022). In addition, strategies aimed at improving N recovery and decreasing Nr losses usually also consider measures focusing on crop yield (while not increasing N inputs), such as improved germplasms, pest and disease control, water management, etc. While these measures are applied at the farm scale, their potential to produce a valuable change can only be assessed at the regional scale. Subregional analyses allow to detect production and pollution hotspots as well as possibilities for their improvement (Gu *et al* 2015, Le Noë *et al* 2017, Compton *et al* 2021, Bai *et al* 2022).

Regions with both crops and livestock can benefit from better N resource recirculation, but in the worst case both systems can be totally disconnected, boosting inefficiency and pollution (Strokal *et al* 2016, van Grinsven *et al* 2018, Jin *et al* 2020). The Murcia region (southeastern Spain) is a relevant case study for understanding the challenges faced by the EU's Mediterranean areas experiencing large and sustained N overfertilization and undergoing transitions towards the adoption of more sustainable agricultural practices to meet policy goals. This region is a world-leading agricultural producer exporting ca. 2.5 Mt of fruit and vegetables per year and has a high livestock production also oriented toward export (i.e. 0.36 Mt pig meat) (MAPA 2020). The intensive nutrient flows have severely impacted freshwaters and coastal areas, a serious concern for biodiversity hotspots such as the nationally and internationally protected Mar Menor, one of the largest coastal lagoons on the Mediterranean coastline in Europe (García-Ayllón and Miralles 2014), which has experienced a succession of catastrophic eutrophication events since 2016 (Alvarez-Rogel *et al* 2020). The most recent and severe one occurred in 2021, which led the national and regional authorities to introduce new regulatory actions and plans for reducing nutrient losses (Guaita-Garcia *et al* 2021, Puertes *et al* 2021, Caballero *et al* 2022).

The main objective of this research was to explore the potential benefits and trade-offs of 8 N fertilization strategies on the diverse cropping systems of this vulnerable region as compared with present practices. We have evaluated the agro-environmental impacts, fully spatializing the N budgets, considering the characteristics of the entire agro-food system for the present, analyzing its historical evolution (1860–2015), and upscaling the outcomes to the Murcia regional scale since although fertilizing practices are performed at farm scale, their impacts are of regional matter. We hypothesized that suitable scenarios can be identified to prevent N losses without inducing unacceptable yield penalties. The implications for policy regulations and actions at both regional and EU levels were also assessed.

2. Materials and methods

2.1. The Murcia region

The Murcia region, located in the southeast of the Iberian Peninsula, has a population of ca. 1.4 million inhabitants (CREM 2019). It covers an area of 11 313 km^2, including over 200 km of coastline on the Mediterranean Sea. Irrigated crops cover about half of the cropland and receive about three-quarters of the N inputs in the region (figure 1). See figure S1 for spatial distribution of land uses in the region. The livestock sector has substantially evolved over the last 40 years, starting as a marginal economic activity and becoming a highly competitive segment supported by high intensification in inputs, notably animal feed, with pigs accounting for 82% of the total regional meat production (CAAP-MA 2022). The region is highly dependent on feed imports, which implies a disconnection between crop and livestock systems and decreases N use efficiency (NUE) associated with overfertilization and a mismatch between crop needs and availability (Bai *et al* 2022). These highly intensive agricultural practices, demanding large external inputs, coexist with lower-input practices (e.g. lower fertilizer and agrochemicals). In fact, in 2021 organic farming (OF) accounted for 29% of the total surface devoted to cropland in the region (MAPA 2022a, 2022b), which is above the 25% target defined by the EU Farm to Fork strategy for 2030 (EC 2020).

2.2. Historical and current N flows in the agro-food system

Historical data on crop areas, rainfed and irrigated areas, fertilization rates and types, as well as N losses for the 1860–2018 period were obtained from Aguilera *et al* (2021b) (figure 1). For the 1990–1994 and 2011–2015 periods, a Generalized Representation of the Agrofood System (GRAFS) was established using data from national databases and comprising the four main compartments—cropland, permanent grassland, livestock, and people—and the N flows connecting them (Billen *et al* 2015, Le Noë *et al* 2017). The GRAFS also specifies N losses (e.g. NH_3 volatilization) at each stage of the production chain, enabling estimates of agronomic indicators (e.g. yield, NUE) and identifying key points in the agro-food system with potential for decreasing N losses (Garnier *et al* 2023). A detailed description of the GRAFS calculation and data sources are included in the Supplementary Information.

2.3. N abatement scenarios based on N fertilization management: eight N fertilizer management options

A baseline scenario (BS) involving existing dominant N fertilization practices, N inputs and outputs in the region was compared with eight different N fertilizer management scenarios (FMSs) (table 1). Surface application of the fertilizer was assumed to be dominant. This is the generalized way of fertilizer application in Murcia and Spain. National legislation transposing the above-mentioned international initiatives limits both the rate and the way in which the N fertilizer is applied. In the case of application rates, cropping areas placed in the so-called vulnerable zones cannot be higher than 170 kg N ha^{-1}. For application type, the recently approved royal ordinance (RD) on sustainable crop nutrition (Gobierno de España 2022; RD 1051/2022) strongly limits the broadcast application of liquid manures but it does not limit surface application.

All FMSs differ in the type of N sources applied to crops (synthetic and/or organic), the ways of application (surface treatment or soil incorporation), and use of urease inhibitors (UIs) together with urea (see table 1 for further details). They are all based on existing on NH_3 abatement practices included in the Guidance Document for Ammonia Abatement of UNECE (Bittman *et al* 2014) and are aligned with the objectives of the Farm to fork strategy of the EU Commission. In addition, some of these fertilizing scenarios were already assessed at national level and a lower degree of detail by Sanz-Cobena *et al* (2014). The first five scenarios maintain N inputs to cropping systems equal comparing to BS (table 1), while the last four reduce N inputs as urea (FMS 6 and 7) or remove all synthetic fertilization (FMS 8 and 9). The scenarios based on a reduction of synthetic N forms are aligned to current limitations, derived from the war in Ukraine, in the access to N fertilizers (EC 2022), and the need to reduce application of N to reach more sustainable agro-food systems as recognized by (e.g.) the F2f strategy (European Commission COM 2020). The effects of changes in N inputs on crop yields were estimated by means of yield-fertilization response curves established for each cropping system (Billen *et al* 2015, Mogollón *et al* 2018). This response curve integrated the duration of a crop rotation cycle over all crop groups. The curve was calculated by a one-parameter hyperbolic relationship between the yield and the effective input of N to the soil (discounting NH_3 emissions) (Lassaletta *et al* 2014, Billen *et al* 2015, Mogollón *et al* 2018) (Y, $Y_{\max}$, Fert are expressed in kg N ha^{-1} yr^{-1}):

$$Y = Y_{\max} \times \mathrm{Fert}/\left(\mathrm{Fert} + Y_{\max}\right). \tag{1}$$

$Y_{\max}$ is a crop group-specific parameter representing the yield value reached at saturating fertilization (see Sanz-Cobeña *et al* 2014 for details) with a particular crop mix and it is estimated as:

$$Y_{\max} = Y \times \mathrm{Fert}/\left(Fert - Y\right). \tag{2}$$

Cropland NUE is estimated as the ratio of N yield and total N inputs to the crops (Zhang *et al* 2020).

2.4. Estimation of atmospheric reactive N losses: NH_3 and N_2O

The MANNER model was used to estimate NH_3 volatilization from soil application of both animal manure and N synthetic fertilizer (Chambers *et al* 2006, Sanz-Cobena *et al* 2014, Aguilera *et al* 2021b). N_2O-N emissions (kg N) for both irrigated and non-irrigated crops were estimated using specific N_2O emission factors for Mediterranean conditions based on the meta-analysis by Cayuela *et al* (2017). The equations used for these two estimations are included in the Supplementary Information.

2.5. Spatialization of N flows within the region

The data on N inputs and N outputs in terms of reactive N fluxes were spatialized using the land use layer available from the Spanish Soil Occupation Information System (SIOSE 2022) for the year 2014. A detailed description of the GRAFS calculation and data sources are included in the supplementary information section.

3. Results and discussion

3.1. Historical evolution of N pools and flows in the Murcia region

At the middle of the 20th century, after one century (1850–1950) of low N inputs to agriculture, there was a progressive transition toward: (a) more irrigation in agriculture, (b) intensification of total N inputs, which increased tenfold during the 1950–2015 period, and (c) a predominance of synthetic fertilization followed by a rise in manure use (figure 1). Irrigated systems in 2015 received six times greater N input than rainfed areas. Increasing application of N fertilizers led to an increased net surplus (both in absolute terms and as a proportion of N inputs). An unknown proportion of this surplus is N leaching. The NH_3 emissions as share of N output remained relatively constant at ca. 10%–20%, but as the total N output increased substantially (approximately fivefold from 1860–1950–1990–2018), also did total NH_3 emissions.

The GRAFS diagram for the 2011–2015 period (figure 2) reveals that the system is fueled by N inputs embedded in the imported feed (34 Gg N yr^{-1}) and the 26.4 Gg N yr^{-1} as synthetic fertilizers. Manure represents 9.9 Gg N yr^{-1} entirely applied to crops in addition to the synthetic fertilizer application of 26.4 Gg N $yr^{-1}$and 2.3 Gg N yr^{-1} from other organic sources. 10 Gg N yr^{-1} are harvested from cropland, of which 13% is allocated to local inhabitants, 15% is used as livestock feed, 59% is exported, and the rest corresponds to losses and other uses. The aggregated NUE of the cropping systems is only 22%, which results in very high risk of Nr losses in the form of NH_3 (5.1 Gg N yr^{-1}) and N_2O (0.2 Gg N yr^{-1}). The remaining 25.5 Gg N yr^{-1} of cropland N surplus suggests a very high risk of N losses in the form of nitrate, which can largely explain the severe water pollution problems in this region. The values of the total N inputs, N production, N pollution, and NUE used in the GRAFS diagram have remained nearly constant during the 1990–2015 period.

3.2. Spatial distribution of crop N budgets within the Murcia region

Figure 3 shows soil N inputs under synthetic or organic forms, as well as outputs through harvest for the 2011–2015 period. N surplus is calculated as the difference between total N inputs and output. Figures 3(d) and (f) show considerable areas with total N inputs and N surplus >200 kg N ha^{-1}, which correspond to irrigated horticultural crops and citrus (see the supplementary information and figures S1 & S2) and are in the central-eastern and southeastern areas of the region, especially in the surroundings of the Mar Menor lagoon, which is consistent with the severe and recurring impacts already reported in the area (Caballero et al 2022).

3.3. Nitrogen fertilization abatement strategies for the Murcia region

The scenario analysis shows a considerable potential for abatement of N losses through various combinations of improved N fertilization management and reduced N inputs (table 1). Total N fertilizer input in the region is 40.9 Gg N in the BS, with a share of 66.7% from synthetic fertilizers, and urea comprising 29% of the latter. The complete removal of synthetic fertilizers (FMS 8 and 9) induces the largest abatement of N inputs (−64%). The removal of urea in synthetic fertilization implied a 19% reduction in N inputs for both FMS 6 and 7. The remaining scenarios (FMS 2–5), based on the combination of different application methods of manures and urea-based synthetic fertilizers, have the same N inputs as the BS. These technical fertilization solutions led to increments in N surplus ranging from 2 to 12%.

The largest reductions in environmental N losses were associated with the total conversion to fertilizing practices fully relying on organic fertilizers (i.e. no synthetic fertilizer at all) (FMS 8 and 9), inducing over 70% reductions in N surplus—65% in N_2O and up to 95% in ammonia emissions—while almost doubling the NUE. These fertilizing practices would be aligned with OF fertilizing principles and our result agrees with the findings of Martin-Gorriz et al (2021), who concluded that the best practice to increase the sustainability of horticultural and fruit crops in the region was the removal of synthetic N forms, thus basing fertilization on animal manure, highly available in the region, mainly from intensive pig farms. In fact, the region is rapidly adopting OF practices. The total cultivated area indeed increased by 7.5% from 2014 to 2021 (Estadística Agraria Regional 2022), while the cultivated area devoted to OF increased by 46.3% in the same period. This overall trend should potentially enhance the re-connection of cropland and livestock subsystems, thus reducing the dependency on synthetic N fertilizers while partly solving two of the major drivers of N surplus found by our study (see figure 2). This decrease in N losses, however, was accompanied by 31%–35% yield reductions, suggesting that the full conversion to OF at the regional level would require not only removing synthetic N inputs but also increasing alternative organic N sources such as legume crops and recirculation of human waste in order to avoid high yield penalties (Billen et al 2021). Thus, currently FMS 6 and 7 (organic N fertilizers and synthetic fertilizers without including urea) would

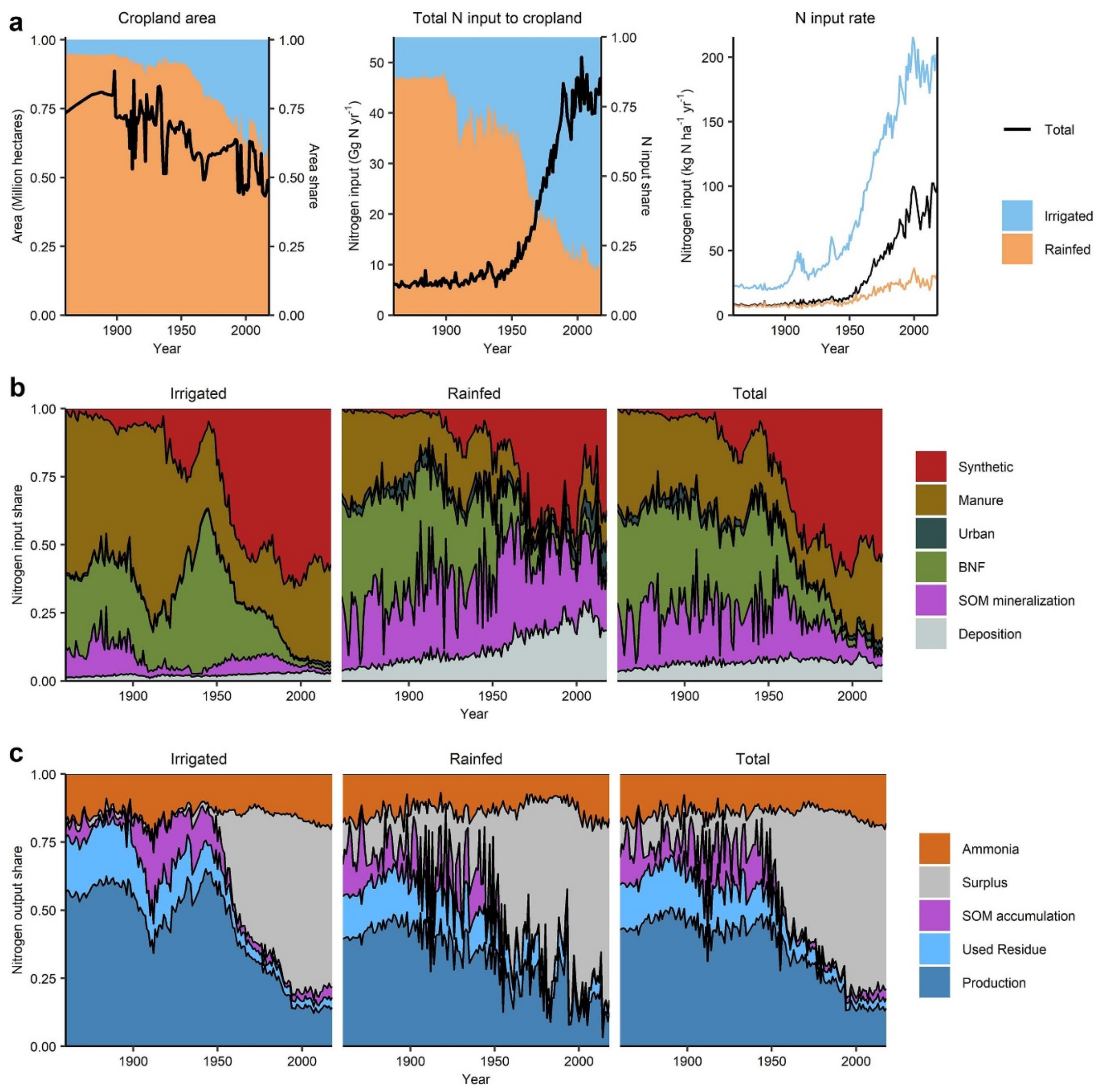

Figure 1. Historical evolution of N flows in the cropping systems in Murcia (1860–2018), (a) cropland area and N inputs split into rainfed and irrigated systems; (b) proportions of N inputs represented by each fertilizer type, including synthetic and organic fertilizers, biological N fixation (BNF), net mineralization of soil organic matter (SOM), and atmospheric deposition, in rainfed, irrigated, and total cropland area; (c) proportion of N outputs including environmental losses as ammonia and other losses ('surplus'), accumulation as organic N in the SOM, harvested crop residues, and crop harvest (production) in rainfed, irrigated, and total cropland area. SOM appears both as an input and as an output because net mineralization occurs in some places at the same time that net accumulation occurs in other places.

be the most feasible regional options for abating N losses for most farms, as their impact on crop yield reduction is almost negligible (2.5 and 0%, for these two scenarios, respectively), while inducing, at the same time, large benefits in reducing NH_3 emissions (52 and 86%, respectively), N surpluses (21 and 15% reductions, respectively), and N_2O emissions (19% in both scenarios), and increasing NUE (21 and 24%, respectively). It is worth noting that the avoidance of urea application (FMS 6 and 7) was about 20% more effective in decreasing both N_2O and NH_3 emissions and N surplus than using UIs (FMS 3 and 5), regardless of the way organic fertilizers were applied (table 1).

When comparing the FMS 6 and FMS 7 scenarios, mechanical incorporation of organic fertilizers within the first 2 h following surface application (FMS 7) would enable further reductions in NH_3 volatilization compared to FMS 6 (table 1) as the contact surface between the fertilizer and the atmosphere is drastically reduced in the very short term (Sanz-Cobena *et al* 2011, Bittman *et al* 2014). We observed almost no effect on N_2O emissions, which are mainly controlled by microbiological drivers (Vallejo *et al* 2005, Cayuela *et al* 2017, Lassaletta *et al* 2021), although there is previous research showed an increase in the flux of this greenhouse gas (GHG) following manure incorporation, mainly due to promotion of anaerobic microsites where denitrification rates were triggered (e.g. Chadwick *et al* 2011).

It should be noted that all scenarios where synthetic N fertilization is partially or fully removed may imply a substantial reduction in the overall regional cropland carbon (C) footprint associated

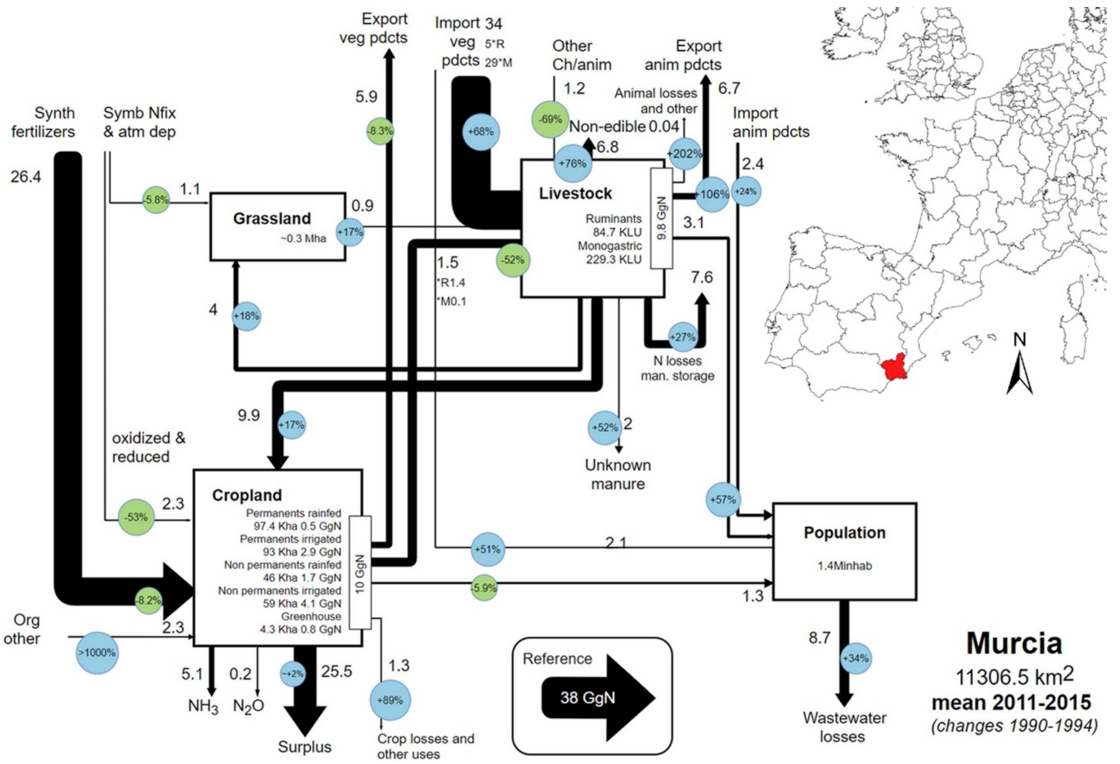

Figure 2. A General Representation of the Agri-Food System (GRAFS) of the Region of Murcia. N flows in Gg N yr^{-1} (mean, 2011–2015). Location of the Region of Murcia (in red) in southwestern Europe is given at the top right part of the figure. N flows are represented with black arrows. Colored circles represent changes between the mean 2011–2015 value and that of the 1990–1994 period. Green reflects a decrease in time and blue an increase. The size of the circle equals the decree of change. In the arrow for imported vegetal products, entering in the livestock compartment, 'R' refers to ruminants and 'M' to monogastric.

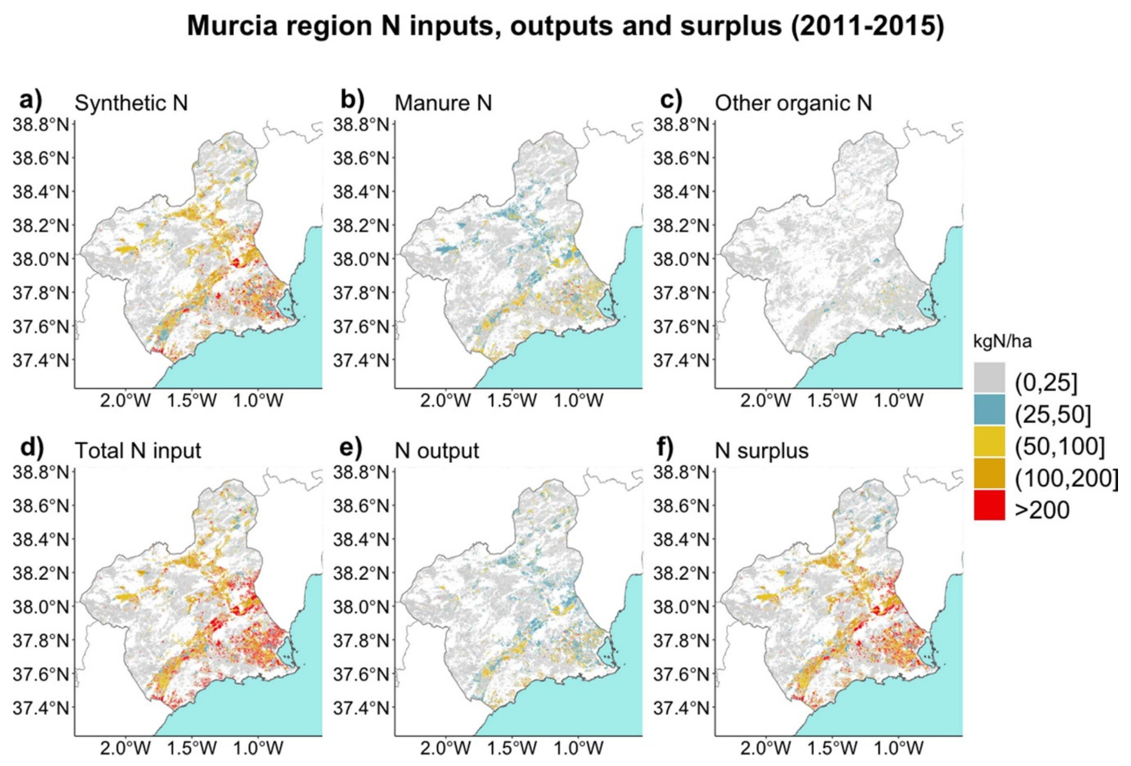

Figure 3. N applied to agricultural soils in the Murcia region (kg N ha^{-1}): N synthetic (a), N in animal manure (b), N in other organic sources (c), total N input (d) and N output (e), and N surplus (f) (mean for 2011–2015).

Table 1. N inputs, reactive N losses and N surplus, crop yields and NUE for each of the eight farm management scenarios (FMS).

Name[a]	Definition	Acronym	N inputs (Gg N; %change over the BS)	NH_3 emissions (Gg N; %change over the BS)	N_2O emissions (tn N; %change over the BS)	N surplus (Gg N; %change over the BS)	N yield (Gg N; %change over the BS)	NUE (%; %change over the BS)
BS	*Baseline (Current N applied in the region. Assumed to be all surface applied)*	*FMS 1*	*40.9*	*5.1*	*197.7*	*25.5*	*10.0*	*24.2*
Ninc	*All N incorporated[a] into soil*	*FMS 2*	40.9	1.0 (−81%)	197.7	29.0 (+12%)	10.7 (+7%)	26.2 (+7%)
UI + Nsurf	*Urea + Urease inhibitor. All N surface-applied*	*FMS 3*	40.9	4.2 (−18%)	197.7	26.0 (+2%)	10.5 (+4%)	25.7 (+5%)
SyntSurf + OrgInc	*All synthetic N surface-applied. All organic N incorporated into soil*	*FMS 4*	40.9	3.4 (−33%)	197.7	26.7 (+4%)	10.5 (+5%)	25.7 (+5%)
UI + OrgInc	*Urea + Urease inhibitor. All organic N incorporated into soil*	*FMS 5*	40.9	2.5 (−52%)	197.7	27.6 (+6%)	10.6 (+6%)	25.9 (+6%)
NoU + OrgSurf	*No application of Urea. All organic and synthetic N surface-applied*	*FMS 6*	33 (−19%)	2.4 (−52%)	159.7 (−19%)	20.7 (−21%)	9.8 (−2.5%)	29.7 (+21%)
NoU + OrgInc	*No application of Urea. All organic and synthetic N incorporated into soil*	*FMS 7*	33 (−19%)	0.7 (−86%)	159.7 (−19%)	22.2 (−15%)	10.0 (0%)	30.3 (+24%)
NoSynt + OrgSurf	*No synthetic N applied at all. All organic N surface-applied*	*FMS 8*	14.6 (−64%)	2.0 (−61%)	70.0 (−65%)	6.0 (−77%)	6.5 (−35%)	44.5 (+82%)
NoSynt + OrgInc	*No synthetic N applied at all. All organic N incorporated into soil*	*FMS 9*	14.6 (−64%)	0.3 (−95%)	70.0 (−65%)	7.3 (−72%)	6.9 (−31%)	47.3 (+93%)

[a] *All fertilizers are incorporated into the soil less than 2 h after application in all scenarios involving fertilizer incorporation.*

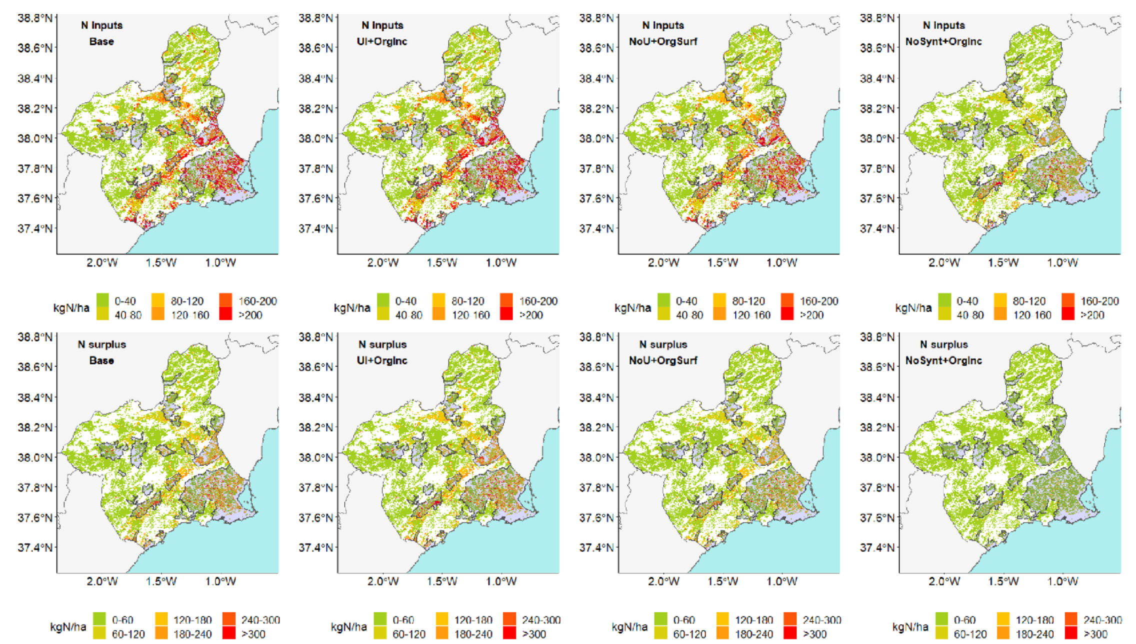

Figure 4. Spatial representation of agro-environmental performance of the baseline and the FMS 5, 6 and 9. N inputs and N surplus in the Murcia region are expressed as kg N ha^{-1} yr^{-1} (a flux), and the baseline is calculated as the mean value of the 2011–2015 period. Shaded areas show the recognized as nitrate vulnerable zones, based on the Nitrate Directive, in the region.

with fertilization, as the CO_2 equivalents generated during its production stage are completely removed (Garnier *et al* 2019, Guardia *et al* 2019), although redistribution of organic manure in the landscape may substantially increase energy consumption if livestock is not reconnected to crops (Wiens *et al* 2008). In addition, the increased share of organic fertilization will likely lead to soil C sequestration (Aguilera *et al* 2013) and the associated beneficial long-term effects on productivity (Oldfield *et al* 2019), helping to adapt to climate change through the improvement of soil quality (Aguilera *et al* 2020). However, it must be noted that increasing soil organic C sequestration could be lower when slurries are applied comparing to solid manures (Aguilera *et al* 2013). In the case of the Murcia region, slurries represent 88% of the total manure applied to croplands (mean from 2011–2015; MAPA 2021). Although the enormous production of slurries in the Murcia region encourages its application as N fertilizing resources prior any synthetic N form, it has to be recognized there could be trade-offs such as an enhancement of phosphorus pollution (Bouwman *et al* 2009).

Cropping systems where horticultural irrigated citrus and other permanent crops are cultivated showed a high risk of N waste. In fact, their associated N surplus represents ca. 85% of total N surplus under FMS 1 (see the SI). Again, FMS 8 and 9 also performed better than any other FMS with respect to N surplus reduction (figure 4). For instance, FMS 8 induced reductions in N surplus ranging from 68.3%–84% for these three crop types, together with noticeable decreases in crop yields (i.e. 28%–33.6%). These yield penalties may help explain why horticulture and citrus groves accounted for only 5% and 4% of the total OF area, respectively (Estadísticas Región de Murcia 2021), while together they cover more than 40% of the region's cropland area and account for ca. 67% of the total regional agricultural N surplus (see the SI). Considering overall crops, FMS 6 and 7 showed a reasonable compromise between substantial N surplus reductions (i.e. 16%–25.8%) and limited yield reductions ranging from 1.9% to 5.4% (see the SI).

Spatialized results were analyzed to test the extent to which the proposed strategies would contribute to reductions of risks from N surplus, and reactive N losses to the atmosphere, in those areas where the highest regional exceedances are recorded (figure 4). These high N surpluses should be seen as major drivers of nitrate pollution of both ground and surface waters. It must be noted that cropping areas with the largest N inputs and associated N surpluses in the region are just located in officially recognized as nitrate vulnerable zones according to the Nitrates Directive (figure 4).

A lower share of the N inputs was volatilized or accumulated in the N surplus because of the implementation of FMS 9, and a substantial abating effect was observed, particularly in the area surrounding the Mar Menor lagoon (figure 4).

3.4. Policy implications

More than half of European water bodies do not show 'good ecological status' even though a wide range of regulations aiming to prevent their eutrophication are in effect (Grizzetti *et al* 2021). The Murcia region is a notable example of this situation, as the number of its nitrate vulnerable zones has increased from 1 to 15 in the last 18 years (figure 4), although both Murcian and Spanish Central administrations have taken regulatory actions to solve this problem. This effort has been enhanced recently (e.g. Law 3/2020 from the regional parliament of Murcia and 'Framework of Priority Actions for the Recovery of Mar Menor' promoted by the Spanish Government in 2021), including the recognition of the Mar Menor lagoon and its catchment as a legal entity through a national law approved by the Spanish Parliament in 2022. This catchment was the only vulnerable zone in the region in 2001.

As broad regulatory actions do not appear to be sufficiently effective, regional and local policymakers may aim to define specific strategies designed to abate local eutrophication problems derived from farming practices. The approach of this study could be useful to formulate such strategies by both encompassing the use of regional N balances to identify the major drivers of N losses and high-resolution spatialization analyses to identify the sources and areas facing adverse impacts. An integrated assessment of the efficacy of the proposed farming practices is needed, by carrying out an overall evaluation of their performance and suitability (e.g. as in this study focusing on fertilizer application) to address the problems identified, analyzing their implications for the abatement of different reactive N forms of environmental concern, and also their potential acceptance by farmers by considering their impacts on crop yields.

When comparing eight fertilizing management practices with those currently used in the area (FMS1), the technical solutions aiming to maintain N inputs were largely outperformed in terms of Nr losses by those practices based on the reduction of N inputs. Largest reductions were associated with a more balanced N fertilization based on the total avoidance of synthetic N forms and the only use of manures as a source of N for crops (FMSs 8 and 9), highly available in the region. This would avoid the reliance on fossil gas for N fertilizer production, which is subject to geopolitical risks (Esfandabadi *et al* 2022), and would also help to achieve the national N application targets established by EU initiatives such as the F2f strategy (European Commission COM 2022). In fact, these two FMSs were the only ones that completely removed areas with N surplus levels over 200 kg N ha^{-1} in the region. A lower decrease was found under FMSs 6 and 7 in areas with N surplus over that level (40% and 23%, respectively, when compared to BS). Therefore, policies prioritizing the application of manures in detriment of N synthetic fertilizers, and expanding the proportion of organic fertilization incorporated into the soil, can be expected to be highly effective in the abatement of N pollution and could be the core of some of the coming initiatives taken in the region, mainly in cropping systems showing most of the N surplus (horticulture, citrus) and in the areas with the highest vulnerability to N pollution (e.g. Mar Menor area) (figure 4). However, the complete removal of synthetic N fertilizers without further measures might not be a suitable short-term option because of its associated 31%–35% reductions in overall crop N yields (e.g. Ponisio *et al* 2014, Anglade *et al* 2015, Benoit *et al* 2016, Knapp *et al* 2018). Therefore, research and innovation policies must be promoted to identify locally adapted solutions, so yields of the most commercially relevant crops are maintained at acceptable levels under manure-based fertilization practices, evaluating a yield loss versus less input. This may include new breeds adapted to lower N inputs, appropriate agroecological practices managing biodiversity at the farm level, and benefitting from a diversity of ecosystems at the landscape level. Reconnecting cropland with livestock and urban areas, and the application of bioproducts originated from the valorization of crop residues and livestock manure would be additional options (Aguilera *et al* 2020). The uptake of these innovations and measures could be accelerated by co-designing and co-implementing them with farmers and other committed actors, following the methodology of, for example, living labs (McPhee *et al* 2021). The development of operational groups associated with the Common Agricultural Policy in the region, and the involvement of relevant actors in Horizon Europe initiatives such as the 'A Soil Deal for Europe' Mission, together with the candidate partnership 'Accelerating farming systems transition: agroecology living labs and research infrastructures' could be relevant, acting as catalysts of the transition.

4. Conclusions and recommendations

The integrated assessment of different N abatement approaches followed in this study allowed to identify their associated benefits and trade-offs. Reduction in synthetic N inputs, preferentially through the removal of urea fertilizers, proved to be an effective short-term strategy to significantly reduce N surplus (15%–21%) in association with nearly negligible yield penalties (0%–2.5%). Additionally, considering a sufficiently high spatial resolution of both N inputs and outputs is crucial when defining suitable strategies. Our results show a heterogeneous distribution of N risks and the causes associated with them in the region. Thus, regional N abatement strategies from agricultural activities would be more effective when focused on the crops and locations contributing the most to N surpluses rather than based on the definition of general regional targets for N abatement. The selection of the agricultural practices supporting the selected strategies must consider both environmental and yield impacts. Their actual implementation will need their adaptation to local conditions followed by on-farm testing, the identification of potential barriers for their uptake, and the provision of appropriate regulatory frameworks and incentives. Therefore, we recommend the involvement of local and regional authorities in the whole process by supporting R&I activities and defining regulations and incentives for the adoption of the selected abatement pathways. This study is an important first step towards mapping out the biophysical operational space to implement effective N abatement strategies in a 'too-much N' region in the EU.

Data availability statement

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

Acknowledgments

Alberto Sanz-Cobena is grateful to the Comunidad de Madrid and the Universidad Politécnica de Madrid for the economic support through the Jovenes Doctores project (APOYO-JOVENES-NFW8ZQ-42-XE8B5K) as well as to the AgroGreen-SUDOE Project (SOE4/P5/E1059), the Spanish Ministry of Science, Innovation and Universities (AgroSceNA-UP, PID2019-107972RB-I00), and the Comunidad de Madrid, Spain (AGRISOST-CM S2018/BAA-4330 project). Mohammad Zaman and Alberto Sanz-Cobena thank to the Coordinated Research Project (No. CRP D15020) of the Soil and Water Management and Crop Nutrition Section, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, for its support through the Technical Contract 'Development, Validation and Refining of New Ammonia Emission Method on Field Scale Using Nuclear' (No. 24236). BSG was also supported by the EJP-SOIL Program (Horizon 2020, Grant Agreement 862695). Luis Lassaletta is grateful to the Spanish Ministry of Economy and Competitiveness (MINECO) and European Commission ERDF Ramón y Cajal grant (RYC-2016-20269). Luis Lassaletta is grateful to the President's International Fellowship Initiative (PIFI) of the Chinese Academy of Sciences (2021VCA0012). Zhaohai Bai is grateful to National Natural Science Foundation of China (T2222016). E Aguilera is supported by a Juan de la Cierva research contract from the Spanish Ministry of Economy and Competitiveness (IJC2019-040699-I). All co-authors are particularly grateful to the Spanish Ministry of Agriculture for permanent support and for providing data.

ORCID iDs

Alberto Sanz-Cobena https://orcid.org/0000-0003-2119-5620
Luis Lassaletta https://orcid.org/0000-0001-9428-2149
Alfredo Rodríguez https://orcid.org/0000-0001-7987-1623
Eduardo Aguilera https://orcid.org/0000-0003-4382-124X
Pablo Piñero https://orcid.org/0000-0003-1027-944X
Josette Garnier https://orcid.org/0000-0001-9416-9242
Gilles Billen https://orcid.org/0000-0003-4413-4169
Rasmus Einarsson https://orcid.org/0000-0002-7587-6280
Margarita Ruíz-Ramos https://orcid.org/0000-0003-0212-3381
Juan Infante-Amate https://orcid.org/0000-0003-1446-7181

References

Aguilera E, Díaz-Gaona C, García-Laureano R, Reyes-Palomo C, Guzmán G I, Ortolani L, Sánchez-Rodríguez M and Rodríguez-Estévez V 2020 Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review *Agric. Syst.* **181** 102809

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

Aguilera E, Reyes-Palomo C, Díaz-Gaona C, Sanz-Cobena A, Smith P, García-Laureano R and Rodríguez-Estévez V 2021a Greenhouse gas emissions from Mediterranean agriculture: evidence of unbalanced research efforts and knowledge gaps *Glob. Environ. Change* **69** 102319

Aguilera E, Sanz-Cobena A, Infante-Amate J, García-Ruiz R, Vila-Traver J, Guzmán G I, González de Molina M, Rodríguez A, Piñero P and Lassaletta L 2021b Long-term trajectories of the C footprint of N fertilization in Mediterranean agriculture (Spain, 1860–2018) *Environ. Res. Lett.* **16** 085010

Alvarez-Rogel J *et al* 2020 The case of Mar Menor eutrophication: state of the art and description of tested nature-based solutions *Ecol. Eng.* **158** 106086

Anglade J, Billen G and Garnier J 2015 Relationships for estimating N2 fixation in legumes: incidence for N balance of legume-based cropping systems in Europe *Ecosphere* **6** 37

Bai Z, Fan X, Jin X, Zhao Z, Wu Y, Oenema O and Ma L 2022 Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population *Nat. Food* **3** 152–60

Benoit M, Garnier J, Beaudoin N and Billen G 2016 A network of organic and conventional crop farms in the Seine Basin (France) for evaluating environmental performance: yield and nitrate leaching *Agric. Syst.* **148** 105–13

Billen G, Aguilera E, Einarsson R, Garnier J, Gingrich S, Grizzetti B, Lassaletta L, Le Noë J and Sanz-Cobena A 2021 Reshaping the European agro-food system and closing its nitrogen cycle: the potential of combining dietary change, agroecology, and circularity *One Earth* **4** 839–50

Billen G, Lassaletta L and Garnier J 2015 A vast range of opportunities for feeding the world in 2050: trade-off between diet, N contamination and international trade *Environ. Res. Lett.* **10** 025001

Bittman S, Dědina M, Howard C, Oenema O and Sutton M 2014 *Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen* (Edinburgh: Centre for Ecology and Hydrology)

Bouwman A F, Beusen A H W and Billen G 2009 Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050 *Glob. Biogeochem. Cycles* **23** GB0A04

Caballero I, Roca M, Santos-Echeandía J, Bernárdez P and Navarro G 2022 Use of the sentinel-2 and landsat-8 satellites for water quality monitoring: an early warning tool in the Mar Menor coastal lagoon *Remote Sens.* **14** 2744
Cayuela M L *et al* 2017 Direct nitrous oxide emissions in Mediterranean climate cropping systems: emission factors based on a meta-analysis of available measurement data *Agric. Ecosyst. Environ.* **238** 25–35
Chadwick D, Sommer S, Thorman R, Fangueiro D, Cardenas L, Amon B and Misselbrook T 2011 Manure management: implications for greenhouse gas emissions *Animal Feed Sci. Technol.* **166–167** 514–31
Chambers B, Lord E, Nicholson F and Smith K 2006 Predicting nitrogen availability and losses following application of organic manures to arable land: MANNER *Soil Use Manage.* **15** 137–43
Compton J E, Pearlstein S L, Erban L, Coulombe R A, Hatteberg B, Henning A, Brooks J R and Selker J E 2021 Nitrogen inputs best predict farm field nitrate leaching in the Willamette Valley, Oregon *Nutr. Cycling Agroecosyst.* **120** 223–42
CREM 2019 Centro Regional de Estadística de Murcia (available at: http://econet.carm.es/inicio/-/crem/sicrem/PU_padron/cifof10/sec1_c11.html)
Esfandabadi Z S, Ranjbari M and Scagnelli S D 2022 The imbalance of food and biofuel markets amid Ukraine-Russia crisis: a systems thinking perspective *Biofuel Res. J.* **9** 1640–7
Estadística Agraria Regional 2022 Consejería de Agua, Agricultura, Ganadería, Pesca y Medio Ambiente (available at: https://econet.carm.es/inicio/-/crem/sicrem/PU_datosBasicos/sec49.html)
Estadísticas Región de Murcia 2021 *Anuario Estadistico de la Region de Murcia* (available at: https://caermurcia.com/estadisticas/)
European Commission COM 2020 381 final (available at: https://eur-lex.europa.eu/resource.html?uri=cellar:ea0f9f73-9ab2-11ea-9d2d-01aa75ed71a1.0001.02/DOC_1%26format=PDF)
European Commission COM 2022 Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions *Ensuring availability and affordability of fertilisers* (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0590%26qid=1668196358061)
Galloway J N, Townsend A R, Erisman J W, Bekunda M, Cai Z C, Freney J R, Martinelli L A, Seitzinger S P and Sutton M A 2008 Transformation of the nitrogen cycle: recent trends, questions, and potential solutions *Science* **320** 889–92
García-Ayllon S and Miralles J L 2014 The environmental impacts of land transformation in the coastal perimeter of the Mar Menor lagoon (Spain) *Int. J. Des. Nat. Ecodyn.* **9** 109–28
Garnier J, Billen G, Aguilera E, Lassaletta L, Einarsson R, Serra J, Cameira M R, Cordovil C M D S and Sanz Cobena A 2023 How much can changes in the agro-food system reduce agricultural nitrogen losses to the environment? Example of France and the Iberian Peninsula *J. Environ. Manage.* **337** 117732
Garnier J, Le Noë J, Marescaux A, Sanz-Cobena A, Lassaletta L, Silvestre M, Thieu V and Billen G 2019 Long term changes in greenhouse gas emissions of French agriculture (1852–2014): from traditional agriculture to conventional intensive systems *Sci. Total Environ.* **660** 1486–501
Gobierno de España G 2022. Real Decreto 1051/2022, de 27 de diciembre, por el que se establecen normas para la nutrición sostenible en los suelos agrarios (available at: www.boe.es/eli/es/rd/2022/12/27/1051)
Grizzetti B *et al* 2021 How EU policies could reduce nutrient pollution in European inland and coastal waters? *EarthArXiv* 10.31223/X5CC91
Gu B, Ju X, Chang J, Ge Y and Vitousek P M 2015 Integrated reactive nitrogen budgets and future trends in China *Proc. Natl Acad. Sci.* **112** 8792–7
Guaita-Garcia N, Martinez-Fernandez J, Barrera-Causil C J, Esteve-Selma M A and Fitz H C 2021 Local perceptions regarding a social-ecological system of the Mediterranean coast: the Mar Menor (Region de Murcia, Spain) *Environ. Dev. Sustain.* **23** 2882–909
Guardia G, Aguilera E, Vallejo A, Sanz-Cobena A, Alonso-Ayuso M and Quemada M 2019 Effective climate change mitigation through cover cropping and integrated fertilization: A global warming potential assessment from a 10-year field experiment *J. Cleaner Prod.* **241** 118307
Guardia G, Sanz-Cobena A, Sanchez-Martín L, Fuertes-Mendizábal T, González-Murua C, Álvarez J M, Chadwick D and Vallejo A 2018 Urea-based fertilization strategies to reduce yield-scaled N oxides and enhance bread-making quality in a rainfed Mediterranean wheat crop *Agric. Ecosyst. Environ.* **265** 421–31
Jin X, Bai Z, Oenema O, Winiwarter W, Velthof G, Chen X and Ma L 2020 Spatial planning needed to drastically reduce nitrogen and phosphorus surpluses in China's agriculture *Environ. Sci. Technol.* **54** 11894–904
Knapp S and van der Heijden M G A 2018 A global meta-analysis of yield stability in organic and conservation agriculture *Nat. Commun.* **9** 3632
Lassaletta L *et al* 2021 Nitrogen dynamics in cropping systems under Mediterranean climate: a systemic analysis *Environ. Res. Lett.* **16** 073002
Lassaletta L, Billen G, Garnier J, Bouwman L, Velazquez E, Mueller N D and Gerber J S 2016 Nitrogen use in the global food system: past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand *Environ. Res. Lett.* **11** 095007
Lassaletta L, Billen G, Grizzetti B, Juliette A and Garnier J 2014 50 year trends in nitrogen use efficiency of world cropping systems: The relationship between yield and nitrogen input to cropland *Environ. Res. Lett.* **9** 105011
Le Noë J, Billen G and Garnier J 2017 How the structure of agro-food systems shapes nitrogen, phosphorus, and carbon fluxes: the generalized representation of agro-food system applied at the regional scale in France *Sci. Total Environ.* **586** 42–55
MAPA 2017a Bases zootécnicas para el cálculo del balance alimentario de Nitrógeno y Fósforo. Aves de carne *Technical report* (Madrid: Ministerio de Agricultura, Pesca y Alimentación)
MAPA 2017b Bases zootécnicas para el cálculo del balance alimentario de Nitrógeno y Fósforo. Porcino blanco *Technical report* (Madrid: Ministerio de Agricultura, Pesca y Alimentación)
MAPA 2017c Bases zootécnicas para el cálculo del balance alimentario de Nitrógeno y Fósforo. Aves de puesta *Technical report* (Madrid: Ministerio de Agricultura, Pesca y Alimentación)
MAPA 2017d Bases zootécnicas para el cálculo del balance alimentario de Nitrógeno y Fósforo. Bovino *Technical report* (Madrid: Ministerio de Agricultura, Ganadería y Pesca)
MAPA 2017e Bases zootécnicas para el cálculo del balance alimentario de Nitrógeno y Fósforo. Ovino *Technical report* (Madrid: Ministerio de Agricultura, Pesca y Alimentación)
MAPA 2019b *Bases zootécnicas para el cálculo del balance alimentario de nitrógeno y de fósforo* (Madrid: MAPA (Ministerio de Agricultura Pesca y Alimentación))
MAPA 2020 Anuario de Estadística Agraria 1904–2019 (Madrid: MAPA (Ministerio de Agricultura Pesca y Alimentación))
MAPA 2021 *Balance de Nitrógeno en la Agricultura Española* (Madrid: MAPA (Ministerio de Agricultura Pesca y Alimentación))
MAPA 2022a *Avance del anuario de Estadística Agraria 2021* (Madrid: MAPA (Ministerio de Agricultura Pesca y Alimentación))
MAPA 2022b Agricultura ecológica. Estadísticas 2021 (Madrid: MAPA (Ministerio de Agricultura, Pesca y Alimentación))
Martin-Gorriz B, Martínez-Alvarez V, Maestre-Valero J F and Gallego-Elvira B 2021 Influence of the water source on the

carbon footprint of irrigated agriculture: a regional study in south-eastern Spain *Agronomy* **11** 351

McPhee C, Bancerz M, Mambrini-Doudet M, Chrétien F, Huyghe C and Gracia-Garza J 2021 The defining characteristics of agroecosystem living labs *Sustainability* **13** 1718

Mogollón J M M, Lassaletta L, Beusen A H W H W, Grinsven H J M V, Westhoek H, Bouwman A F F, Van Grinsven H J M, Westhoek H and Bouwman A F F 2018 Assessing future reactive nitrogen inputs into global croplands based on the shared socioeconomic pathways *Environ. Res. Lett.* **13** 044008

Oldfield E E, Bradford M A and Wood S A 2019 Global meta-analysis of the relationship between soil organic matter and crop yields *Soil* **5** 15–32

Ponisio L C, M'Gonigle L K, Mace K C, Palomino J, de Valpine P and Kremen C 2014 Diversification practices reduce organic to conventional yield gap *Proc. R. Soc.* B **282** 1799

Puertes C, Bautista I, Lidon A and Frances F 2021 Best management practices scenario analysis to reduce agricultural nitrogen loads and sediment yield to the semiarid Mar Menor coastal lagoon (Spain) *Agric. Syst.* **188** 103029

Quemada M, Baranski M, Nobel-de Lange M N J, Vallejo A and Cooper J M 2013 Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield *Agric. Ecosyst. Environ.* **174** 1–10

Sanz-Cobena A *et al* 2014 Yield-scaled mitigation of ammonia emission from N fertilization: the Spanish case *Environ. Res. Lett.* **9** 125005

Sanz-Cobena A *et al* 2017 Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: a review *Agric. Ecosyst. Environ.* **238** 5–24

Sanz-Cobena A, Misselbrook T H, Hernáiz P and Vallejo A 2019 Impact of rainfall to the effectiveness of pig slurry shallow injection method for NH_3 mitigation in a Mediterranean soil *Atmos. Environ.* **216** 116913

Sanz-Cobena A, Misselbrook T, Camp V and Vallejo. A 2011 Effect of water addition and the urease inhibitor NBPT on the abatement of ammonia emission from surface applied urea *Atmos. Environ.* **45** 1517–24

SIOSE 2022 SIOSE. Sistema de Información de Ocupación del Suelo en España, Gobierno de España (available at: www.siose.es/SIOSEtheme-theme/documentos/pdf/Doc_tec_SIOSE2014_v1.pdf) (Accessed 9 December 2023)

Smith C, Nicholls Z R J, Armour K, Collins W, Forster P, Meinshausen M, Palmer M D and Watanabe M 2021 The Earth's energy budget, climate feedbacks, and climate sensitivity supplementary material *Climate Change: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al*

Spiegal S *et al* 2020 Manuresheds: advancing nutrient recycling in US agriculture *Agric. Syst.* **182** 102813

Strokal M, Ma L, Bai Z, Luan S, Kroeze C, Oenema O, Velthof G and Zhang F 2016 Alarming nutrient pollution of Chinese rivers as a result of agricultural transitions *Environ. Res. Lett.* **11** 024014

Sutton M A *et al* 2013 *Our Nutrient World. The Challenge to Produce More Food and Energy with Less Pollution* (Edinburgh: UNEP)

Sutton M A, Howard C M, Erisman J W, Billen G, Bleeker A, Grennfelt P, van Grinsven H and Grizzetti B 2011 *The European Nitrogen Assessment* (New York: Cambridge University Press)

Sutton M A, Howard C M, Kanter D R, Lassaletta L, Móring A, Raghuram N and Read N 2021 The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond *One Earth* **4** 10–14

Sutton M A, Howard C M, Mason K E, Brownlie W J and Cordovil C M D S 2022 Nitrogen opportunities for agriculture, food & environment. UNECE guidance document on integrated sustainable nitrogen management

Thompson R L *et al* 2019 Acceleration of global N_2O emissions seen from two decades of atmospheric inversion *Nat. Clim. Change* **9** 993–8

Vallejo A, Garcia-Torres L, Diez J A, Arce A and Lopez-Fernandez S 2005 Comparison of N losses (NO_3^-, N_2O, NO) from surface applied, injected or amended (DCD) pig slurry of an irrigated soil in a Mediterranean climate *Plant Soil* **272** 313–25

van Grinsven H J M, Holland M, Jacobsen B H, Klimont Z, Sutton M A and Willems W J 2013 Costs and benefits of nitrogen for Europe and implications for mitigation *Environ. Sci. Technol.* **47** 3571–9

van Grinsven H J M, van Dam J D, Lesschen J P J, Timmers M H G, Velthof G L and Lassaletta L 2018 Reducing external costs of nitrogen pollution by relocation of pig production between regions in the European Union *Reg. Environ. Change* **18** 2403–15

Wiens M J, Entz M H, Wilson C and Ominski K H 2008 Energy requirements for transport and surface application of liquid pig manure in Manitoba, Canada *Agric. Syst.* **98** 74–81

Zeng G *et al* 2022 Attribution of stratospheric and tropospheric ozone changes between 1850 and 2014 in CMIP6 models *J. Geophys. Res.* **127** 16

Zhang X, Davidson E A, Zou T, Lassaletta L, Quan Z, Li T and Zhang W 2020 Quantifying nutrient budgets for sustainable nutrient management *Glob. Biogeochem. Cycles* **34** e2018GB006060

Zhang X and Lassaletta L 2022 Manure management benefits climate with limits *Nat. Food* **3** 312–3