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Security vs efficiency of the water-energy-food nexus. A study of the economies of the regions of Spain

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ABSTRACT

This article addresses the conflict between socio-economic efficiency versus security-related sustainability in the provision of limited natural resources. We use the framework of the water, energy and food nexus in a novel approach that allows us to identify strengths and weaknesses in the economic structure of the regions analysed. We use the economies of the 17 autonomous regions of Spain as a case study. We simultaneously use integrated indicators of security, based on the availability, sufficiency and sustainability of resources, and data envelopment analysis to assess socio-economic and environmental efficiency. The results show significant differences in the sustainability of the nexus, with values ranging from 62% in Madrid to 83% in Galicia, while socio-economic and environmental efficiency ranges from 1.16% in the Basque Country to 0.63% in Navarre. A growing trend is also detected in the gap between the most and least resource-efficient regions. The two-dimensional analysis of security versus efficiency, as well as the separation of the latter into efficiency change and technical change, makes it possible to detect weaknesses and classify the 17 autonomous communities into 4 groups according to their success in both dimensions. The conclusions offer possible lines of public policy for the improvement of regional economies based on this analysis.

1. Introduction

Economic activity occurs within a physical setting characterised by environmental factors that restrict its ability to supply resources and absorb waste. Providing clean air, water and biomass are examples of environmental services that are inextricably linked to human well-being and the success of economic activities (Goodland & Ledec, 1987). Excessive reliance on outside resources, the over-exploitation of available resources or waste emissions that exceed the rate of the environmental metabolism indicate how the physical environment of an economy imposes certain limits (Daly, 1987).

The increase in demand for food, energy and water, owing to growing socio-economic pressures, overstretches the capacity of the ecosystem (Arthur et al., 2019). Currently, nearly 70% of the World's freshwater is used for agriculture and energy production. (FAO, 2011), and the demand for water is expected to increase by 55% by 2050 (IRENA, 2015). Energy consumption is projected to grow by 50% over the current levels by 2050 (U.S. Energy Information Administration, 2021). Finally, as the demand for food is expected to soar to 50% over current levels by 2050 and arable land requirements will grow by 165 million hectares by 2050 (FAO, 2018), food security, along with water and energy supply, represent key questions with regard to their availability, accessibility and utilisation (Mekonnen et al., 2019).

In order to analyse an economy's performance and examine its sustainability from three different perspectives–economically, environmentally and socially–the water-energy-food nexus (WEFnX) paradigm was developed as a concept that describes an interwoven system that transforms and transports resources from natural systems to anthropogenic consumption (Higgins and Abou Najm, 2020). By highlighting the synergies and conflicts between economic activity and the utilisation of environmental resources, WEFnX provides a first approach to understanding the interdependence between the two. This framework is useful for investigating in particular the effects of mutual reliance and feedback on the complex interactions of WEFnX to highlight the long-term implications of resource consumption (Endo et al., 2015).

WEFnX's framework defines the study's boundaries, both in terms of the pillars and subsystems covered as well as the temporal and spatial scope (scale). The nexus research structure centres on the interdependence of the use of water, energy and food (McGrane et al., 2019) which are the nucleus of the nexus. Yet it also encompasses its interrelationship

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with the economic, social and environmental systems in which it is embedded. Studies of the nexus methodically analyse the use of resources and offer ways to improve technical and economic efficiency (Yi et al., 2020). Being able to strike a balance between the effective management of the nexus and its sustainability is one of the most difficult aspects of political decision making, as poor resource management also has negative effects on society and the economy (Bai and Sarkis, 2022). The key issue is creating strategies that ensure viable utilisation of assets in a way that is open to all society and at an acceptable level of environmental protection (Simpson and Jewitt, 2019).

Our work addresses this key conflict between nexus resource security and efficiency from a socio-economic and environmental perspective (Biggs et al., 2015). We look comparatively at both dimensions in the 17 Spanish autonomous communities (AACCs) from 2000 to 2018. This approach is useful to capture the hierarchy implicit in the structures of authority that shape the multilevel governance of environmental resources (Rasul and Sharm, 2015), given the highly decentralised nature of the government in Spain, where the AACC are responsible for more than 49% of all public spending. (OECD / UCLG, 2016). The pertinence of this research is supported by the scarcity of comprehensive studies on the Spanish economy from the nexus perspective. The recent study by Raya-Tapia et al. (2023) on nexus security indicators reaches, with a different methodology to ours, very similar conclusions regarding the availability and self-sufficiency of the nexus pillars in Spanish regions. Up to now other studies have focused on only two of the three nexus pillars, or on a single region or economic sector (Rezaei Kalvani and Celico, 2023).

As a result, we found a gap in efficiency and security between the AACCs, as well as a tendency for this gap to widen. Using the intensity of fixed capital and resource use, as well as the critical points in resource security, we establish conclusions and recommendations for improving the security and economic efficiency of nexus management, which can serve as a guideline for regional economic policy.

Studies on WEFnX cover a wide range of scales and methodologies (Simpson and Jewitt, 2019) as well as goals, such as resource optimisation (Chamas et al., 2021; Liu et al., 2020; Yi et al., 2020) or minimising GHG emissions (Tabatabaie and Murthy, 2021; X. Zhang & Vesselinov, 2017), or operational and capital costs (Núñez-López et al., 2021; Saif et al., 2020), the assessment of the effects of climate change (Mercure et al., 2019; Wicaksono and Kang, 2019), the implementation of sustainable development policies (Niva et al., 2020) and changes in water management (Ding et al., 2019; Wu et al., 2021). There is also an abundance of studies on the nexus aimed at meeting sustainable development goals (Saladini et al., 2018; Storey et al., 2017). These methodologies range from econometric and statistical techniques (Ozturk, 2017; Taniguchi et al., 2018) and/or optimisation models to the use of system dynamics models (Izquierdo et al., 2008; Kulat et al., 2019; Tan et al., 2020, etc.), ecological network analysis (Mekonnen et al., 2019; Owen et al., 2018; Willaarts et al., 2020) or even purely qualitative studies.

For our purposes, we use integrated indicators to evaluate nexus security, as well as data envelopment analysis (DEA) and Malmquist productivity indices (MI) to study the Total Factor Productivity (TFP). Therefore, we employ the nexus as a widely accepted concept that can replace the classic approaches centred on the productivity of individual sectors with a more global philosophy focused on maximising the efficiency of the system as a whole. (Higgins and Abou Najm, 2020).

After this introductory section, our work includes a section detailing our data sources, region of study and the methodologies used, another presenting the results obtained with each of them, a third in which we interpret the results relating aspects of both security and efficiency and a final section in which we present some conclusions and possible directions for future research.

2. Methodology, data and region of study

2.1. Integrated indicators for WEFnX security

To assess the security of WEFnX in the long term, we will build integrated indicators for water, energy and food security, based on their respective availability, sustainability and accessibility (Putra et al., 2020; Sánchez-Zarco et al., 2020; Yuan et al., 2021) and an integrated indicator for WEFnX security as a whole (Y. Feng et al., 2020; Mohammadpour et al., 2019; Nhamo et al., 2020). Availability refers to the amount of resources consumed in a region that can be effectively supplied by that region. Sustainability relates to the impact that the production and consumption of resources have on the environment, which may affect future production. Finally, accessibility expresses the degree to which the population has the capacity to use resources on the basis of its socio-economic situation (Mahlknecht et al., 2020; Sánchez-Zarco et al., 2020; Yuan et al., 2021).

For water, as a resource limited by the natural environment, we used the percentage of water not consumed by human activity over the total water available annually in the region as an availability indicator:

$$W_{Disp} = \frac{W_{Rec} - W_{Con}}{W_{Rec}} \tag{1}$$

As an indicator of water sustainability, we used the general water quality index (Mingo, 1981) calculated as a weighted average of nine basic quality parameters aggregated according to the following expression:

$$W_Q = \sum_{i=1}^{N} VQ_i x P_i \tag{2}$$

Where VQ_i represents the quality value for each parameter measured, and P_i is the weight assigned to parameter i. For a more detailed explanation of the water quality indicator and all the data employed, please refer to ANNEX I.

Regarding accessibility, we can consider universal access to drinking water in Spain, given the low cost of this service in relation to family income and the existence of ample social protection mechanisms that prevent cuts in water supply or ensure reconnection, even in case of default (García-Rubio et al., 2019). According to the Spanish Association of Sanitation and Water Supply, the total number of residential supply cuts without later reconnection affects just approximately 0.01% of homes. (AEAS, 2016). Therefore, considering the study scale, we took a value of 100% for this indicator in all AACCs.

The ratio of the total energy produced to the total energy consumption in a region was used as an indicator of energy availability.

$$E_{Disp} = \frac{E_{Pro}}{E_{Con}} \tag{3}$$

The ratio of the total energy production from RES to the total energy production in the region was employed as an indicator of energy sustainability.

$$E_{Sost} = \frac{E_{Ren}}{E_{Pro}} \tag{4}$$

As an indicator of energy accessibility, we consider the percentage of the population that can afford to keep the home at an adequate temperature.

Regarding the nexus food pillar, we used the ratio of food production in a region to total food consumption through the economy in that region as a food availability indicator.

$$F_{Disp} = \frac{F_{Pro}}{F_{Con}} \tag{5}$$

We took the percentage of total cultivated area with ecological production certification in relation to the total agricultural area as a proxy indicator for food sustainability.

$$F_{Sost} = \frac{FS_{Eco}}{FS_{Pro}} \tag{6}$$

Finally, as an indicator of food accessibility, we take the percentage of the population that can afford a meal of meat, poultry, or fish at least every alternate day.

As food and energy availability indicators have been defined, a value greater than 1 means that the territory has a surplus in these resources and becomes a net supplier, while a value lower than 1 indicates that the territory has a deficit and is dependent on other economies to satisfy its demand. All other indicators are defined in a way that cannot be greater than 1, and their proximity to 1 indicates how close the territory is to having secure provision, sustainable use or universal access to that resource.

To assess the security in the provision of the central resources of WEFnX, it is essential to explain the starting hypothesis regarding the degree of substitutability of these resources (Venghaus and Dieken, 2019). Although the provision and economic utilisation of water, food and energy are interlinked (this is the essence of the nexus perspective), it cannot automatically be assumed that one can directly take over the economic functions of the other. Bogardi et al. (2012) showed the irreplaceable and non-substitutable character of water as a resource provided by the ecosystem. Similarly, in the nexus framework, both energy and food are considered non-substitutable goods given their complementarity and scarcity, corresponding to a Leontieff-type function for the complementarity relationship between them. Therefore, we adopted the criterion of non-substitutability between the three core resources of the nexus. Consequently, because more than 100% availability of one resource does not compensate for the lack of another, we limit the values for our assessment to a scale between 0 and 1.

We built integrated indicators with the aim of showing in one single numerical value the security of each of the three pillars and of the nexus as a whole. The use of integrated indicators allows the state and performance of the nexus to be represented through a small set of magnitudes with a standardised format (Yuan et al., 2021). The employment of these indicators is very useful for the orientation of policies, as they present the information from a complex system in a condensed and comprehensible manner, albeit at the expense of simplifying reality (C. Zhang et al., 2018). Another important limitation of the proposed approach is that it requires significant and accurate data for the studied resources in the region. (Cansino-Loeza et al., 2020). As a result, indicators often have to be adapted to existing data, preventing horizontal integration of nexus studies (Endo, 2017). Similarly, by varying the scale of the study region, significant differences in the outcome of an indicator may appear. (Mohammadpour et al., 2019). In this sense, indicators are useful to assess temporal evolution or to compare regions on the same scale, but it is not rigorous to grant them an absolute value outside the framework of the study.

In our case, these integrated indicators are constructed using the analytic hierarchy process (AHP) based on the indicators of availability, sustainability and accessibility already presented. AHP has been used in several studies within the nexus framework (Nhamo et al., 2020; Xu et al., 2019; Yi et al., 2020; Yuan et al., 2021; T. Zhang et al., 2019) to assign to each factor that makes up the final indicator a weight according to its relevance in relation to the other factors. We applied AHP to the responses of 15 experts with different perspectives and roles in the management of the resources of the three nexus pillars.

The AHPSurvey package in R-Studio software was used to calculate the consistency ratios and weights, first obtaining the weights for the assessment of the security of each pillar and then for the security of the nexus as a whole, as well as for the indicators of environmental impact and socio-economic success, also included in the survey and which will be used later for the assessment of efficiency in the management of the nexus.

2.2. Efficiency of nexus management using DEA

Technical efficiency is defined as the relationship between the yields obtained (outputs) and the resources used (inputs) in production, with an economic unit that obtains a higher output/input ratio being more efficient. In complex structures, with various inputs and outputs, the calculation of efficiency requires knowledge not only of the quantities consumed or produced but also of the parameters expressing the relative value or weight of each, which is not always possible. This is particularly true in the absence of a pricing system.

DEA is a non-parametric technique that allows estimation of the relative technical efficiency of a set of decision-making units (DMUs). The method is based on the calculation of the distance of each DMU to an empirical production frontier, constructed for the group of DMUs. The empirical frontier is structured as a linear combination of the DMUs that achieves a comparatively better result than others in terms of the output/input ratio. The main advantage of this method is that it allows us to obtain a value for the relative technical efficiency without the need to know the weights of the inputs or outputs or the specific shape of the production frontier (Junior et al., 2022). In addition, DEA offers the DMU a guide to improve efficiency based on the values of the targets or points on the efficient frontier closest to each DMU. (Aparicio, 2007).

In the nexus framework, DEA has previously been employed as a method to estimate the efficiency of core nexus management in relation to the economic, social and environmental performance of the regions of China (Li et al., 2016; Sun et al., 2021) and Pakistan (Ali et al., 2022), as well as a preliminary step for the calculation of total factor productivity using MI (J. Chen et al., 2019).

We employed the input-oriented DEA model of super-efficiency and assumed constant returns to scale, as we eliminated any element of scale by taking per capita values of the variables considered. The inputs considered were the resource consumption of water, energy and food, as well as the existing stock of fixed capital in the region. Regarding the outputs, we evaluated socio-economic performance on the one hand and environmental performance on the other.

The economic performance indicator was based on three variables: per capita income, employment rate and household economic well-being, the exact definition and source of which can be consulted in appendix ANNEX (I Variables). The environmental performance indicator was based on three variables: municipal solid waste, greenhouse gas emissions and water quality. We built joint indicators using AHP. The results obtained for the weights are as follows.

Ecocomic performance		
GDPpc	Employment	Welfare
0.221	0.291	0.489
Enviromental performance		
$Waste_{sol.}$	GHG.	$Water_{Q.}$
0.243	0.335	0.422

The DEA methodology is subject to significant limitations (Spinks and Hollingsworth, 2009; Smith and Street, 2005). The choice of inputs and outputs in the DEA model is crucial. If relevant variables are omitted or irrelevant variables are included, the results can be misleading, even more so in the nexus framework, where interdependence relationships may not be evident (Zhang et al., 2018). For our purposes, in line with this framework, we assume the intensity of use of the three pillars of the nexus, as well as the crucial role of fixed capital available in a region, as key inputs to its productive system. Our selection of output indicators meets the criteria of the nexus framework, which includes the natural, economic and social environment, while their relative weights have been established using the AHP technique by interviewing 15 experts (Annex II). On the other hand, the statistical significance for a set of the six factors considered (four inputs and two outputs) for the population of

17 DMUs satisfied both the representativeness criterion proposed by Golany and Roll (1989) and that of Dyson et al. (2001). Multicollinearity, which may hinder the interpretation of results and the identification of sources of inefficiency (Kalita & Lyer, 2015) has also been ruled out, with an average value for inflation of the variance of 1.73, and a maximum of 2.35. Finally, with regard to the isotonic character of inputs and outputs, this requirement is also fulfilled, since a lower consumption of resources will always be indicative of greater efficiency, as well as a lower degree of pollution or the achievement of a higher index of socio-economic well-being.

To evaluate TFP, as well as technical and efficiency changes, we use MI, based on the relationship between the distances to the empirical production frontier determined by DEA for each DMU in two different periods, t and t+1(Caves et al., 1982).

MI is widely used as a method to evaluate total factor productivity from a purely economic perspective (Leonida et al., 2004; Park, 2010) including in the case of Spanish regions (Maudos et al., 1998; Rodríguez and Ayuso, 2003). In the WEFnX framework, Chen et al. (2019), Li GJ: et al. (2019) and Zhang et al. (2019) used MI to study the evolution of total factor productivity in Chinese regions, and Branco et al. (2022) are conducting a similar study for Brazil. We will apply the calculation of these indices to the 17 Spanish autonomous communities for the period 2000 to 2018 using the R package deaR.

2.3. Region of study and data sources

Spain is a clear example of how water, energy and food systems are interconnected, given the intensive use of water for crop irrigation or electricity production, the high use of energy in agriculture or the important role in the energy mix of thermal power plants, consumers of water, (Raya-Tapia et al., 2023).

The main water consumer in Spain is irrigation, emerging and in constant growth during the 20th century through state development policies. Recently, freshwater resources are decreasing significantly in some regions (Bazzana et al., 2023) and policies have been directed towards the optimisation of water resources, reaching a figure of 79% of irrigation with efficient systems (MAPA, 2023). The accelerated growth of the tourism sector also increases water consumption. The differences in climate and the weight of the tourism sector, and the fact that regional governments with different criteria are responsible for water issues, introduce significant variations in the management of this resource.

Spain is deficient in energy resources, with a high dependence on imported fossil fuels, a situation aggravated by the abandonment of coal to meet GHG emission targets. The development of RES is allowing progress to be made on a triple front of sustainability, availability and self-sufficiency, in line with EU directives and strategies (Labriet et al., 2010), again with notable variation between regions, due to different generation potential and administrative decentralisation.

Regarding the food pillar of the nexus, Spanish agricultural production grew steadily at the end of the 20th century, only to enter a period of stagnation that has recently ended with its recovery since 2015. The Spanish agricultural sector, heavily supported by European agricultural policy aid, is undergoing an intense process of modernisation, concentration and professionalisation, with a notable increase in productivity (Gamazo, 2022). The National Rural Development Programme, currently under implementation, focuses on competitiveness, efficient use of natural resources and innovation.

In addition, the AACCs present intense heterogeneities in factors such as water balance, economic structure and unemployment. Thus, for example, regions of the so-called España Húmeda ('wet' Spain), such as Galicia or Asturias, present an average rainfall of 1255 and 1129 l/m2 respectively, which gives them a large availability of water resources, while others, such as Murcia or the Canary Islands, have an annual rainfall of only 297 and 250 l/m2 respectively. Another example of high regional disparity can be found in the economic structure, with regions such as Murcia, where more than 10% of the employed are in the primary sector, compared to 0.5% in the Balearics, or others such as La Rioja, where more than 24% of the working population is employed in the industrial sector, compared to 4.3% in the Canaries. Finally, the degree of urbanisation and population density also vary extremely, from 800 inhabitants per square kilometre in highly urbanised Madrid to 26 in rural regions such as Castile-La Mancha. These intense heterogeneities indicate that it may be of interest to study Spain's economy on a regional scale, in the hope of finding significant differences in the management of the WEFnX and its socio-economic and environmental output.

Our data sources include the Spanish National Institute of Statistics, annual reports from the Ministries of Ecological Transition, Industry and Energy or Agriculture, annual reports of the autonomous communities, impact statements of power plants, as well as the national pollutant register, raw data from the NABIA network of water quality stations and the annual reports of the Corporation of Strategic Reserves of Petroleum Products, among others. The result of this work was the construction of a proprietary database which is offered as part of the research results and can be consulted in the supplementary material. For further information, a detailed description of the source of each of the data used in this study, together with an explanation of the construction of the indicators can be found in ANNEX I.

3. Results

3.1. Availability, sustainability and accessibility of water, energy and food

Based on the selected indicators, we can graphically represent (Fig. 1) the evolution of the security of the nexus pillars between 2000/2004 and 2014/2018, which mark the beginning and end of our study period. We have taken several years to represent average values and thus minimise the effect of temporary fluctuations, such as droughts or transitory production or supply problems.

This first approach already allows us to observe some elements of interest.

- An extreme problem of water security in Valencia and Murcia, with their consumption close to 100% of their resources. Madrid, the Canaries and Andalusia also stand out, with consumptions close to 50%.
- There was a positive evolution in the reduction of water stress in the Canaries and somewhat in Andalusia, Murcia and Valencia, whereas it has increased in Madrid.
- Water quality remained close to 75%, with a tendency to improve slightly in all communities, except in Catalonia, Navarre and Castile-Leon.
- Energy self-sufficiency is less than 50% in all regions because of the Spanish economy's external dependence on fossil fuels. Aragon, Castile, Extremadura and La Rioja have a relatively better self-sufficiency of 30% or higher.
- Energy sustainability shows a generalised improvement, with Andalusia, Aragon, Castile-La Mancha, Castile-Leon, Extremadura and Galicia having a positive impact on the energy sufficiency of these regions.
- In Asturias, Castile-Leon and, to a lesser extent, Aragon, the progress in RES is accompanied by a significant loss of energy sufficiency due to the abandonment of coal mining, which went from extracting ore with an annual energy value of 17,597, 31,332 and 11,928 GWh, respectively, during the period 2000/04 to 4,309, 3,255, and 4409 GWh in the period 2014/18.
- La Rioja has experienced a six-fold increase in its energy generation capacity, very much bolstered by the exploitation of its natural gas reserves. As a result, we observed a significant increase in energy

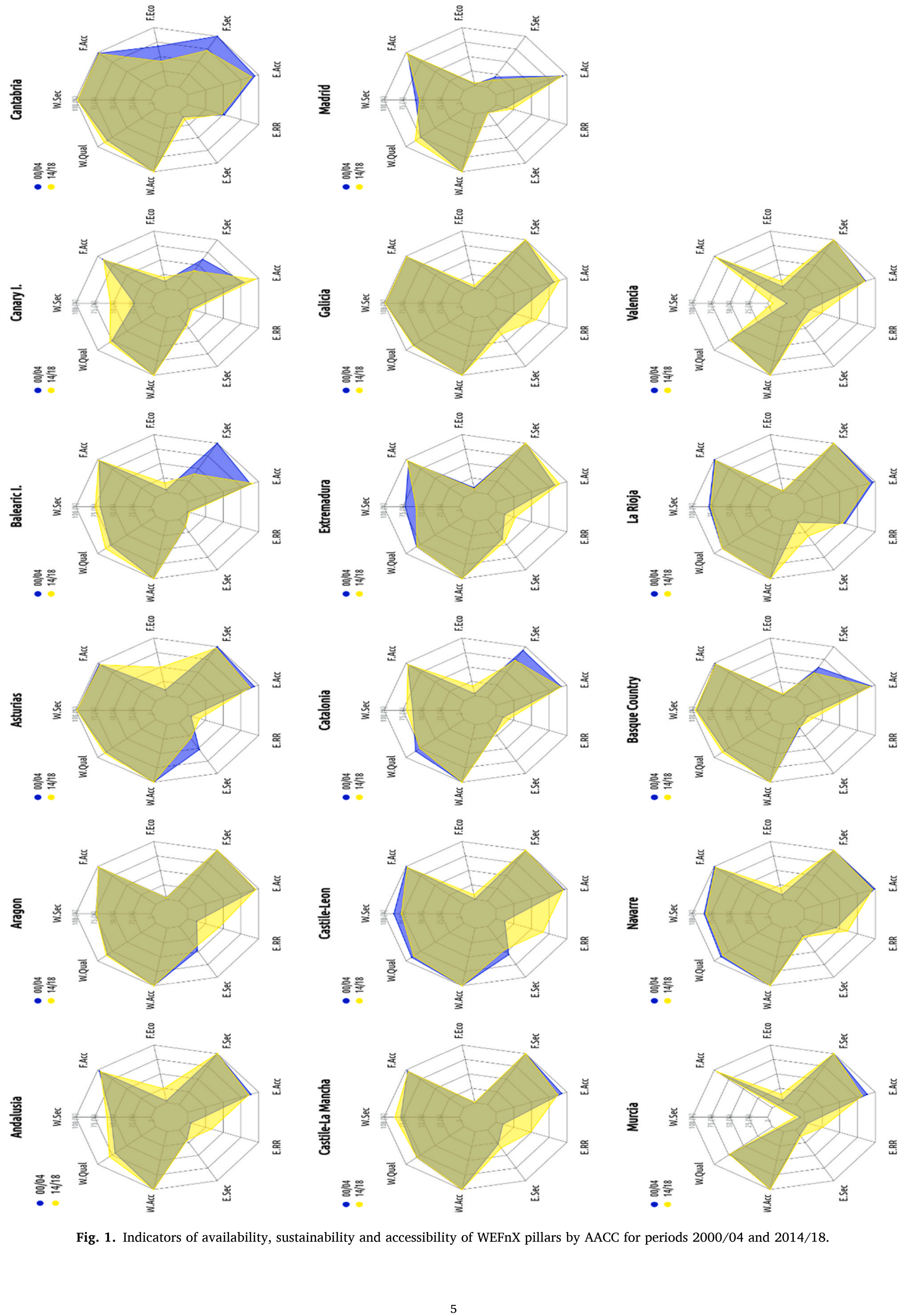

Fig. 1. Indicators of availability, sustainability and accessibility of WEFnX pillars by AACC for periods 2000/04 and 2014/18.

sufficiency, which was not accompanied by significant changes in the share of RES in the energy mix.

- Organic food production is poor in the majority of all AACCs, with percentages of less than 25%, with the exception of Asturias and Cantabria. This index shows a positive evolution in all territories. Andalusia stands out, already at the threshold of 25%.
- We found a greater diversity in terms of food self-sufficiency. The majority of regions have a high production capacity, which allows them to satisfy their needs and makes them net exporters. On the other hand, highly urbanised communities, such as Madrid and the Basque Country, show high and increasing external dependence. Finally, the Balearics, the Canary Islands, Cantabria and Catalonia stand out, which, starting from a scenario of almost self-sufficiency, have fallen back significantly.
- The accessibility of food and energy resources shows a slight fluctuation over the period during which both indicators generally evolve in parallel. Thus, while some regions showed improvements in both indicators (Aragon, the Balearics, Extremadura and Galicia), many others showed an increase in the population's difficulties in accessing both resources, reflecting a deterioration in living conditions.

By using the AHP methodology, the weights obtained for availability, sustainability and accessibility factors for each of the three pillars show, on the following table, that the factor considered to have the greatest weight is accessibility, followed by sustainability in the case of water and energy and availability (self-sufficiency of the territory) for food.

	Availability	Sustainability	Accessibility
W	0.251	0.298	0.451
E	0.264	0.295	0.441
F	0.354	0.240	0.405

Applying these weightings to each AACC's data, we obtain a more integrated view of the security of each of the pillars of the nexus (Fig. 2).

First, we must always take into consideration that the established system of weightings gives predominant weight to accessibility, so that the values of the indicators are generally quite high. From there, we find a generalised scheme in which water appears as the pillar with the greatest security, followed by food and, in third place, energy, in line with Spain's high external dependence, together with the low percentage of RES in the energy mix. Valencia and Murcia are exceptions, with both intense irrigation activity and serious water self-sufficiency problems. There is also a separate case of the intensely urbanised community of Madrid, which also has a very low level of security in terms of both energy and food, again due to its limited capacity for self-sufficiency and consequent external dependence.

Second, we also observe a generally positive evolution of the security of the pillars, with only Cantabria, Catalonia and La Rioja showing a decrease in two indicators, while Andalusia, Aragon, Galicia, Murcia and Valencia showed an intermediate result, with one of the indicators decreasing.

There was a general improvement in security in the water pillar, with the communities of only Castile-Leon, Extremadura, Navarre and La Rioja showing a slight decline. The energy pillar shows a very homogeneous evolution, with increases in all regions, mainly due to the increase in the production of RES, which results in both greater availability and sustainability of the resource. Only Asturias and Cantabria showed a decline due to the abandonment of coal. Finally, the food pillar showed the most uneven evolution, with some regions experiencing setbacks with respect to food security: very significant in the Balearics, the Canaries and Cantabria, and somewhat milder in Catalonia, Madrid and the Basque Country.

Finally, we integrated the indicators of the three pillars by applying the weights obtained with the AHP preference matrices in relation to the comparison of the relative weight of the three pillars. Thus, we produced an indicator of the security of the nexus as a whole. The weights obtained for the three nexus pillars were as follows.

W	E	F
0.424	0.222	0.355

Applying these weights to the security values for the three pillars, we obtained the following nexus security indicators, whose values for the period 2014/18 are shown in (Fig. 3).

There is a great disparity between AACCs in terms of the evaluation of nexus security and a general trend towards improvement in this indicator, with the exception of Cantabria and Catalonia.

The communities with the least security in the nexus and their respective critical factors are Madrid, with ample margins for improvement in energy and food self-sufficiency, and Murcia, with a severe problem of water sufficiency and water quality, as well as Valencia. The Canary and Balearic Islands are somewhat better, but with problems of both sufficiency and sustainability in terms of energy and food, while for the Basque Country, its overall nexus security is somewhat higher, thanks to its abundance of water resources.

3.2. Efficiency of nexus management

A vertical comparison, considering a DMU for each year and region, yields the following values using the DEA super-efficiency model with constant returns to scale (Table 1).

Within a generalised trend towards efficiency losses, we can distinguish the first large group of less efficient communities (Fig. 4 a.), with an average value for the period of less than 0.8 and with a unanimous downward trend. Castile-La Mancha, Extremadura and Murcia stand out and have gone from an initial value above or close to unity to become three of the most inefficient regions in Spain as a whole. In second place (Fig. 4 b), a small group of three regions remains at an average efficiency value between 0.8 and 0.9. In the case of Cantabria and La Rioja the tendency is to worsen, and to remain unchanged in Valencia. Finally (Fig. 4 c.), there is a group of more efficient communities, with an average value above 0.9 and characterised by a stable or slightly improving trend (Madrid and Andalusia).

A scenario of polarisation in efficiency is taking place, with the most efficient AACCs improving in obtaining socio-economic and environmental results from the management of nexus resources, while the least efficient communities worsen in this management.

The calculation of MI (Table 2) provides an estimate of TFP for each year and the AACC. Only five regions, Andalusia, the Balearics, the Canaries, Madrid and the Basque Country, obtained a positive cumulative value of their annual productivity growth rates, while the other 12 registered a net loss of productivity in the period. Madrid stands out, followed by the Canaries and the Basque Country for their productivity gains, while on the negative side, Murcia and Extremadura show the sharpest decline in productivity. If the average value for the autonomous communities as a whole is analysed over three subperiods, the intermediate period of 2008/12, coinciding with the effects of the global financial crisis of 2008, shows a significant loss of productivity, which can be attributed to the effects of the loss of income, employment, and the worsening of the family situation.

By decomposing MI into Efficiency Change (EC) and Technical Change (TC), we observe (Table 3) that of the five regions that recorded cumulative productivity gains, both Madrid and the Basque Country owe this progress entirely to TC and not to EC, which has remained at unit values throughout the period. Similarly, the progress of the Canary Islands is mostly due to TC and exclusively in the case of the Balearic Islands, which can compensate for the marked decline in efficiency. In contrast, the slight progress in productivity achieved in Andalusia is exclusively due to improvements in efficiency, having registered a technical downturn in the period.

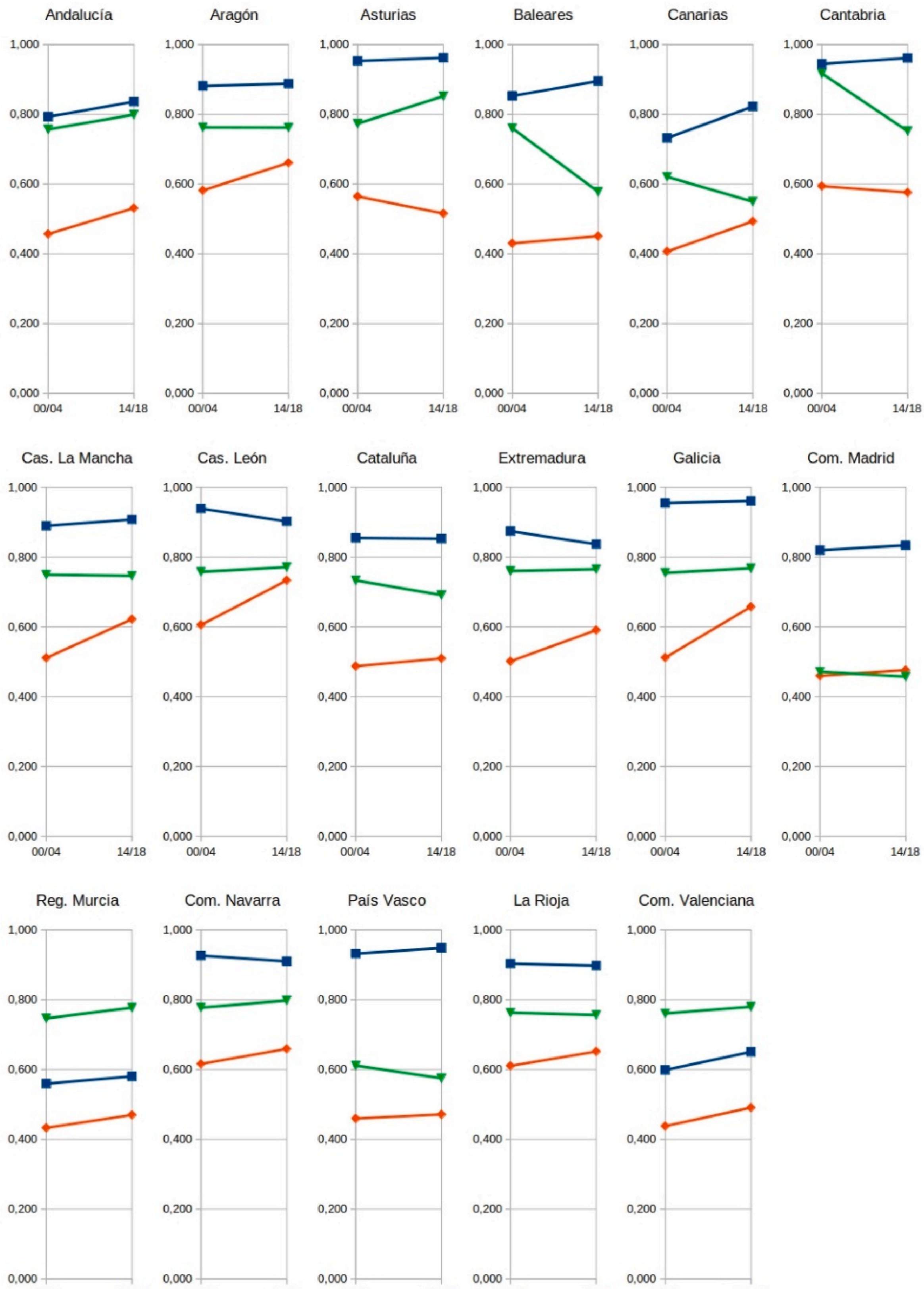

Fig. 2. Security Indicators for the three nexus pillars for the periods 2000/04 and 2014/18.

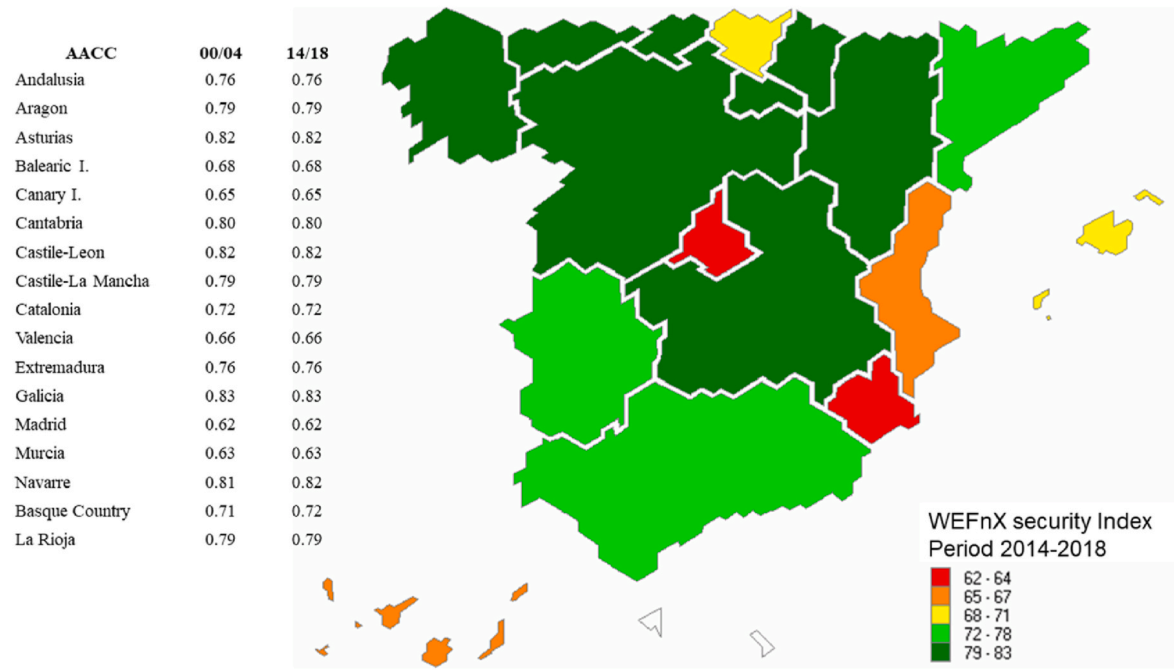

Fig. 3. WEFnX security 2014/18.

Table 1
Super-efficiency DEA crs model.

Super-efficiency DEA crs model											Accumulated change	
Community	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018	00–08	10–18
Andalusia	0.862	0.808	0.846	0.914	0.948	0.891	0.894	0.900	1.095	0.864	0.875	0.929
Aragon	0.906	0.878	0.836	0.897	0.868	0.765	0.719	0.659	0.695	0.666	0.877	0.701
Asturias	0.831	0.880	0.821	0.905	0.869	0.756	0.737	0.709	0.729	0.806	0.861	0.747
Islas Baleares	0.833	0.843	0.793	0.816	0.777	0.727	0.738	0.758	0.765	0.769	0.812	0.752
Canary Islands	0.759	1.013	0.907	1.013	0.858	0.888	0.911	1.058	0.942	0.792	0.910	0.918
Cantabria	1.032	0.991	0.858	0.910	0.910	0.740	0.944	0.868	0.902	0.923	0.940	0.876
Castile-La Mancha	1.013	0.987	0.953	0.916	0.858	0.705	0.753	0.777	0.765	0.727	0.945	0.745
Castile-Leon	0.858	0.807	0.717	0.744	0.751	0.726	0.627	0.713	0.678	0.675	0.775	0.684
Catalonia	0.793	0.806	0.815	0.832	0.835	0.772	0.734	0.712	0.717	0.808	0.816	0.749
Extremadura	0.973	0.929	0.912	0.880	0.855	0.736	0.765	0.803	0.785	0.649	0.910	0.748
Galicia	1.109	0.925	0.954	0.924	0.951	1.052	0.963	0.898	0.882	0.987	0.973	0.956
Madrid	0.903	0.862	0.878	0.983	1.023	0.947	1.000	1.071	1.007	1.155	0.930	1.036
Murcia	1.065	0.942	1.012	0.943	0.794	0.735	0.686	0.750	0.840	0.739	0.951	0.750
Navarre	0.800	0.715	0.641	0.661	0.645	0.628	0.693	0.671	0.673	0.628	0.693	0.659
Basque Country	1.038	1.016	0.975	1.100	0.976	0.947	1.035	1.003	0.987	1.161	1.021	1.027
La Rioja	1.012	1.023	1.058	0.919	0.875	0.855	0.917	0.916	0.850	0.791	0.977	0.866
Valencia	0.818	0.778	0.807	0.963	0.896	0.841	0.831	0.798	0.851	0.844	0.852	0.833

Similar to the case of Andalusia are those of Catalonia, Valencia and Asturias, where EC gains were not able to compensate for the decline in TC, reaching a final result of productivity loss during this period.

Regarding the regions that experienced a greater decline in productivity, both Murcia and Extremadura declined to a greater extent in TC than in EC, where they also recorded losses.

Overall, we found that the Spanish regions recorded a decline in productivity due to both EC and TC. The decline worsened during the financial crisis, with rates below unity in the 2008–2012 sub-period. Likewise, the data seem to suggest an upward trend in TC in the post-crisis years, with an average value for the 2014–2018 sub-period, mainly, because of the generally good data in 2016 and 2018, with the notable negative exception of Andalusia with respect to TC as discussed above.

4. Conclusions

In our study we have addressed the security and efficiency of nexus management in Spanish regional economies by following two methodologies already consolidated in this type of research, namely the elaboration of an integrated nexus security index and an analysis of the socio-economic efficiency of nexus resource management.

From the point of view of the indicators, we found important differences in nexus security between regions, with a general tendency to improve. The most important factors that hinder nexus security are low production of organic food, water deficit and external energy dependence. A summary of the main areas for improvement from this perspective for the autonomous communities is presented in Table 4.

From the point of view of efficiency and TFP, a negative trend of productivity loss appears in terms of managing nexus resources and capital stock for employment and welfare generation (economic performance), compatible with low environmental impact. We detect the influence of the 2008 economic crisis, with a generalised loss of productivity in the period 2008–2012, but also the emergence of polarisation in this respect, with high-efficiency communities registering productivity gains and a larger group of low-efficiency communities

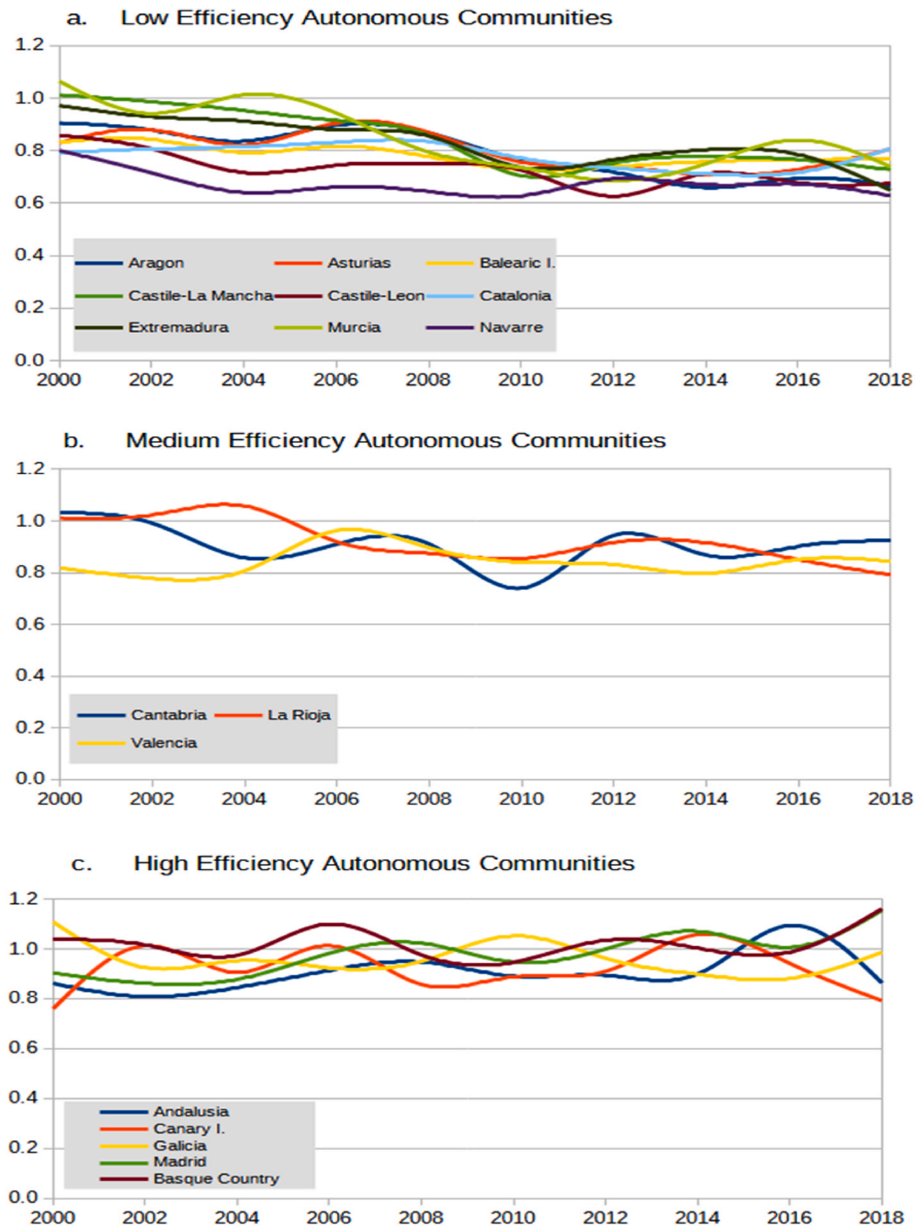

Fig. 4. Evolution of regional efficiency.

registering a loss of productivity. Thus, the TFP differential from the nexus perspective in Spanish regions has widened in the last two decades.

AACCs characterised by low or negative EC, notably Navarre, Extremadura and the Balearics, should orient their policies towards institutional changes in resource management, introducing more efficient or productive technologies and reorienting economic activity towards less resource-intensive and higher value-added sectors. On the other hand, autonomous communities that have been unable to achieve TC progress in the period, among which the regions of Murcia, Extremadura and Castile-Leon stand out, have a clear margin for improvement, not so much in pure technical innovation, since the MI should be interpreted as referring to the average level of the region. (Li et al., 2019). In this sense, education and industrial relocation are appropriate policies to improve the average technical level of these regions.

In this study, we used two methodologies: integrated indicators and DEA analysis, which are usually used separately to evaluate the nexus. Therefore, it is of particular interest to compare the results of both methodologies to obtain a comparative view of the security-based approach to the nexus versus the efficiency-based approach. (Fig. 5.). The cross-use of both criteria allows us to observe a more complex reality in the management of the nexus than that detected by the separate use of only one of them, which is common in other studies:

Galicia, Cantabria, La Rioja and Andalusia appear to be the most advanced in both categories; the Basque Country, the Canary Islands and Madrid have achieved a higher than average level of socio-economic and environmental efficiency of nexus resources, but at the cost of sacrificing the security of these resources, while Castile-Leon, Navarre, Aragon, Castile-La Mancha, Asturias and Extremadura have a high value in the overall security of the nexus, but have a long way to go to improve the efficiency of their management. Finally, Catalonia and Valencia, as well as the Balearics and Murcia, appear to be the furthest behind in terms of both nexus security and management efficiency.

To explain the factors that generate these results, we analyse the different intensities of use of each nexus resource, as well as of fixed capital and the level of environmental and socio-economic performance in each community, their evolution over time, and in relation to the

Table 2
Total factor productivity. Malmquist index.

Community	2002	2004	2006	2008	2010	2012	2014	2016	2018	2000–2018
Andalusia	0.924	1.045	1.037	1.021	0.988	0.998	1.016	1.134	0.866	1.007
Aragon	0.968	0.953	1.071	0.978	0.970	0.915	0.918	1.034	0.956	0.778
Asturias	1.064	0.933	1.103	0.981	0.856	0.878	0.990	1.067	1.047	0.893
Balearic Islands	1.065	0.940	1.069	0.936	0.954	1.022	1.014	1.044	0.995	1.029
Canary Islands	1.302	1.001	1.125	0.883	1.064	1.049	1.098	0.951	0.850	1.284
Cantabria	0.974	0.861	1.029	1.015	0.805	1.275	0.920	1.040	1.022	0.879
Castile-La Mancha	0.974	0.967	0.960	0.938	0.862	0.996	1.023	1.021	0.983	0.748
Castile-Leon	0.916	0.869	1.026	1.009	0.975	0.836	1.134	0.967	0.990	0.730
Catalonia	1.039	1.008	1.029	1.001	0.911	0.919	0.961	1.014	1.125	0.989
Extremadura	0.952	0.997	0.891	0.954	0.937	0.943	1.059	1.041	0.863	0.678
Galicia	0.851	1.078	0.935	1.023	1.059	0.960	0.927	0.985	1.111	0.906
Madrid	0.989	1.045	1.184	1.055	0.944	1.090	1.033	1.080	1.056	1.565
Murcia	0.859	1.099	0.912	0.836	0.928	0.910	1.083	1.124	0.920	0.680
Navarre	0.855	0.884	1.028	0.986	0.931	1.101	0.971	1.031	0.958	0.754
Basque Country	1.023	1.018	1.094	0.954	0.973	0.988	1.046	1.039	1.071	1.216
La Rioja	1.033	1.027	0.892	0.985	0.954	0.990	1.021	0.992	0.954	0.850
Valencia	0.930	1.038	1.155	0.953	0.901	0.953	0.960	1.090	0.991	0.946
Subperiod Mean	1.000			0.968			1.011			

national average (ANNEX III).

High-security (Hs) and high-efficiency (He) regions show different patterns in achieving this result. Andalusia stands out for its low use of all inputs except water, while the communities of the so-called "wet Spain" (Cantabria and Galicia) benefit from very low water consumption. All HsHe regions show a continuous increase in available capital, which is in line with the national trend. Regarding outputs, HsHe communities show environmental performance at or above average. Cantabria and La Rioja also obtain economic and social results well above the average, while Andalusia and Galicia achieve an eco-social performance well below the national average and base their high efficiency on the reduced use of resources.

Low security (Ls) and low efficiency (Le) regions present a level of socio-economic performance close to the average, significantly higher in the case of Catalonia and the Balearic Islands, which share a high capital stock, and below the average in the case of Murcia, with a use of capital also lower than the national average. The Balearics, owing to their insularity, have a high level of external dependence that affects nexus security; thus, the development of RES generation, as well as the recovery of food production capacity, preferably organic, would allow them to increase nexus security.

In environmental matters, the LsLe regions all show a poor environmental performance. On analysing the data, we see that the main burden in this issue is the low water quality, and efforts should be made to mitigate this impact. Finally, intensive livestock farming has increased food consumption in Catalonia, where feed consumption has increased from 43% to 53% of all food consumption; in Murcia (from 43% to 56%) and in Valencia (from 24% to 31%).

Regions with low security and high efficiency (LsHe) share a high dependence on the exterior, which explains the low nexus security, but which, from the point of view of efficiency, has a low intensity of resource consumption. The intensity is very low in the case of the Canary Islands, which allows them to obtain good efficiency ratios despite their poor economic and social performance. In the cases of Madrid and the Basque Country, their high socio-economic performance together with a moderate environmental impact allow them to obtain high efficiency ratios, more than compensating for the somewhat higher energy intensity in the case of the Basque Country and capital usage intensity in both cases. The challenge for these regions is to achieve a greater degree of energy and food self-sufficiency without causing negative impacts on the environment and, in the case of the Canaries, to achieve a level of investment that modernises their productive capacity, income and employment generation without increasing resource consumption intensity.

Regions with high security but low efficiency (HsLe) are characterised by a high use of energy and water, as well a trend towards intensive food use in Castile-Leon, Aragon and Extremadura, associated with intensive livestock farming. The good socio-economic (Aragon and Asturias) or environmental (Castile-Leon and Navarre) performance of some of these regions is not sufficient to compensate for the high consumption of resources. Extremadura stands out because of its low level of fixed capital use, which, in the efficiency calculation, is not sufficient to compensate for the excessive use of nexus resources.

HsLe communities could improve their efficiency by introducing technical improvements or revising some of their excessively resource-consuming productive activities, moving towards RES generation (Asturias, Extremadura and Navarre), reducing water consumption (Aragon, Castile-Leon and Extremadura) or reducing intensive livestock farming.

Overall, the results show a high degree of regional specialisation, with highly differentiated profiles of production, consumption and impacts on resources. There exists a polarisation between peripheral regions (net providers of nexus resources) and central regions (consumers of resources) (Carpintero et al., 2015). This polarisation also translates into a great disparity in investment levels and results in terms of economic dynamics and capacity to generate income and employment. The perhaps most striking result is that this regional inequality in the efficiency of nexus management is growing, widening the gap between the most and the least advanced regions.

In order to achieve greater regional equity, to increase the security of the nexus and to achieve efficiency gains, policies should be promoted aimed at rebalancing the level of investment in different regions, orienting such investments towards the provision of greater endogenous productive capacity for organic food and renewable energy. From an environmental point of view, together with the positive trend in the reduction of GHG and solid waste emissions, greater effort is needed to conserve water quality and control the effluents that deteriorate it. It is also desirable to review the concentration and impact of intensive livestock farming on the use of resources, especially food. Finally, the unsustainable use of irrigation water in some regions, particularly Murcia and Valencia, is alarming.

This study was limited by the statistical data available, especially those related to water and food consumption, and it is necessary to interpolate some of them. Likewise, in a chronological sense, it has been impossible to obtain a complete set of data available prior to 2000. Furthermore, the technique used does not allow the evaluation of the indirect externalised impact of resource consumption, which means that communities with highly tertiarised and externally dependent economies (Madrid) appear to be very efficient in comparison with the rest.

Future research could focus on the evaluation of recently implemented public policies in Spain. The National Rural Development Programme, which was in effect until 2022, focuses on resource efficiency

Table 3
Efficiency change and technical change.

	Efficiency Change										Technical Change									
	2002	2004	2006	2008	2010	2012	2014	2016	2018	00–18	2002	2004	2006	2008	2010	2012	2014	2016	2018	00–18
Andalusia	0.989	0.991	1.093	1.000	1.000	1.000	0.988	1.012	1.000	1.072	0.934	1.054	0.949	1.021	0.988	0.998	1.028	1.121	0.866	0.939
Aragon	0.989	0.990	1.005	1.019	1.033	0.907	0.952	1.057	0.930	0.879	0.979	0.962	1.065	0.960	0.939	1.009	0.964	0.978	1.027	0.884
Asturias	1.086	0.982	1.019	1.024	0.897	0.950	0.993	1.079	1.007	1.023	0.979	0.951	1.082	0.958	0.954	0.925	0.997	0.989	1.039	0.872
Balearic Islands	1.005	0.938	0.926	0.968	0.984	0.974	1.034	1.044	0.963	0.841	1.059	1.002	1.155	0.968	0.970	1.049	0.981	1.000	1.034	1.223
Canary Islands	1.235	1.000	1.000	1.000	0.964	1.034	1.004	1.000	0.868	1.072	1.055	1.001	1.125	0.883	1.104	1.015	1.094	0.951	0.979	1.197
Cantabria	1.000	0.951	1.050	1.001	0.805	1.243	0.936	1.055	0.983	0.970	0.974	0.906	0.980	1.014	1.000	1.026	0.983	0.986	1.040	0.906
Castile-La Mancha	1.000	0.986	0.964	0.966	0.924	1.008	1.081	1.024	0.934	0.884	0.974	0.981	0.996	0.971	0.933	0.988	0.946	0.997	1.052	0.845
Castile-Leon	1.021	0.857	1.051	1.026	1.038	0.850	1.181	0.946	0.969	0.901	0.897	1.015	0.977	0.984	0.939	0.983	0.961	1.022	1.022	0.810
Catalonia	1.066	1.038	1.072	0.988	0.968	0.889	0.984	1.022	1.102	1.118	0.975	0.972	0.960	1.013	0.941	1.033	0.976	0.992	1.021	0.885
Extremadura	1.028	0.996	0.974	0.943	0.995	0.978	1.122	0.999	0.821	0.844	0.926	1.001	0.914	1.011	0.942	0.964	0.944	1.041	1.051	0.804
Galicia	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.851	1.078	0.935	1.023	1.059	0.960	0.927	0.985	1.111	0.906
Madrid	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.989	1.045	1.184	1.055	0.944	1.090	1.033	1.080	1.056	1.565
Murcia	0.959	1.043	1.000	0.861	0.991	0.919	1.126	1.124	0.887	0.881	0.895	1.054	0.912	0.970	0.937	0.990	0.962	1.000	1.037	0.772
Navarre	0.895	0.849	1.113	0.989	0.977	1.118	1.000	1.003	0.920	0.844	0.955	1.042	0.924	0.997	0.953	0.985	0.971	1.027	1.041	0.892
Basque Country	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.023	1.018	1.094	0.954	0.973	0.988	1.046	1.039	1.071	1.216
La Rioja	1.000	1.000	0.986	0.999	1.015	0.983	1.018	0.937	0.910	0.853	1.033	1.027	0.904	0.985	0.940	1.007	1.003	1.059	1.047	0.996
Valencia	0.936	1.052	1.197	0.979	1.000	0.915	0.977	1.087	0.978	1.097	0.993	0.987	0.965	0.973	0.901	1.042	0.982	1.003	1.013	0.862
Mean	1.012	0.981	1.026	0.986	0.976	0.986	1.023	1.023	0.957	0.969	0.970	1.005	1.007	0.985	0.966	1.003	0.988	1.016	1.030	0.969
Sub period mean	1.019			0.949			1.002				0.982			0.954			1.034			

Table 4
Areas for WEF Index improvement by AACC.

Autonomous Community		Andalusia	Aragon	Asturias	Balearic Islands	Canary Islands	Cantabria	Castile-La Mancha	Castile-Leon	Catalonia	Extremadura	Galicia	Madrid	Murcia	Navarre	Basque Country	La Rioja	Valencia
Water	Efficiency gains.	*				*					*		*	*				*
	Demand reduction.	*				*					*		*	*				*
Energy	Efficiency gains.	*		*	*	*	*			*			*	*	*	*		*
	Demand reduction.	*		*	*	*	*			*			*	*	*	*		*
	RES increase	*		*	*	*				*	*		*	*		*		*
Food	Eco farming	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	Increase production				*	*							*			*		
	Demand reduction				*	*							*			*		
Efficiency	Efficiency change		*				*	*	*		*			*	*		*	
	Technical change	*	*	*			*	*	*	*	*	*		*	*			*

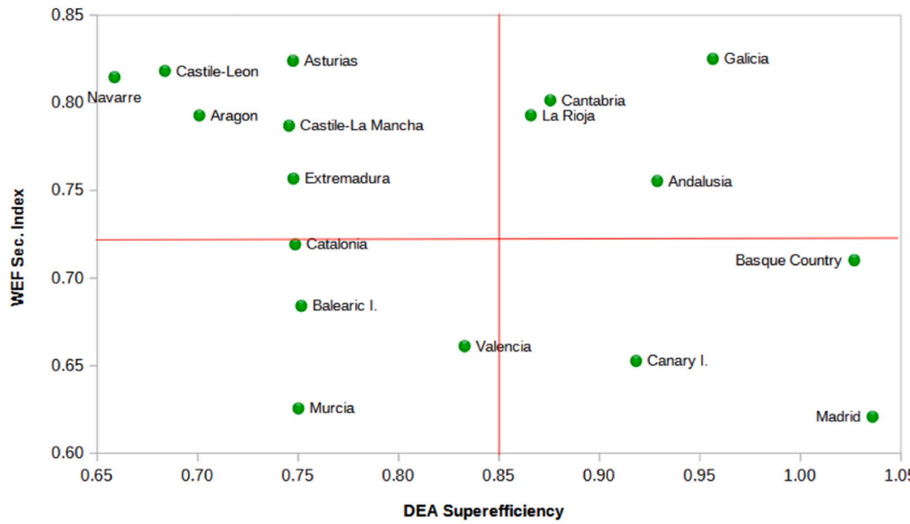

Fig. 5. WEFnX Security Index vs WEFnX super-efficiency index.

and improving agricultural productivity, affecting both water and energy use, as well as food production. Its impact should be reflected in the safety and efficiency indicators used in this study. In the same vein, in line with the EU Regulation 2018/1999, Spain is working on its National Energy and Climate Plan for the period 2021–2030, aimed, among other objectives, at achieving greater efficiency and energy self-sufficiency based on RES-E. The methodology developed in this study can be useful to assess the outcome of these plans when updated data are available.

On the other hand, we are considering the extension of this study by investigating the relationship between the dynamics of the nexus and elements such as the economic structure or the degree of urbanisation of the different regions, by using systems of simultaneous equations to capture the endogeneity inherent in the nexus framework. As a result, the indirect influence of these factors on nexus security and efficiency could be estimated.

Finally, it may be of interest to apply this methodology by extending the set of comparison to the European level. It will also be valuable, in the coming years, to observe the impact of the COVID19 crisis and the subsequent economic recovery on the management of the nexus based on data for 2020 and beyond, which are not yet available.

CRediT authorship contribution statement

Manuel Morales-García: Writing – original draft, Investigation, Formal analysis, Data curation. **Miguel A. García-Rubio:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization.

Data availability statement

The data used for this research are available on request from the authors.

Compliance with ethical standards

All authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

All procedures performed in the survey conducted on 15 experts as part of the hierarchical analysis (section 2.1.) were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Declaration of Generative Ai and AI-assisted technologies in the Writing process

During the preparation of this work, none of the authors used artificial intelligence technologies.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2024.100543.

Data availability

Data will be made available on request.

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