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Abstract:	Water scarcity and water quality degradation are major problems in many basins across the world, especially in arid and semiarid regions. The gradual intensification of agricultural production systems in recent decades has placed strong pressures on water resources, thus contributing to their degradation. The agricultural sector is the major consumer of water resources, driving the depletion of water systems. Agriculture is also a source of nutrient pollution into water media and greenhouse gas emissions to the atmosphere. Climate change will exacerbate these problems threatening both natural ecosystems and human water security. This study analyzes water allocation and agricultural pollution in the Ebro River Basin, one of the major basins in Southern Europe and the Mediterranean region. The hydroeconomic modeling approach, combining hydrological, economic and water quality aspects is developed, capturing the main spatial and sectoral interactions in the basin. This model is used to analyze water scarcity and agricultural pollution into watercourses and the atmosphere, providing information for jointly evaluating mitigation and adaptation policies. Both water quantity and water quality are important for human water security and for ecosystem protection, and the results highlight the tradeoffs between water quantity and water quality outcomes under drought scenarios. Droughts increase nitrates concentration at the river mouth by around 50%, while farmers' income deteriorates. The implementation of mitigation and adaptation policies could reduce the effects of climate change and improve water quality, thus lowering environmental damages and improving social well-being. However, drought conditions decrease the effectiveness of policies and increase the tradeoffs between water availability and nitrate pollution. This paper illustrates that a hydroeconomic model has the potential to become a valuable tool in the design of sustainable water management policies that include the control of agricultural pollution.
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Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain

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ABSTRACT

Water scarcity and water quality degradation are major problems in many basins across the world, especially in arid and semiarid regions. The gradual intensification of agricultural production systems in recent decades has placed strong pressures on water resources, thus contributing to their degradation. The agricultural sector is the major consumer of water resources, driving the depletion of water systems. Agriculture is also a source of nutrient pollution into water media and greenhouse gas emissions to the atmosphere. Climate change will exacerbate these problems threatening both natural ecosystems and human water security. This study analyzes water allocation and agricultural pollution in the Ebro River Basin, one of the major basins in Southern Europe and the Mediterranean region. The hydroeconomic modeling approach, combining hydrological, economic and water quality aspects is developed, capturing the main spatial and sectoral interactions in the basin. This model is used to analyze water scarcity and agricultural pollution into watercourses and the atmosphere, providing information for jointly evaluating mitigation and adaptation policies. Both water quantity and water quality are important for human water security and for ecosystem protection, and the results highlight the tradeoffs between water quantity and water quality outcomes under drought scenarios. Droughts increase nitrates concentration at the river mouth by around 50%, while farmers' income deteriorates. The implementation of mitigation and adaptation policies could reduce the effects of climate change and improve water quality, thus lowering environmental damages and improving social well-being. However, drought conditions decrease the effectiveness of policies and increase the tradeoffs between water availability and nitrate pollution. This paper illustrates that a hydroeconomic model has the potential to become a valuable tool in the design of sustainable water management policies that include the control of agricultural pollution.

Keywords: hydroeconomic modeling, nonpoint pollution, droughts, water quality, climate change, abatement policies.

1. Introduction

Water resources are vitally important for both human livelihoods and natural ecosystems. Water withdrawals have risen sharply in the last century, placing massive pressures on water resources and causing severe water scarcity and degradation problems in most river basins worldwide. These negative impacts are linked to the strong growth in population and income. Climate change is altering precipitation patterns and making extreme weather events more frequent and intense. Water scarcity induced by human activities and climate change portents critical water resource degradation in arid and semiarid regions (Greve et al., 2018, Dasgupta, 2021). Water quality is essential for keeping rivers alive with healthy aquatic ecosystems, and quality degradation is caused by point and nonpoint pollution sources. This pollution limits ecosystems' ability to provide environmental goods and services, thereby reducing social well-being (Esteban and Albiac, 2016). Agriculture is a major source of water quality deterioration and GHG emissions to the atmosphere. Both, water pollution by nutrients and GHG loads are complex problems arising from excessive use of fertilizers and intensive livestock farming (Bluemling and Wang, 2018). Rivers receive large quantities of nutrients, which cause water eutrophication and create large hypoxic dead zones in some regions (Breitburg et al., 2018).

Protecting water resources and natural ecosystems requires robust institutions and compelling and enforceable water policies. Sustainable river basin management is a quite challenging task. The methodologies needed to address these difficulties call for a better understanding of water management problems in order to deploy effective and politically viable measures dealing with water scarcity, droughts, climate change and nonpoint pollution. Sustainable management of water resources for different uses will not only depend on water quantity withdrawals, but also on nutrient loads, organic matter, salinity, water temperature, and other pollutants (Van Vliet et al., 2017). Several studies investigate the problem of water allocation among sectors using hydroeconomic modeling to assess water policies (Kahil et al., 2015; 2016; Escriva et al., 2018). Other studies emphasize sectoral and spatial interactions in catchment areas (Kahil et al., 2016; 2018; Dogan et al., 2018; Crespo et al., 2019). However, few studies analyze nutrient water emissions and water quality deterioration using hydroeconomic modeling. The tradeoffs between water scarcity and water degradation remain unsettled in the literature and it is important to strengthen hydroeconomic modeling, in order to understand and realize its full power to inform critical policy debates.

This paper addresses both water allocation and agricultural nonpoint pollution, looking at the tradeoffs between water quality and water quantity under different drought events using hydroeconomic modeling. The model is also used to assess the impacts of agricultural pollution on watercourses and the atmosphere, by estimating the nitrogen loads into water streams together with the emissions of nitrous oxide (N_2O) and methane (CH_4) to the atmosphere from crops and livestock. Selected climate change mitigation and adaptation policies are evaluated under normal climate and severe drought conditions in order to identify the effectiveness and robustness of policies. These policies could boost the efficient use of nitrogen and water in agricultural activities, reduce pollution loads and improve water quality, or protect environmental flows. The hydroeconomic model is developed to analyze the Ebro River Basin in northeastern Spain, which is under mounting scarcity pressures and water quality problems like most of the basins in Spain that require policy intervention (Lassaletta et al., 2009). Climate change and agricultural nonpoint pollution problems have to be tackled locally to find the best alternatives in addressing water depletion and pollution abatement. The model integrates hydrological, economic and environmental components. The interaction among components provides a better assessment of water allocation options among sectors and spatial locations, showing the specific impacts of droughts on the system.[1] Hydroeconomic modeling can be used to find the optimal water allocation that maximizes economic and environmental benefits over space and time in basins (Exposito et al., 2020).

This study contributes to the literature performing a detailed concurrent assessment of water allocation and pollution abatement solutions at river basin level, using hydroeconomic modeling. The study analyzes how to achieve a more sustainable management of the Ebro Basin, but also contributes to the scientific debate on sustainable policies and measures for water management worldwide. The results of this paper highlight the strong links between water quality and water quantity in the basin, and show that drought conditions reduce water availability and dilution processes, increasing nitrate concentration in water media. Our results indicate also that mitigation and adaptation policies have a double effect by abating pollution into the atmosphere and in watercourses, thus reducing environmental damages and enhancing social welfare.

The paper is organized as follows. Section 2 presents a general description of the study area and the main economic activities in the basin. Section 3 explains the development of the integrated hydroeconomic model for the Ebro basin. Section 4 describes the main results of the mitigation and adaptation policies, and the drought impact in water quantity and quality, and section 5 discusses the main findings. Finally, section 6 summarizes the main conclusions.

2. The Ebro Basin

The Ebro Basin, located in the northeast of the Iberian Peninsula, is one of the main European Mediterranean basins. It covers an area of 85,600 km^2, a fifth of the Spanish territory, and its streamflow is one of the largest in the country. Natural ecosystems of great value cover 30% of the basin area. Precipitation occurs mainly in the Pyrenees, where it exceeds 1000 mm/year, while it does not exceed 350 mm/year in the central part of the basin, where conditions are semi-arid (CHE, 2015). The most important tributaries (Zadorra, Aragon, Gallego, Cinca and Segre) supply the canals of the main irrigation districts and also the most important urban areas in the basin (Fig.1).

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[1] Costs of drought damages have been estimated at $8 billion per year in the United States (NOAA, 2021), and around 9 billion € per year in the European Union (Cammalleri et al., 2020). Hernandez et al. (2013) estimate the cost of the 2005 drought in the Ebro basin at 0.5% of GDP. The evidence during recent years indicates that the drought anomaly in Europe is unprecedented (Büntgen et al., 2021).

FIGURE 1 AROUND HERE

Fig.1. Map of the Ebro Basin

The renewable resources of the Ebro basin are estimated at 14,600 Mm^3, and withdrawals amount to 8,460 Mm^3, of which 8,110 Mm^3 are surface diversions and 350 Mm^3 are groundwater extractions (CHE, 2015). Water use in agricultural activities is estimated at 7,680 Mm^3 and urban extractions amounts to 357 Mm^3 supplying three million inhabitants, including households and industries connected to urban networks. The irrigated crops in the Ebro Basin are field crops, fruit trees and vegetables covering an area of 750,000 ha, distributed under surface, sprinkle and drip irrigation technologies (CHE, 2016). The Ebro River is one of Spain's rivers with substantial minimum environmental flows at river mouth. The Ebro water plan of 2015 established the current level of this environmental flow at 3000 Mm^3/year.

The Ebro Basin authorities are responsible for water management, water allocation, water quality, and water planning and control. The special characteristic of this institutional approach is the key role played by stakeholders, which are involved at all decision making in the basin governing bodies and in local watershed boards. The Water Authority (CHE, 2016) indicate that Ebro basin is under water quality pressures from agricultural nonpoint pollution and urban sources identifying that 26% of surface water bodies do not meet environmental quality targets, and 21% of groundwater bodies are in bad conditions.

3. The hydroeconomic model

The hydroeconomic model is used to analyze water allocation among sectors and spatial locations, nonpoint pollution loads across the basin, and also to evaluate drought scenarios and climate change mitigation and adaptation measures. The policy analysis focuses on reducing nutrient loads in streams, on reducing GHG emissions, and on water management adjusted to droughts and climate change. The model includes the main water uses in the basin: irrigation, livestock, and urban and industrial uses. Dryland crops are also included in the assessment of nonpoint pollution emissions. The model integrates three components: (1) the hydrological component, (2) the regional economic component, and (3) the environmental component (Fig. 2).

3.1. The hydrological component

The hydrological component is a reduced form of the basin’s hydrology, calibrated with observed streamflows. It is represented by a system of linked nodes, where streamflows between supply and demand nodes are characterized by simplified equations using the hydrological concepts of mass balance and continuity of river flows (Kahil et al., 2015). The representation of the interactions among nodes is based on detailed information on each node’s spatial location and physical characteristics. The component incorporates information on inflows, withdrawals, return flows and losses, and water metering at selected measurement stations in the basin. The model can simulate the flows at each node and the distribution of water availability between sectors and spatial locations. The hydrologic component is developed using the databases of CHE (2016), and it is calibrated with the observed historical allocations in selected stations of the basin (see Fig. 1S for further details on the Ebro hydrological system). The mathematical formulation is as follows:

$$\mathrm{Wout}_{\mathrm{d}} = \mathrm{Win}_{\mathrm{d}} - \mathrm{Wloss}_{\mathrm{d}} - Div_d^{IR} - Div_d^{URB} - Div_d^{LIV} \tag{1}$$

$$Win_{d+1} = Wout_d + r_d^{IR} \cdot (Div_d^{IR}) + r_d^{URB} \cdot (Div_d^{URB}) + r_d^{LIV} \cdot (Div_d^{LIV}) + RO_{d+1} \tag{2}$$

$$Wout_d \geq E_d^{min} \tag{3}$$

The first equation shows the mass balance and determines the water outflow $Wout_d$ in river reach *d*, which is equal to the inflow Win_d minus water loss $Wloss_d$, and minus the diversions for irrigation Div_d^{IR}, urban use Div_d^{URB} and livestock use Div_d^{LIV}. The second equation guarantees flow continuity in the basin. Win_{d+1} is the water inflow into the following river reach *d+1* as the sum of the outflow from the upstream water reach $Wout_d$, the return flows from upstream irrigation districts $[r_d^{IR} \cdot (Div_d^{IR})]$, urban return flows $[r_d^{URB} \cdot (Div_d^{URB})]$, livestock return flows $[r_d^{LIV} \cdot (Div_d^{LIV})]$, and the runoff entering the river reach from tributaries RO_{d+1}. The third equation specifies that the water outflow in river reach *d* must be greater than or equal to the minimum environmental flow imposed on that river reach.

The hydrologic component is calibrated by introducing slack variables in every river reach to balance supply and demand at every node. These variables represent unmeasured water sources or uses. This calibration procedure reproduces the water flows observed in the reference conditions. Water inflows, outflows and characteristics of flow rates in rivers and channels have been taken from databases and reports by CHE (2016) and CEDEX (2020).

FIGURE 2 AROUND HERE

Fig. 2. Modeling framework

3.2. The regional economic component

The regional economic component consists of optimization models for irrigation districts, for livestock and dryland crops, and for urban economic surplus. For irrigation, the component is set at irrigation district scale to maximize the benefits of crops subject to a set of technical and resource constraints. Yield functions are linear and decreasing in cropland area, with constant input and output prices. The optimization problem is as follows:

$$Max\ B_k^{IR} = \sum\nolimits_{ij} C'^{(IR)}_{ijk} \cdot X_{ijk}^{IR} \tag{4}$$

subject to

$$\sum\nolimits_i X_{ijk}^{IR} \leq Tland_{kj}; \qquad i: crop;\ j: flood, sprinkler, drip;\ k: irrigation\ district \tag{5}$$

$$\sum\nolimits_{ij} W_{ijk} \cdot X_{ijk}^{IR} \leq Twater_k \tag{6}$$

$$\sum\nolimits_{ij} L_{ijk} \cdot X_{ijk}^{IR} \leq Tlabor_k \tag{7}$$

$$\sum_{ij} N_{ijk} \cdot X_{ijk}^{IR} \leq Tnitrogen_k \tag{8}$$

$$X_{ijk}^{IR} \geq 0 \tag{9}$$

where B_k^{IR} is the private benefit in each irrigation district *k* and $C_{ijk}^{\prime(IR)}$ is net income per hectare of crop *i* using irrigation technology *j*. The decision variable of the optimization problem is X_{ijk}^{IR}, the area of crop *i* with irrigation system *j*. Irrigated crops are grouped into field crops, vegetables and fruit trees, using surface, sprinkler and drip irrigation systems. Field crops are irrigated by surface and sprinkler irrigation, while vegetables and fruit trees are irrigated by surface and drip irrigation.

Equation (5) is the land constraint and it represents the land available in each irrigation district *k* equipped with irrigation system *j*, $Tland_{kj}$. Equation (6) is the water constraint and it represents the water available in each irrigation district *k*, $Twater_k$, where W_{ijk} is the requirement for water per hectare and per crop *i* with irrigation system *j*. The level of available water, $Twater_k$, is the variable linking the optimization model of the irrigation districts and the hydrological component. Equation (7) is the labor constraint and it represents the labor available in each irrigation district *k*, $Tlabor_k$. L_{ijk} is the requirement for labor per hectare of crop *i* with irrigation system *j*. Equation (8) is the nitrogen constraint and it represents the nitrogen available in each irrigation district *k*, $Tnitrogen_k$. N_{ijk} is the nitrogen applied per hectare of crop *i* with irrigation system *j*. Equation (9) is the non-negativity constraint of the crop surface area. Net income per hectare $C_{ijk}^{\prime(IR)}$ is the difference between revenues and costs and it is defined as:

$$C_{ijk}^{\prime(IR)} = P_i Y_{ijk} - CP_i \tag{10}$$

where P_i is the price of crop *i*, Y_{ijk} is the yield of crop *i* under irrigation system *j* in irrigation district *k*, and CP_i represents the direct and indirect costs of crop *i*.

The Ricardian rent principle is used in the yield function by assuming that yield decreases as the scale of production increases. The yield function is linear and decreasing in the area of crop *i* under irrigation system *j* and it is expressed by:

$$Y_{ijk} = \beta 0_{ijk} + \beta 1_{ijk} X_{ijk}^{IR} \tag{11}$$

Positive mathematical programming (PMP) is used to calibrate irrigated crop production following the approach of Dagnino and Ward (2012) and solving aggregation and over-specialization problems, whereby linear yield function parameters $\beta 0_{ijk}$ and $\beta 1_{ijk}$ can be estimated.

Livestock and dryland cultivation components are set at watershed board scale, and maximize benefits subject to technical and resource constraints. A constant yield production function for crops and constant input and output prices are used (see A1 in Appendix A of Supplementary Materials for further details).

The economic benefits of urban water use are determined using a social surplus model, by maximizing the consumer and producer surpluses for the main urban centers in the basin, subject to the water supply and demand balance constraint. The optimization problem is expressed as follows:

$$MaxB_u^{URB} = (a_{du} \cdot Q_{du} - \frac{1}{2} \cdot b_{du} \cdot Q_{du}^2 - a_{su} \cdot Q_{su} - \frac{1}{2} \cdot b_{su} \cdot Q_{su}^2) \tag{12}$$

subject to

$$Q_{du} - Q_{su} \leq 0 \tag{13}$$

$$Q_{du} ; Q_{su} \geq 0 \tag{14}$$

where B_u^{URB} is the sum of the consumer and producer surpluses in urban center *u*. The variables Q_{du} and Q_{su} are water supply and demand in urban center *u*, respectively. The parameters a_{du} and b_{du} are the intercept and the slope of the inverse demand function, $P_{du} = a_{du} - b_{du} . Q_{du}$. The parameters a_{su} and b_{su} are the intercept and the slope of the inverse water supply function, $P_{su} = a_{su} + b_{su} . Q_{su}$. Equation (13) indicates that water supply is greater than or equal to demand. The variable Q_{su} is the quantity of water supplied and it is the variable linking the urban model with the hydrological component. The water demand parameters have been obtained from the estimates by Arbués et al. (2004) and Arbués et al. (2010).

3.3. The environmental component: water and atmosphere pollution

Agricultural nonpoint pollution is analyzed in the environmental component, assessing the environmental damage derived from agricultural activities in the Ebro Basin. The impact of nonpoint pollution is assessed by estimating the nitrate loads into watercourses and GHG emissions from irrigated and dryland crops, and from livestock. GHG emissions from cropland include direct and indirect nitrous oxide (N_2O), while livestock emissions include methane (CH_4) from enteric fermentation and nitrous oxide and methane from manure management. The environmental component includes the minimum environmental flows at each section of the basin. The estimation of the social costs of agricultural nonpoint pollution is a complex task that requires a detailed analysis of the biophysical processes generating source emissions and transport and fate processes, the environmental damages from water and atmosphere pollution, and the costs of these damages.

In this study, the methodology applied to estimate GHG emissions from agriculture is the Tier 1 method of the IPCC (2019a; 2019b). The nitrogen pollution is estimated from leaching and runoff from crops, and from the nitrogen excreted by livestock. The biophysical information for each crop and irrigation system are taken from literature reviews and fertilization practices in Spain published by the Spanish Ministry of Agriculture. Emission factors and the data used in the estimation of GHG emissions are taken from IPCC (2019a; 2019b). We assume also that the NO_3-N loads reaching watercourses are 40% of all nitrogen loads at the source of pollution, and the NO_3-N loads reaching the Ebro river mouth represent only 10% of all nitrogen loads at the source of pollution. This is based on the results of Lassaletta et al. (2012), which indicate a high level of retention in the basin (90%).

The environmental damage of agricultural activities is the sum of the cost of GHG emissions and the cost of nitrogen pollution into watercourses, and are given by the expression:

$$\mathrm{ED} = \mathrm{GHG\,E} \cdot \mathrm{SC} + 0.4 \cdot Nload \cdot \mathrm{NC} \quad (15)$$

where the damage of GHG emissions is determined by the volume of GHG emissions (GHG E) and the social cost of carbon (SC) set at 40 €/tCO_2e, which is taken from OECD estimates (Smith and Braathen, 2015) which are close to current US EPA regulation ($51 t$CO_2$e). The environmental damage from nitrates is calculated multiplying the volume of nitrate loads from crops and livestock (Nload), by the cost to removing nitrate from water (NC) at 1.3 €/kg NO_3-N (Martínez and Albiac, 2006). Details on calculations are presented in Appendix A of Supplementary Materials.

3.4. Ebro optimization model and model application

The optimization model of the Ebro Basin integrates the three components described above, and the objective function represents social benefits, the sum of private benefits (B) minus environmental damages (ED) (See A3 in Appendix A of Supplementary Materials for further details). The maximization of social benefits covers all water sectors and spatial locations. The optimization problem is given by:

$$Max\ (B - ED) \quad (16)$$

subject to all hydrological, technical, economic and environmental constraints of irrigated, dryland, and livestock activities. The hydroeconomic model of the Ebro is used to analyze the interdependence between water quantity and water quality, under normal water inflows and drought scenarios. Drought scenarios are used to understand future drought severity levels, and the ensuing impacts of water scarcity and pollution on social benefits in the basin. Moderate and severe drought scenarios assume reductions of 30% and 40% in water inflows, respectively, relative to the flows under normal climate conditions. Then, the model is used to assess selected mitigation and adaptation policies under normal climate and severe drought conditions.

This assessment highlights the role that policies could play in the abatement of nonpoint pollution in watercourses and the atmosphere, and also in identifying the tradeoffs between water quality and water scarcity. The analysis shows the effectiveness of policies under extreme droughts and the impacts on water use, pollution loads and their environmental damages, and social benefit outcomes. The selected policies are P1: Optimization of nitrogen fertilization (by reducing fertilization to crop requirements); P2: Substitution of synthetic fertilization by organic fertilization; P3: Irrigation modernization; P4: Manure treatment plants, (Table 1).

Table 1.
Description of policies

Policies	**Description**
P1	Efficient use of nitrogen fertilization at crop requirements without impacts on yields.
P2	Substitution of synthetic by organic fertilization up to 60% share (from current 27%).
P3	Replacing surface irrigation by more efficient irrigation technologies.
P4	Use of manure treatment technologies to reduce nitrogen emissions.

4. Results

4.1. Water allocation, and nonpoint pollution under normal and drought scenarios

The results of water allocation, environmental damages and social benefits under the baseline and drought scenarios are presented in Table 2. Under normal climate conditions, the social benefits are 3,375 M€ and the total water use reaches 3,874 Mm^3. The irrigated land covers 557,000 ha of field crops, fruit trees and vegetables. Dryland covers 1,194,000 ha and livestock herds amount to 2769 Livestock Units (LSU). Employment in the basin is 37,000 Annual Work Units (AWU) for irrigated crops, 21,500 AWU for dryland crops, and 34,000 AWU for livestock rearing. Results show that nitrogen emissions at the source are 236,000 tNO_3-N and GHG emissions are 7.15 $MtCO_2e$ from agricultural activities, which concentrate in Canal de Urgel, Canal de Bardenas, and the lower sections of the Segre and Gallego tributaries, given the large irrigated cropland and swine herds in these areas (Fig. 3a; Fig. 4). Nitrogen loads entering watercourses in the Ebro are around 94,000 tNO_3-N, and the nitrate concentration at the river mouth is estimated at 11.3 mg/l NO_3^- under normal climate (Fig. 3b). The environmental damages from water pollution and GHG emissions are 409 M€, which are subtracted from the farming private benefits in order to calculate social benefits.

Under drought conditions, water allocation to irrigation districts is reduced proportionally to their regular allocation, while water allocation to urban areas and livestock is maintained. Urban areas take priority over any other water use, followed by livestock. In normal weather conditions, animals only use 1% of water withdrawals, and during droughts water is not a limiting factor for livestock. Under moderate drought, water diversions for irrigation are reduced by 30% with private benefits dropping to 739 M€. Moderate drought reduces irrigated acreage by 35%, especially for less efficient irrigation system. GHG emissions and nitrogen pollution at the source are reduced, while the nitrate concentration at the Ebro River mouth increases by 40% due to the reduction of river flows. Under severe drought conditions, water withdrawals for irrigation are reduced proportionally by 40%. Irrigated cropland generates 686 M€ in private benefits using 2,098 Mm^3 of water. The irrigated acreage falls almost by half and nitrogen pollution at the source decreases. However, the nitrate concentration at the mouth of river increases by 63%.

The results show that droughts reduce crops with low profitability and high water requirements, and the cropland acreage under less efficient irrigation technologies (Fig.2S in Appendix B of Supplementary Materials). The drought scenarios illustrate what are the more efficient water and land management options for adaptation to water scarcity, which vary between irrigation districts and respond to factors such as crop diversification, the level of modernization of irrigation systems, and the access to water resources (Fig. 3S in Supplementary Materials). In addition, results highlight the tradeoff between nitrate concentrations and water availability. Nitrate concentrations increase under drought conditions, as the dilution processes worsen driven by water scarcity.

Table 2.
Agricultural use of resources, pollution and benefits under drought scenarios

Climate conditions	**Normal flow**	**Moderate drought**	**Severe drought**
Land (1,000 ha)			
Irrigated land	**557**	**362**	**315**
Field crops	399	225	184
Vegetables	36	30	28
Fruit trees	122	107	103
Dryland	**1,194**	**1,194**	**1,194**
Field crops	900	900	900
Fruit trees	294	294	294
Livestock (1,000 head)			
Swine	12,913	12,913	12,913
Ovine	2,380	2,380	2,380
Beef cattle	724	724	724
Dairy cattle	74	74	74
Water use (Mm^3)			
Agriculture			
Irrigated land	3,497	2,448	2,098
Livestock	55	55	55
Urban	322	322	322
Total	**3,874**	**2,825**	**2,475**
Irrigation system (1,000 ha)			
Flood	292	158	129
Sprinkler	174	120	104
Drip	91	84	82
Streamflow at the river mouth (Mm^3)	9,272	6,366	5,406
Nitrogen emissions (1000 tNO_3-N)			
At the source	236	227	225
Entering water bodies	94	91	90
Nitrate concentration (mg/l NO_3^-)			
Ebro River mouth	11.3	15.8	18.4
GHG emissions ($MtCO_2e$)			
N_2O from crops	0.76	0.58	0.54
CH_4 from Enteric Ferm.	1.92	1.92	1.92
N_2O from Manure Manag.	0.85	0.85	0.85
CH_4 from Manure Manag.	3.62	3.62	3.62
Total	**7.15**	**6.97**	**6,93**
Private benefits (M€)			
Agriculture			
Irrigated land	813	739	705
Dryland	301	241	211
Livestock	811	811	811
Urban	1,859	1,859	1,859
Total	**3,784**	**3,650**	**3,586**
Environmental damages (M€)			
Irrigated land	34	22	19
Dryland	14	14	14
Livestock	361	361	361
Total	**409**	**397**	**394**
Social benefits (M€)			
Irrigated land	779	717	686
Dryland	287	227	197
Livestock	450	450	450
Urban	1,859	1,859	1,859
Total	**3,375**	**3,253**	**3,192**

FIGURE 3 AROUND HERE

Fig. 3. Nitrogen emissions at the source and in water bodies at municipal level

4.2. Policy analysis under normal and drought conditions[2]

4.2.1. Optimization of nitrogen fertilization

The efficient use of nitrogen fertilization in irrigated and dryland crops in the Ebro Basin is an interesting policy that can reduce nonpoint pollution into the atmosphere and watercourses. This policy increases the profit of crops by 45 M€ while reducing environmental damages by 12 M€, achieving higher social benefits. The increase in private benefits results from the drop of nitrogen fertilization (-39,000 tN) which reduces nitrogen leaching (-7,000 tN) and crops N_2O emissions (-196,000 tCO_2e). Cultivated area and water withdrawals increase, reducing the streamflow at the Ebro mouth. Nitrate loads at the source in the basin are reduced to 229,000 tNO_3-N, declining nitrate concentrations at the river mouth by 0.3 mg/l NO_3^-.

Under drought conditions, despite the reduction of streamflow at the mouth to 5,341 Mm^3, this policy still improves water and atmosphere quality by reducing nitrate concentration to 18.2 mg/l NO_3^- and GHG emissions to 6.79 $MtCO_2e$, compared to drought conditions without policies. The results point out also that the policy under drought reduces nitrate loads at the source to 220,000 tNO_3-N but increases water withdrawals to 2,566 Mm^3. Compared with the policy in normal flow, nitrate concentration at the mouth rises 65%, and the reason is drought decreases water availability and impairs the dilution processes. In both cases, normal and drought conditions, this policy is efficient in mitigating agricultural pollution into the atmosphere and watercourses (although reductions are moderate), and in enhancing private profits. The policy benefits both farmers and the environment generating synergies between environmental and economic outcomes (Table 3). However, its implementation requires the training and willingness to cooperate of farmers.

FIGURE 4 AROUND HERE

Fig. 4. Agricultural GHG emissions in the Ebro Basin at municipal level

4.2.2. Substitution of synthetic fertilization by organic fertilization

Substituting synthetic fertilization by organic fertilization is also an interesting policy for reducing nonpoint pollution to the atmosphere and water streams, and avoid the high abatement costs of manure treatment plants. Increasing the circular use of manure as fertilizer from the current 27% up to 60% would promote a more sustainable agriculture by reusing nutrients in the soil and preventing pollution. This study assumes that the cost of manure application amounts to 3.7 €/m^3 for a distance of 10 km, which includes transport and specialized equipment costs (Daudén et al., 2011). Results show that manure fertilization

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[2] Detailed results on the baseline and policy scenarios are presented in Table 1S, Fig. 4S and Fig. 5S of Supplementary Materials.

increases irrigated land to 584,000 ha and water withdrawals to 4,031 Mm^3, reducing streamflow at the river mouth by 112 Mm^3. This policy increases organic fertilization up to 153,000 tN, while synthetic fertilization declines, achieving a reduction of 300,000 tCO$_2$e in GHG emissions and 28,000 tNO$_3$-N in nitrate loads into watercourses, which decreases nitrate concentration at the Ebro mouth by 32% to 7.7 mg/l NO$_3^-$. Environmental damages decrease by 109 M€ and private benefits increase by 30 M€ because of the cost savings of organic fertilization, augmenting social benefits up to 3,531 M€.

Under drought conditions, the policy abates nitrate loads at the source to 189,000 tNO$_3$-N and GHG emissions to 6.81 MtCO$_2$e, while water withdrawals amount to 2,564 Mm^3. However, nitrate concentration increases at the river mouth by 39% to 15.7 mg/l NO$_3^-$ because of the drought lower streamflows. Compared with drought conditions without any policy, manure fertilization improves water and air pollution, lowering environmental damages (-82 M€) and increasing social benefits (+119 M€). This policy entails synergies in reducing both atmosphere and water pollution, and synergies between economic and environmental outcomes under normal and drought conditions. It shows also an acceptable tradeoff between water quantity (streamflow at the mouth) and quality (pollution abatement) (Table 3).

Table 3.
Use of resources, pollution and benefits for each policy under normal and drought conditions

	Normal flow					**Severe drought**				
Policies	**Without policies**	**P1**	**P2**	**P3**	**P4**	**Without policies**	**P1**	**P2**	**P3**	**P4**
Land (1,000 ha)										
Irrigated land	557	584	584	566	557	315	330	347	328	315
Dryland	1,194	1,194	1,194	1,194	1,194	1194	1,194	1,194	1,194	1,194
Livestock (LSU)										
Animals	2,769	2,769	2,769	2,769	2,769	2,769	2,769	2,769	2,769	2,769
Water use (Mm^3)	**3,874**	**4,031**	**4,031**	**3,549**	**3,874**	**2,475**	**2,566**	**2,564**	**2,280**	**2,475**
Agriculture	3,552	3,709	3,709	3,227	3,552	2,176	2,244	2242	1,958	2,176
Urban	322	322	322	322	322	322	322	322	322	322
Streamflow at the river mouth	9,272	9,160	9,160	9,290	9,272	5,406	5,341	5,342	5,416	5,406
Nitrogen emissions (1000 tNO$_3$-N)										
At the source	236	229	160	234	115	225	220	189	224	105
Entering water bodies	94	91	66	93	46	89	87	73	89	42
NO$_3^-$ concentration (mg/l NO$_3^-$)										
Ebro River mouth	11.3	11.0	7.7	11.1	5.5	18.4	18.2	15.7	18.3	8.6
GHG emissions (MtCO$_2$e)	7.15	6.96	6.85	7.11	6.65	6.93	6.79	6.81	6.92	6.43
Private benefits (M€)										
Agriculture	1,925	1,970	1,937	1,937	1,642	1,727	1,764	1,772	1,761	1,444
Urban	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859
Total	**3.784**	**3,829**	**3,796**	**3,796**	**3.501**	**3,586**	**3,623**	**3,623**	**3,620**	**3,303**
Env. damages (M€)	**409**	**397**	**300**	**406**	**326**	**394**	**386**	**312**	**393**	**312**
Social benefits (M€)										
Agriculture	1,516	1,573	1,672	1,531	1,316	1,333	1,378	1,452	1,418	1,133
Urban	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859
Total	**3,375**	**3,432**	**3,531**	**3,390**	**3,175**	**3,192**	**3,237**	**3,311**	**3,277**	**2,292**

4.2.3. Irrigation modernization

Modernization investments involve upgrading irrigation technologies, which enhance the efficiency of water use and reduce nitrate and GHG emissions. Modernization increases cultivated land to 566,000 ha after substituting surface irrigation by sprinkler and drip systems. However, advanced irrigation systems reduce water withdrawals to 3,173 Mm^3 and nitrogen fertilization to 85,000 tN, increasing the efficiency of water and nitrogen use. Therefore, nitrate loads at the source and nitrate concentration at the Ebro mouth are reduced, while the streamflow at the mouth increases. N_2O emissions also decrease to 0.72 $MtCO_2e$. This shows that modernization generates suitable tradeoffs between streamflow, nitrate concentrations and GHG emissions. Advanced irrigation technologies increase yields and farmers' benefits, but modernization costs are very high. As a consequence, the private benefits of irrigation decrease but they are still advantageous compared with the baseline.

Under drought, modernization reduces water use, nitrogen leached, and GHG emissions, increasing social benefits by 85 M€ compared to drought without policies. Although modernization increases streamflow at the mouth, the abatement of nitrate concentration is very small, which shows the tradeoff of this policy between water quantity and quality (Table 3).

4.2.4. Manure treatment plants

Manure treatment plants reduce direct and indirect nitrogen loads into watercourses and nitrous oxide emissions into the atmosphere from manure management. These abatement technologies involve high investment, operation and maintenance costs. This study considers plants of 50,000 m^3/year with nitrification and denitrification processes, with total cost at 7 €/m^3 of manure (Flotats et al., 2011). Results under normal flow and drought conditions show that the installation of manure treatment plants maintains water withdrawals by agriculture and streamflow at the river mouth, but achieves significant abatement of both nitrate concentration at the Ebro mouth (by more than half to 5.5 and 8.6 mg/l NO_3^-, respectively for normal and drought years) and GHG emissions (down to 6.65 and 6.43 $MtCO_2e$, respectively). Environmental damages are curbed by around 80 M€ but the costs of this policy are close to 280 M€, reducing both private and social benefits (Table 3). The investments in manure treatment plants would be reasonable for higher social carbon costs above the current estimates of 40 €/tCO_2e, or for river reaches where highly valuable aquatic ecosystems are damaged by nitrates. Also, manure treatment plants could be the only alternative in areas generating large quantities of manure that cannot be reused as fertilizer because of the lack of cropland in the surroundings.

5. Discussion

In this paper, we develop a hydroeconomic model to analyze the assignment of water and pollution abatement among sectors and locations. The model was applied to the Ebro basin in order to assess the impacts of different water availability scenarios, and the effectiveness and robustness of various mitigation and adaptation policies, while at the same time considering the interactions between agricultural and urban sectors. Water resources in the Ebro are linked to important economic activities and aquatic ecosystems, and the impacts of climate change in coming decades call for a more sustainable management based on accurate assessments of the water quantity and water quality outlooks in the basin. Drought scenarios reduce water availability and increase nitrate concentration at the Ebro mouth, showing the tradeoffs between water quantity and water quality during droughts. However, drought conditions also reduce nitrogen loads and water withdrawals from agriculture. Results from drought scenarios are good indicators of future climate change impacts on agricultural activities, water allocations and water quality. This information provides effective policy support and assistance to policymakers in the choice of efficient and robust policy interventions that minimize the tradeoffs between water quantity and water quality in the basin.

Furthermore, this study provides important insights on water withdrawals and nonpoint pollution under various mitigation and adaptation policies in normal and severe drought conditions, presenting a full comparison of water use, nutrient pollution, environmental damages and social benefits under alternative policies. All policies contribute to the abatement of nonpoint pollution, and improve both water and air quality. The results reveal the tradeoffs and synergies between the economic and environmental effects of these abatement policies. Nitrogen optimization (P1), manure fertilization (P2) and irrigation modernization (P3) are interesting policies that reduce polluting emissions into the atmosphere and watercourses, while enhancing the private benefits of farmers. Those policies deliver synergies between the economic and environmental outcomes. However, Manure treatment plants (P4) have an important effect in decreasing nonpoint pollution and environmental damages, while reducing private benefits because of the high investment and operating costs.

The use of manure as fertilizer is of major interest in the Ebro Basin, especially in Aragon, because the volume of available manure in the region can meet all nitrogen requirements by crops (Orus, 2006). Albiac et al. (2016) indicate that the use of organic fertilizers in Europe could decrease the use of synthetic fertilizers by almost half, thus reducing nitrous oxide emissions and nitrogen loads in watercourses, which would generate around 5,200 M€ in environmental benefits. This policy is more efficient in reducing nitrate concentration and improving water quality compared to other policies.

Irrigation modernization is the policy that increases water efficiency and streamflows at the Ebro mouth. However, Grafton et al. (2018) emphasize the paradox of irrigation efficiency, which indicates that changes to advanced irrigation technologies increases irrigation efficiency at district level, but could also increase water consumption in the basin. Gains in irrigation efficiency promote more water-intensive crops, double crops or irrigated land expansion, resulting in higher evapotranspiration and lower return flows to watersheds. To avoid the paradox, modernization projects of irrigation districts should include water balances that prevent increases in evapotranspiration. Albiac et al. (2017) indicate that irrigation modernization in Spain could reduce GHG emissions by 2.1 $MtCO_2e$, but involves quite high investment costs.

Droughts could limit the effectiveness of abatement policies in curbing nonpoint emissions and improving water and air quality compared with normal weather. However, these policies still have significant economic and environmental positive effects compared to drought conditions without policies. The analysis of mitigation policies could support decision makers and contribute to the ongoing policy discussion for designing basin wide sustainable water management policies.

The choice of policies depends on the objectives of decision makers, but also on the availability of biophysical and economic information. The uptake of policies is related to their cost-efficiency, acceptability by stakeholders, appropriate design of implementation and enforcement mechanisms, and resulting transaction costs. Besides, the success of policies could be thwarted by several barriers, such as farmers' lack of knowledge of the right production techniques, lack of incentives to adopt policies, or high investment costs. Successful implementation requires effective policies that are socially viable and include appropriate enforcement mechanisms ensuring compliance by stakeholders. Collective action and cooperation among farmers, policymakers, scientists, and other stakeholders are needed to overcome these barriers and achieve sustainable policies (Jiao et al., 2016).

A certain number of simplifying assumptions have been used in defining the structure of the hydroeconomic model. The model includes a reduced form hydrological framework, which does not include reservoirs and their linkages with streamflows. Moreover, the model is static and does not include dynamic aspects regarding water allocations, basin streamflows, and drought events. This may change the effectiveness of mitigation and adaptation policies over a multi-year horizon. Despite these limitations, the hydroeconomic model is a good analytical tool to assess the effects of drought scenarios and selected mitigation and adaptation policies for enhancing water allocation and curbing water and air pollution. Future work could address the improvement of the model structure, incorporating significant additional biophysical processes (transport and fate and other pollutants), including reservoirs, stochastic variables, and the strategic behavior of stakeholders.

6. Conclusions

In this study, we develop a hydroeconomic model, which integrates water quantity and quality aspects, including biophysical, technological, hydrological, economic, and environmental features at basin level. This modeling approach is an essential instrument for spatial and sectoral analysis of the problems involved in managing water quantity and quality. The embedded linkages between drought events and mitigation and adaptation policies contribute to evaluate the effectiveness of agricultural nonpoint pollution abatement under extreme drought and future climate change conditions. Results of this study are found to be consistent with previous studies assessing the costs and social benefits of water allocation under future climate change conditions. Moreover, the results provide insight into several critical areas related to nutrient water pollution and atmosphere quality, the synergies and tradeoffs between environmental and economic objectives under various policies, and the potential tradeoffs among water quantity and water quality. Overall, results highlight the capacity of integrated hydroeconomic modeling to address challenging research questions involved in the sustainable management of water resources. As such, we believe that hydroeconomic modeling could support decision-making and contribute to the ongoing policy discussions for designing basin wide sustainable policies. The findings in the Ebro could have interest for other rivers basin, especially in arid and semiarid regions with similar agricultural and climate conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary Materials. Additional data on land use, livestock herds, pollutants and policy outcomes can be found in the online version at

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Highlights

- A novel integrated hydro-economic model for basin-scale optimal planning is developed
- Water scarcity and agricultural nonpoint pollution are addressed
- Hydrological, economic and pollution features capture spatial and sectoral interactions
- Results evaluate mitigation and adaptation policies under climate change
- Water quantity and quality tradeoffs are also assessed

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Dear Editors,

I am pleased to submit the manuscript entitled “***Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain***” to be considered for publication in the *Journal of Cleaner Production*. I am the corresponding author of the paper.

I think that the paper could deserve consideration in your journal, since the results and implications are of interest to experts and stakeholders involved in water allocation, water quality and climate change policy analysis. The paper could be of interest because it assesses water allocation and agricultural nonpoint pollution in a large river basin using hydroeconomic modeling. The paper analyzes a series of mitigation and adaptation policies under normal climate and severe drought conditions in order to identify the effectiveness and robustness of these policies to address water scarcity and water pollution.

The hydroeconomic modeling approach combines hydrological, economic and water quality aspects, and captures the main spatial and sectoral interactions in the basin. The interaction among components provides a better assessment of water allocation options among sectors and spatial locations, showing the specific impacts of droughts on the system and the tradeoffs between water quantity and water quality. The findings call for policy efforts focused on nurturing stakeholders’ collective action.

We appreciate your attention and help, and look forward to hearing from you.

Sincerely,

José Albiac

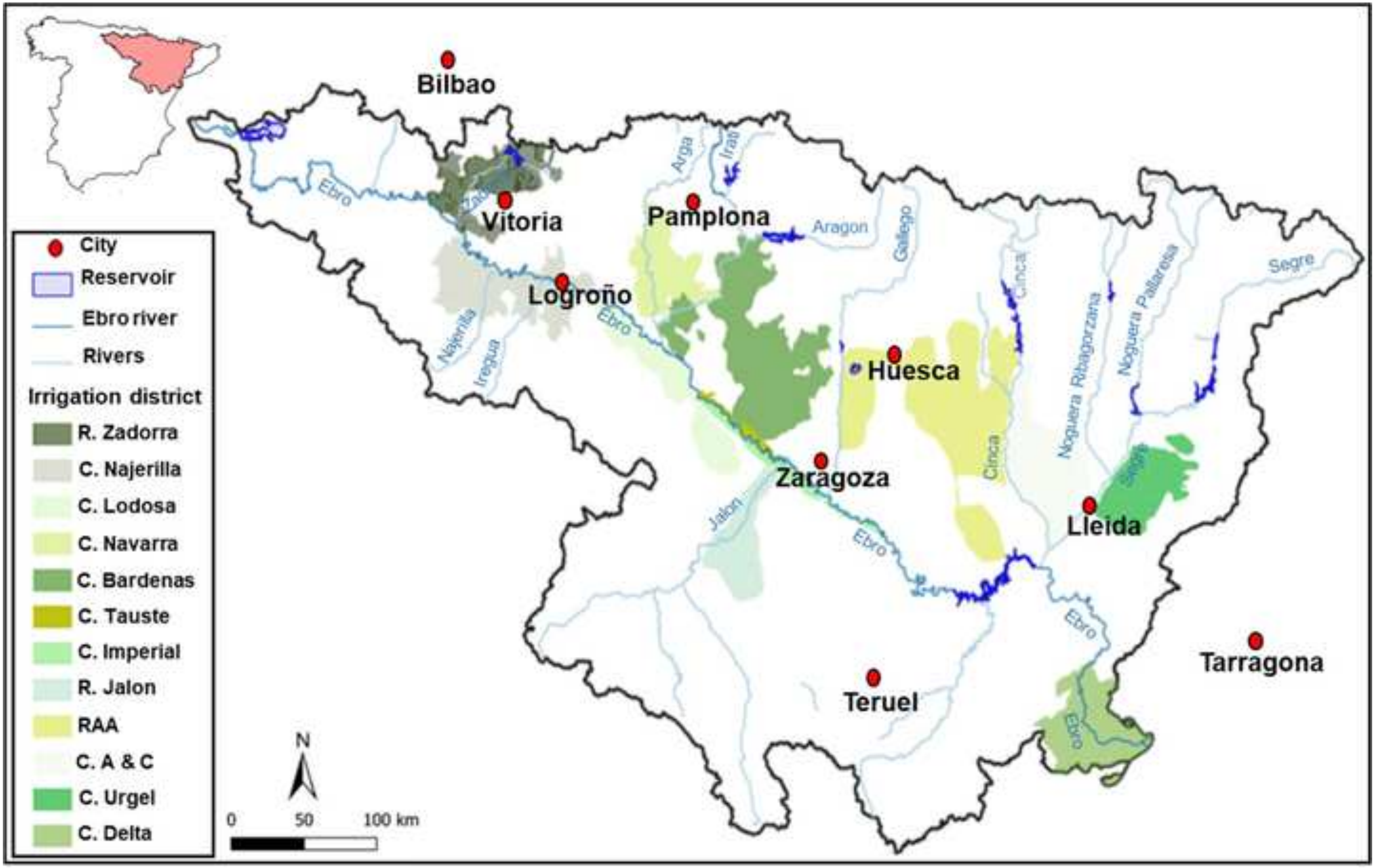
Declaration of Interest Statement

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Figure 1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Aragon
Gallego
Cinca
Noguera Ribagorzana
Noguera Pallaresa
Segre
Najerilla
Iregua
Jalon
City
Reservoir
Ebro river
Rivers
Irrigation district
R. Zadorra
C. Najerilla
C. Lodosa
C. Navarra
C. Bardenas
C. Tauste
C. Imperial
R. Jalon
RAA
C. A & C
C. Urgel
C. Delta
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Figure 2

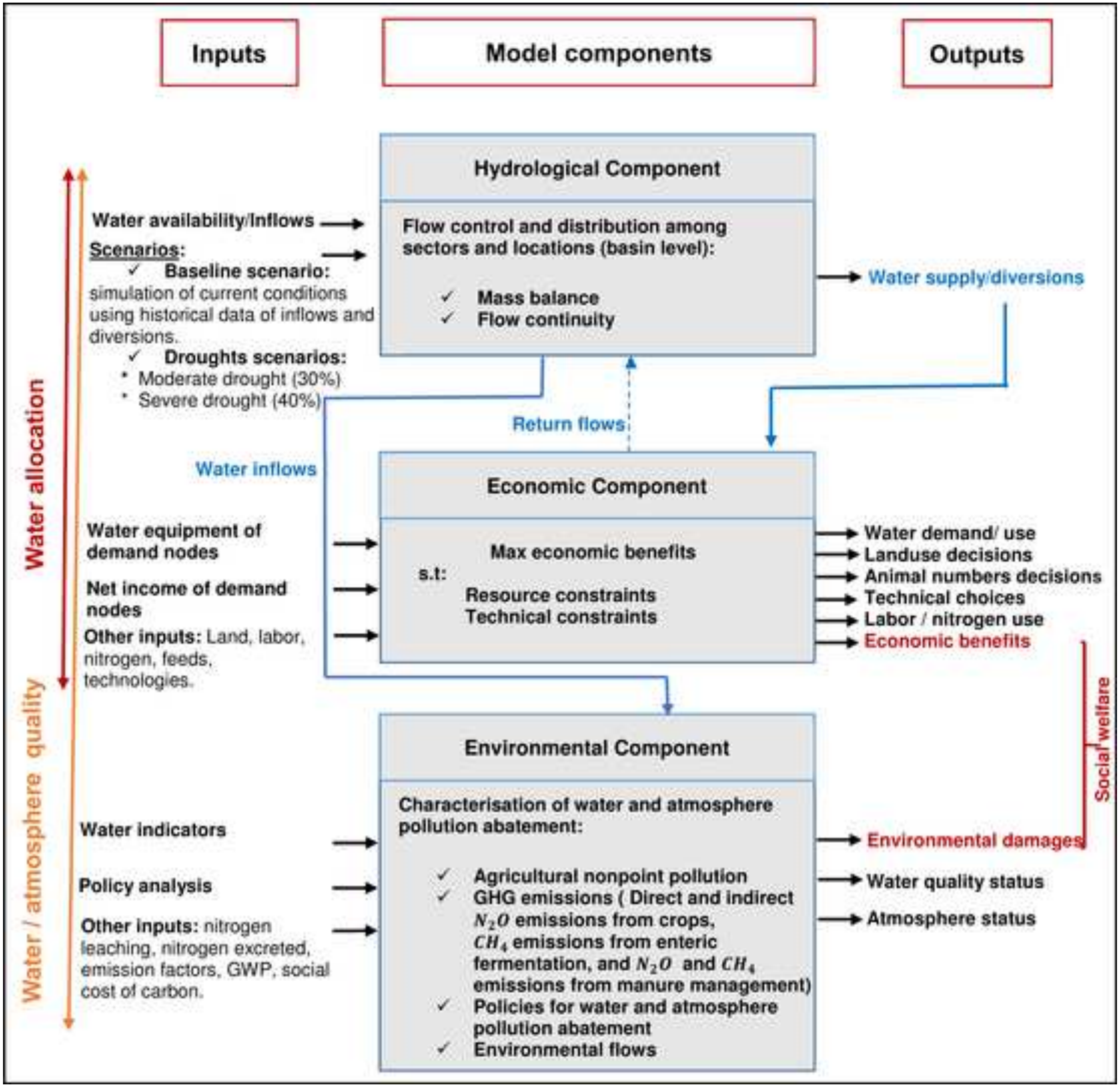
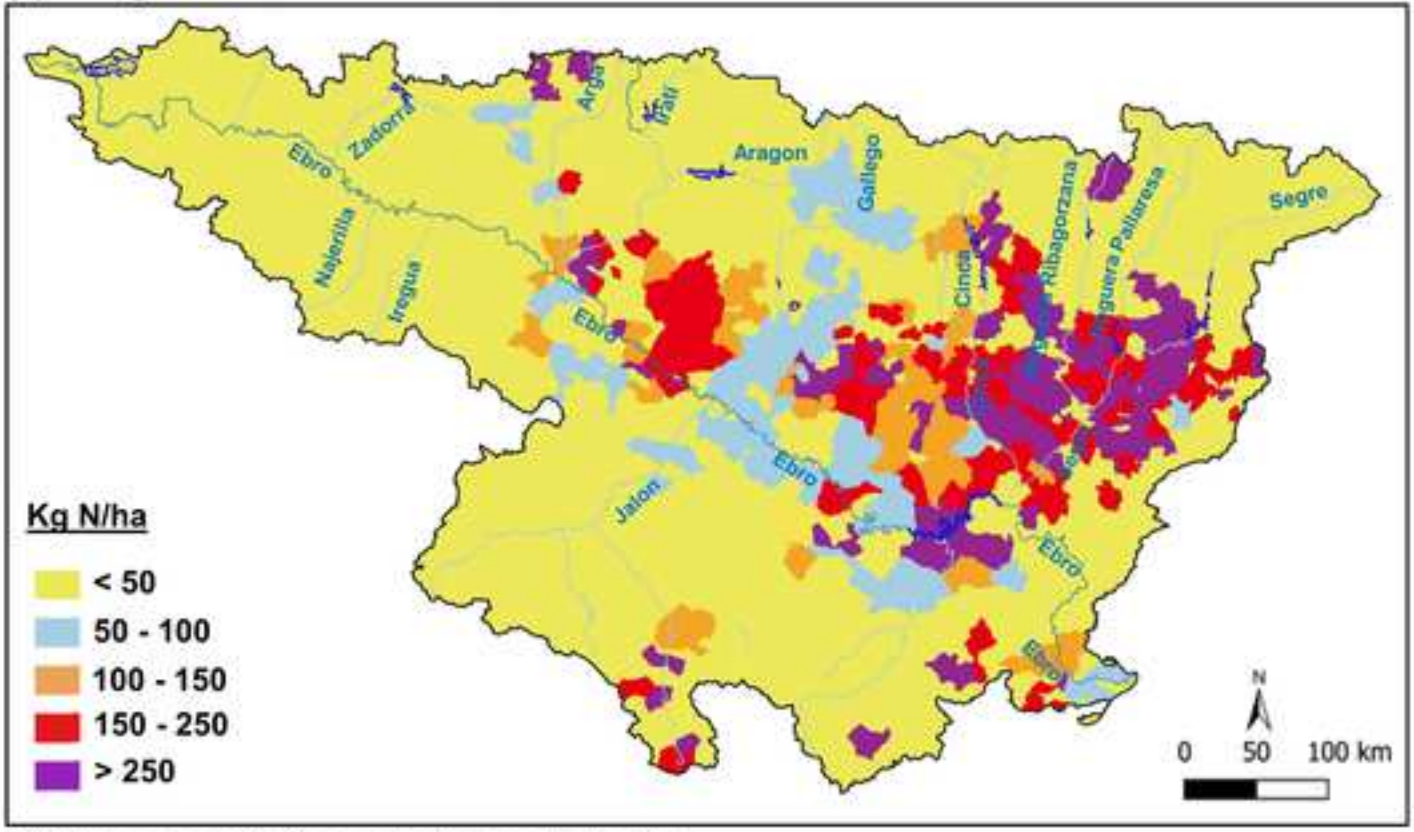

Inputs
Model components
Outputs
Water allocation
Water / atmosphere quality
Water availability/Inflows
Scenarios:
✓ Baseline scenario:
simulation of current conditions using historical data of inflows and diversions.
✓ Droughts scenarios:
* Moderate drought (30%)
* Severe drought (40%)
Hydrological Component
Flow control and distribution among sectors and locations (basin level):
✓ Mass balance
✓ Flow continuity
Water supply/diversions
Return flows
Water inflows
Economic Component
Max economic benefits
s.t:
Resource constraints
Technical constraints
Water equipment of demand nodes
Net income of demand nodes
Other inputs: Land, labor, nitrogen, feeds, technologies.
Water demand/ use
Landuse decisions
Animal numbers decisions
Technical choices
Labor / nitrogen use
Economic benefits
Social welfare
Environmental Component
Characterisation of water and atmosphere pollution abatement:
✓ Agricultural nonpoint pollution
✓ GHG emissions (Direct and indirect N_2O emissions from crops, CH_4 emissions from enteric fermentation, and N_2O and CH_4 emissions from manure management)
✓ Policies for water and atmosphere pollution abatement
✓ Environmental flows
Water indicators
Policy analysis
Other inputs: nitrogen leaching, nitrogen excreted, emission factors, GWP, social cost of carbon.
Environmental damages
Water quality status
Atmosphere status

Figure 3

(a) Nitrogen emissions at the source



(b) Nitrogen emissions entering water bodies

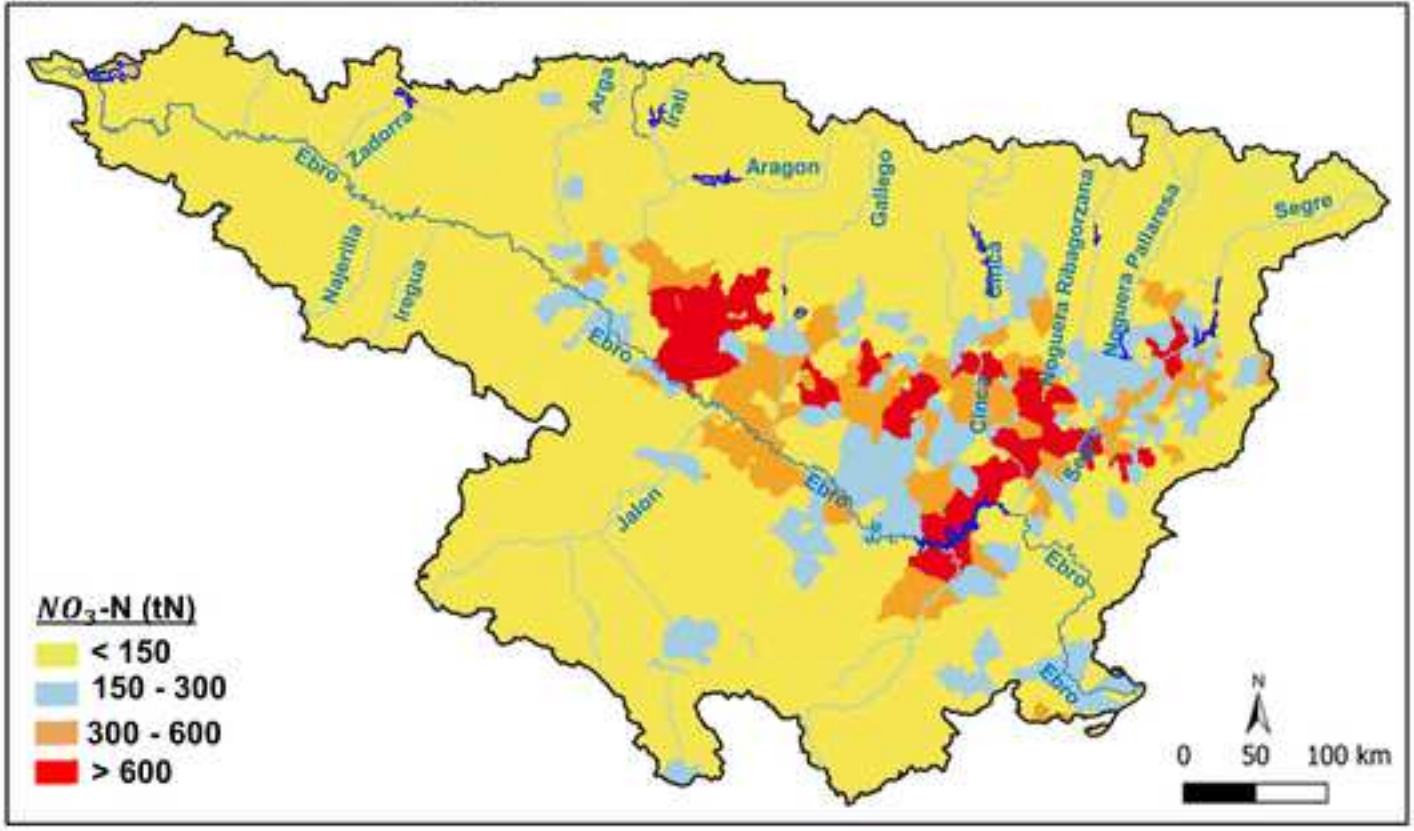


Figure 4

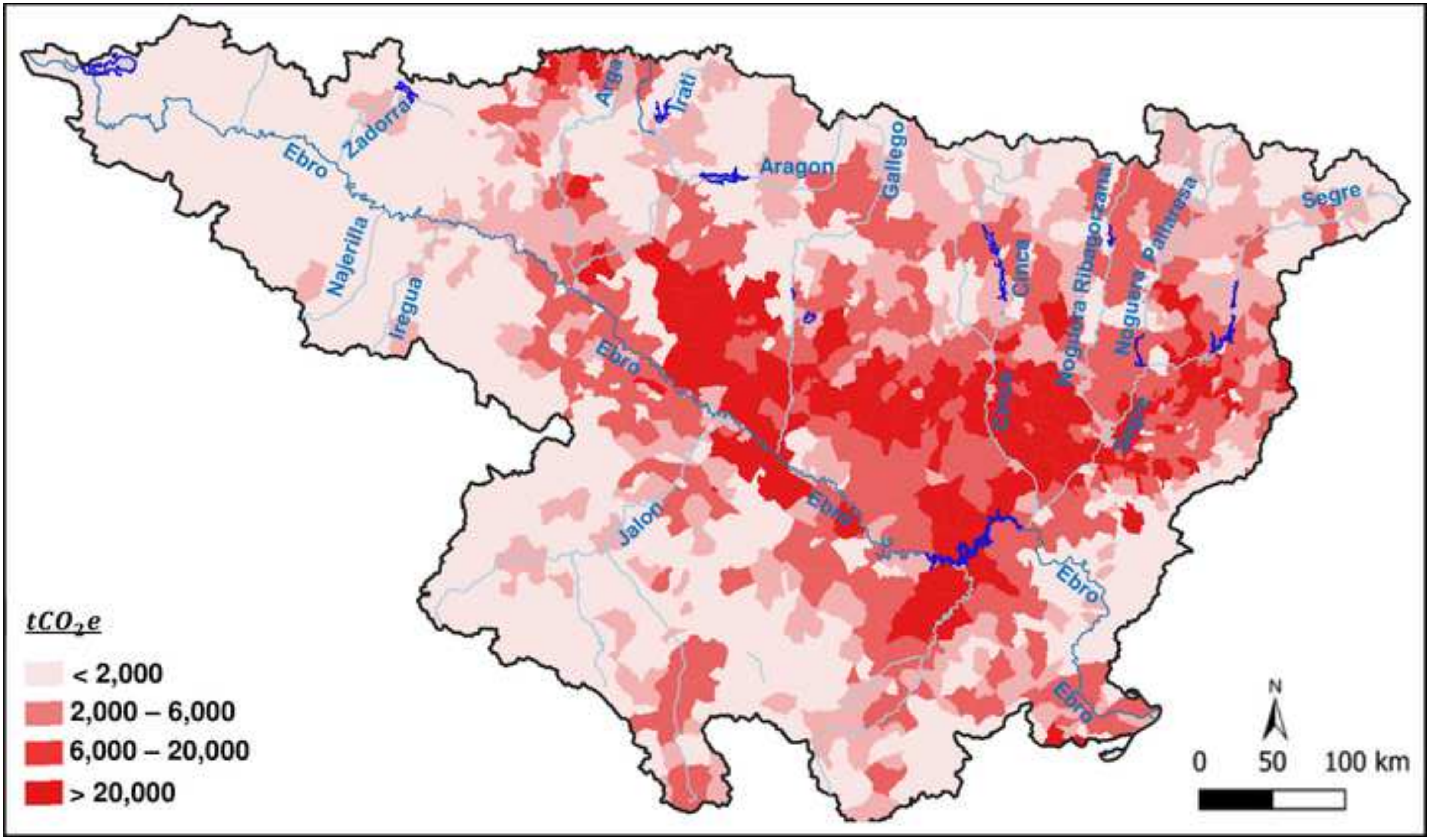

Ebro
Zadorra
Arga
Irati
Aragon
Gallego
Segre
Najerilla
Iregua
Cinca
Noguera Ribagorzana
Noguera
Pallaresa
Ebro
Cinca
Segre
Jalon
Ebro
Ebro
Ebro
tCO₂e
< 2,000
2,000 – 6,000
6,000 – 20,000
> 20,000
N
0
50
100 km

Figure Captions

Fig.1. Map of the Ebro Basin

Fig. 2. Modeling framework

Fig. 3. Nitrogen emissions at the source and in water bodies at municipal level

Fig. 4. Agricultural GHG emissions in the Ebro Basin at municipal level

Supplementary Materials