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Disentangling the effect of climate and cropland changes on the water performance of agroecosystems (Spain, 1922–2016)

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ABSTRACT

The main type of consumptive water use is crop evapotranspiration. The historical evolution of crop evapotranspiration depends on climate and cropland changes. These two latter variables present complex interactions and are expected to continue changing in the future, but the coupling between these two processes is insufficiently addressed in the literature. The objective of this study is to disentangle the impact of historical climate and cropland changes on four water performance indicators of agroecosystems in a Mediterranean country (Spain) between 1922 and 2016: crop water requirements actual evapotranspiration, the net primary productivity-based water intensity and violet water, accounting for water stress. These indicators were estimated based on soil water balances and the effects of climate and cropland were unravelled through counterfactual scenarios. The results showed that climate change tended to increase actual evapotranspiration (9%), crop water requirements (14%) and net primary productivity-based water intensity (8%), its greatest impact being on violet water (increasing it by 34%). The cropland variable produced effects of different positive or negative signs according to the parameters considered (type of crop, crop management and point in space-time). In aggregate terms, however, the cropland effect pushed in the same direction as climate change, causing increases in actual evapotranspiration (11%), violet water (15%) and crop water requirements (3%), while reducing net primary productivity-based water intensity (−15%). This approach allows us to quantify and show the importance of agricultural industrialization on the water performance of agroecosystems. In this way, our results highlight great opportunities to manoeuvre to adapt agriculture to climate change through agronomic management and hydrological planning options. Complex interaction patterns between climate and cropland effects were shown. Moreover, geographical, crop-type and temporal evapotranspiration hotspots and drivers were uncovered, and interrelations among the water performance indicators were discussed, thus raising relevant points of discussion in the field.

1. Introduction

Water has been identified as a key variable in socio-ecosystem resilience and sustainable development (Boltz et al., 2019). Moreover, the availability of water is essential for the global reduction of yield gaps (Mueller et al., 2012). The central role of water in socio-ecosystems implies that water has a variety of effects on the systems' resilience: water can be an agent of change or be affected by another agent (Falkenmark et al., 2019). In the case of agricultural systems, on the one hand, the joint action of land use changes and global warming are expected to escalate agriculture's consumption of green and blue water worldwide (Huang et al., 2019), increasing pressure on aquatic ecosystems and competing for the resource with other human activities and with the rest of the ecosystems (Falkenmark and Rockstrom, 2004; Zikos and Hagedorn, 2017). This issue is of particular concern given that agriculture is the main consumer of water resources globally (Shiklomanov, 2000; Wada and Bierkens, 2014). On the other hand, climate change has already negatively impacted on the agricultural production, both in biophysical (Ray et al., 2019), and economic terms (Ortiz-Bobea et al., 2021), with the resulting impact on food security (Falkenmark et al., 2009; Mueller et al., 2012).

We believe that new insights are necessary: in the years to come,

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changes of a different nature regarding the interactions between the climate and agricultural systems are expected to occur, leading to water performance alterations. Climate change is forecast to continue to lead to higher temperatures and to alter precipitation patterns (IPCC et al., 2014), increasing water consumption in agriculture and driving new transformations in the sector. For example, climate change has been identified as a cause of the evolution of crop mixes in the USA (Cho & McCarl., 2017), as well as the future expansion of global agricultural borders in a northerly direction (King et al., 2018). In the case of Spain, based on the worst-case climate change scenario (SSP5-8.5), by the end of this century, almost all the southern half of the country will be outside the "Safe Climatic Space" (Kummu et al., 2021). To date, only a small number of studies have addressed the specific subject of climate and cropland co-evolution in an integrated way. Such studies include that of Vila-Traver et al. (2021), Zou et al. (2017) and Li et al. (2020) focusing on the past, and that of Huang et al. (2019) focusing on the future.

Mediterranean countries are particularly vulnerable to climate change (Cramer et al., 2018). Indeed, the Mediterranean climate presents a marked dry season which leads to soil water depletion. This depletion brings about, in turn, a decoupling between the crops' water demands and the water available in the soil (Allen et al., 1998), leading to a greater vulnerability to climate change. In irrigated agriculture, the imbalance is usually totally or partially compensated with blue water (BW), while in the case of rainfed crops, it leads to water stress (WS). A study focusing on the water stress of Spanish agriculture (Vila-Traver et al., 2021) estimated the evolution of this gap between water requirements and the water available to crops. In that paper, a new indicator called violet water (VW), integrating blue water in irrigated crops and water deficit in rainfed crops, was developed. For VW estimation, climate change as well as different aspects of the industrialization of agriculture were considered simultaneously such as: varietal changes, weeds' reduction, crop intensification, production specialization, irrigated area increases and the spatio-temporal restructuring of crop patterns. The results of this study showed that VW had increased by 54% in ~one century due to the combined effect of climate change and the industrialization of agriculture.

Recently, Degroot et al. (2021) coined the phrase 'history of climate and society', thus highlighting the need for rigorous and integrated analyses that identify the complex and most successful patterns of adaptation to climate change in the past. This study's main novelty is its specific focus on the effects of climate change and agricultural industrialization on the performance of Mediterranean agroecosystems between 1922 and 2016. This work allowed us to: disentangle the complex relationships between climate and croplands in greater detail; discuss whether croplands have adapted in any way to climate change; provide new insights that help to design climate change adaptation and mitigation strategies; and draw fresh conclusions.

Our approach was to use two counterfactual scenarios and compare them to the actual evolution. In the first counterfactual scenario, the 1922 climate remained static throughout the whole time series while the cropland was historically dynamic; in the second scenario, the opposite was applied, the 1922 croplands remained static, and the climate was dynamic over the entire series. This pattern enabled us to separate the effects of both, climate alterations and cropland changes on the evolution of a set of four complementary water performance indicators (WPI), as follows:

Crop water requirements (CWR) is the total crop demand, without considering any crops' water stress.

Actual evapotranspiration (AET) is the real amount of water evapontranspired.

Violet water (VW) is the proportion of crop water requirements that is not satisfied by precipitation as green water, including two components: water stress for rainfed and blue water for irrigated crops (Vila-Traver et al., 2021).

Net primary productivity-based water intensity (NPP-WI) reflects the amount of AET per carbon unit produced in a given agroecosystem (NPP).

The specific objectives were:

a) To quantify the historical changes of the WPI (VW, AET, CWR and NPP-WI) in Spanish agroecosystems between 1922 and 2016.
b) To estimate the climate and cropland effects on WPI at different aggregation levels: spatial, temporal, crop, crop type and rainfed crops/irrigated crops to uncover the complex interaction patterns between both effects.
c) To test the ability of the proposed framework to separate the effects of climate and cropland, as well as their interactions (synergistic or antagonistic), through comparisons with the actual scenario.
d) To study the interrelations among the WPIs.

2. Methodology and data

2.1. Selection of indicators

The evolution of the water performance of Spanish agroecosystems was assessed using a geographically explicit model, based on four different and complementary water performance indicators (WPI): CWR, AET, VW and NPP-WI. The CWR represent the total crop water requirements, which, in the case of rainfed crops, may not be satisfied due to soil water depletion (AET < CWR), causing water stress. In the case of irrigated crops, soil water depletion is compensated (AET = CWR) with the amount of blue water required. Therefore, in the model used in this study, the AET can be equal to, or below the CWR in the case of rainfed crops and is always equal to the CWR in the case of irrigated crops. The VW is the sum of BW and WS and represents the share of CWR that is not covered by precipitation (Vila-Traver et al., 2021). The NPP-WI represents the amount of water required per unit of carbon (NPP) produced. Each selected WPI is directly affected by a combination of factors (Table 1). For example, CWR are sensitive to global warming, which is reflected in the generalized increase in ET_0, and to crop coefficients (Kc) changes, that represent vegetation growing and its effect on soil covering, but they are not affected by changes in precipitation. For their part, AET, VW and NPP-WI also depend on soil water balances and therefore on precipitation. The AET is dependent on the rainfed-irrigated crop ratios. Indeed, in the irrigation regime, the CWR are completely satisfied, therefore, the higher the share of irrigated crops, the greater the AET. For its part, the NPP-WI includes the NPP as well as the factors that affect the AET, and this allows to evaluate whether water consumption is optimized (less water consumed per unit of carbon produced) in the case of an NPP increase, or the opposite in the case of a reduction in NPP.

2.2. Computation of indicators and data sources

The computation of the WPI is mainly based on estimations of crop evapotranspiration following the methodology described in FAO-56 (Allen et al., 1998) and adapted by Vila-Traver et al. (2021). The surface areas and production of the 90 main crops, at the provincial level,

Table 1
Dynamic factors directly affecting water performance indicators, integrating cropland and climate effects.

WPI	Dynamic factors	
	Climate effect	Cropland effect
CWR	ET0	Kc, spatiotemporal structure and areal changes
AET	ET0 and Precip	Kc, spatiotemporal structure, rainfed-irrigated shares and areal changes
VW	ET0 and Precip	Kc, spatiotemporal structure and areal changes
NPP-WI	ET0 and Precip	NPP, Kc, spatiotemporal structure, rainfed-irrigated shares and areal changes

were directly obtained from historical sources. The NPP was estimated in Mg of C, using the methodology of Guzmán et al. (2014) and the carbon content coefficients of Aguilera et al. (2018). Subsequently, the crop information (surface areas and NPP) was resampled in a grid (0.5°) via areal weighting. The climatic data, including precipitation and reference evapotranspiration (ET_0) were obtained from the CRU TS 4.01 (Harris and Jones, 2017) and the climatic normals (means per grid-cell and per month for 30 years) were computed for each temporal cross-section. The CWR were computed based on the ET_0 and the crop coefficients (Kc) (Allen et al., 1998). The Kc were historically and geographically adapted to each crop's level of development. Subsequently, the Available Water Capacity (AWC) values were obtained using data on soil granulometry (Ballabio et al., 2016) and soil organic content (Zomer et al., 2017) based on the SPAW model (Saxton and Rawls, 2006). The crop calendar and the duration of the stages was obtained from Allen et al. (1998) and adapted to local conditions following Mateo-Box (2005). We computed the daily soil water balance to calculate the crops' AET, WS (rainfed crops' case) and BW (irrigated crops' case). needed to satisfy the CWR. For the agriculture total, the WS and BW values were added to form the VW. To finish, the NPP-WI (m^3 Mg C^{-1}) was obtained by dividing the entire crop cycle's AET by the NPP. Table A.1.1. details the units, disaggregation levels, and original data sources.

2.3. Separating the cropland and climate effects

The cropland and climate effects have been isolated using a counterfactual scenario model, which consists in considering different settings of the model inputs' to separate the effects of the different dynamic factors affecting the WPI. This combination of model simulations and counterfactual schemes is a useful tool to study causal effects in socio-ecological analysis (Meyfroidt, 2016) and it has been previously used in environmental studies (Burney et al., 2010; Le Noë et al., 2021), including one focused on the drivers of terrestrial evapotranspiration (Mao et al., 2015). In this scheme, the effects produced by cropland changes (the cropland effect) were isolated, setting the climate to that of 1922, and applying the evolution of the cropland throughout the series. Conversely, the effects produced by climate change (the climate effect) were determined by setting the croplands to that of 1922 and applying the dynamic climate to the whole series. By doing so, we considered 1922 as a base year to compare with, as it is the first year having complete and reliable cropland's information available; and because both anthropogenic climate change and agriculture's industrialization were incipient processes in this year. The factors that compose the climate effect and cropland effect are shown in Table 1. Table A.1 contains other model inputs that are not considered in Table 1 because they are not historically dynamic. The results were compared with the Actual scenario, which includes, inherently, the combination of cropland and climate changes. The effects of each type were calculated based on the study's first temporal cross-section—1922—and were computed using the following equation:

$$EWPI^{Y}_{x,y,r,c,t} = \frac{\left(WPI^{Y}_{x,y,r,c,t} - WPI^{1922}_{x,y,r,c,t}\right)}{\left|WPI^{1922}_{x,y,r,c,t}\right|} * 100 \quad (1)$$

Where the effect on any water performance indicator *(EWPI)* in year *Y,* for the pixel *(x,y),* of the type of annual water management *(r),* crop *(c)* and month*(t),* is calculated in relation to the value of the same WPI, defined by the same sub-items *(x,y,r,c,t),* for the base year (Y = 1922). Eq. (1) is presented at the highest disaggregation level, but all the dimensions (subindices) can be collapsed to raise the aggregation level (for example, if we are not interested in the monthly disaggregation, we can fold subscript *t* and analyse the annual effects).

Finally, we calculated the effect of the interactions between the two counterfactual scenarios, applying the equation:

$$Int_{x,y,r,c,t} = Act_{x,y,r,c,t} - \left(Cli^{ef}_{x,y,r,c,t} + Cro^{ef}_{x,y,r,c,t}\right) \quad (2)$$

Where *Int* is the interaction of the two effects and is calculated for the actual scenarios *(Act),* climate effect *(*Cli^{ef}*)* and cropland effect *(*Cro^{ef}*).*

2.4. Analyzing interrelations among water performance indicators and the geographical patterns of the main drivers affecting them

To analyse empirically the interrelations among the WPI of the different agroecosystem types' Pearson coefficient has been used to identify both the strength of the correlations and the direct or indirect proportionality.

Finally, the geographical patterns of the main drivers affecting the WPI have been identified by choosing the best linear correlation, that is the highest R^2, between each one of the WPI and their related dynamic factors, which are detailed in Table 1.

3. Results

3.1. The climate and cropland effects on the water performance indicators

This section presents the evolution of the four WPI (AET, VW, CWR and NPP-WI), as well as the role of cropland and climate effects in determining the observed trends. The results are disaggregated according to the types of crops, i.e., herbaceous or woody; the types of water management, i.e., rainfed or irrigated crops; and disaggregated geographically or referred to specific crops.

The evolution of the CWR, AET and VW (Fig. 1) presented similar trends across the different types of agriculture, since the variables are logically correlated with each other: the more CWR, the greater will be AET, provided that water is available in the soil. If CWR were larger than the available water in the soil, the increase in CWR would result in an increase in VW, in the form of WS in rainfed crops and BW in irrigated crops.

The CWR (Fig. 1a) of rainfed crops (including herbaceous and woody crops) varied slightly throughout the series, as a result of the opposite action between climate-induced increases (~12%) and cropland-induced reductions (−15%, −6% and −4% for herbaceous, woody and total crops, respectively), resulting in a 9% increase in CWR for total rainfed crops. The effects of cropland and climate changes on the CWR, however, were of the same sign in the case of irrigated crops, thus causing larger increases—around 27%, 7% and 34% for herbaceous, woody and total irrigated crops, respectively. Although the cropland effect reduced the total CWR in rainfed crops and irrigated crops, it tended to increase the CWR of the grand agriculture total, due to the upturn in the proportion of woody crops across all irrigated lands, with higher rates of CWR (). Thus, the evolution of the CWR of the agriculture total resulted in an increase of 17%, caused mainly by the climate (13%), and to a lesser extent by the croplands (3%).

The variations in AET (Fig. 1b) of the rainfed crops were minimal because the cropland effect counterbalanced the rise caused by the climate, in the case of both herbaceous and woody crops. Despite this, the AET increased by 5% for the whole rainfed cropland, due to the increase in the proportion of woody crops in the drylands, with higher rates of AET (Fig. A.2.2. & A.3.9). The results of the AET of irrigated crops were the same as those of the CWR, since we considered that the CWR were completed with BW. Finally, the AET of total agriculture grew by 21% due to the combined effect of both climate and cropland, to an equal extent.

The VW variations were modulated by the interactions between climate and cropland in a similar way to the previous variables, though with greater variations. The climate and croplands had opposite effects on all drylands resulting in variations of −25%, 14% and 23% for herbaceous, woody and total crops, respectively. The reverse was found in the case of irrigated crops, since they were generally affected by the

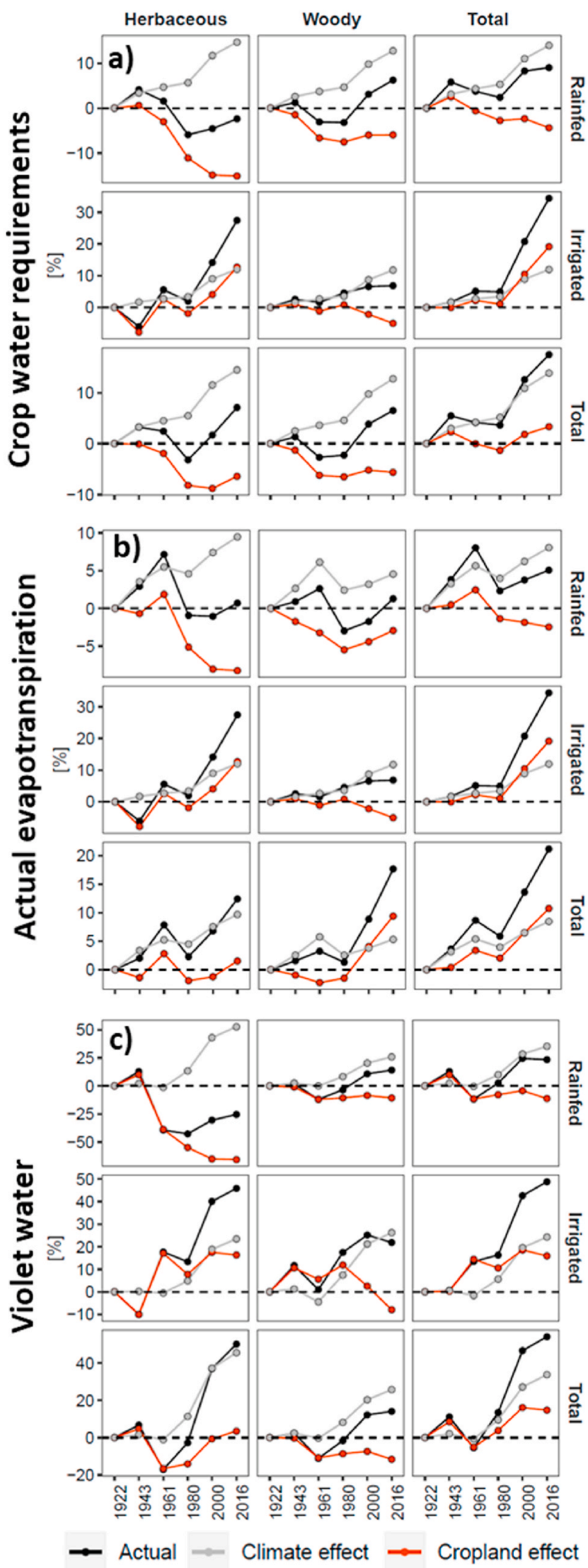

Fig. 1. Climate & Cropland effects and actual evolution (in percentages, over the year 1922) of water performance indicators for rainfed, irrigated crops and total cropland: a) Crop water requirements; b) Actual evapotranspiration; and c) Violet water (namely, water stress for rainfed crops, blue water for irrigated crops, and violet water for the total cropland). The effects were calculated for all indicators expressed in mm year^{-1}.

cumulated action of climate and cropland, resulting in large increases of BW, a component of VW, of 46%, 22% and 49% for herbaceous, woody, and total irrigated crops, respectively. Thus, the grand VW total increased by 54%, the separated effects of climate and cropland accounting for 34% and 15%, respectively.

The water intensity of NPP (NPP-WI), calculated as the ratio between AET and NPP, depends on the evolution of both variables, which in turn are historically determined by climate and cropland changes (except in the case of NPP, which, being one of the model's data inputs, is not affected by the Climate Effect in our counterfactual analysis). The NPP (Fig. 2a) of herbaceous rainfed crops decreased in the early years of the series due mainly to varietal changes (Soto et al., 2016; Aguilera et al., 2018). It then increased due to production intensification. In contrast, in the case of rainfed woody crops, the widespread use of herbicides reduced weed biomass, which constitute a big proportion of the NPP in this type of cropland, therefore reducing it a 38% (Vila-Traver et al., 2021; Soto et al., 2016; Aguilera et al., 2018); subsequently, production intensification did not lead to a considerable recovery in NPP levels. Regarding irrigated crops, the NPP increased for both types of crops, rebounding considerably in herbaceous crops (69%) and to a lesser degree in woody crops (28%), accounting for an average change in irrigated crops of 55% and of 32% for the total agriculture.

The major driver of the NPP-WI was cropland changes, specifically the NPP, and as observable in Fig. 2, both variables present an inversely proportional relationship. The NPP-WI, however, is tempered by climate change, which accounted for an increase in NPP-WI of around 10% in all cases. Thus, the NPP-WI decreased for rainfed herbaceous crops (−13%), for irrigated herbaceous crops (−25%), and woody irrigated crops (−17%), but notably increased for rainfed woody crops (64%), resulting in a very small reduction (−7%) for the agriculture total.

In short, the climate effect had a moderate impact on the first temporal cross-sections for the CWR, AET and VW indicators, and began to grow more rapidly for CWR and AET as from 1980, and as from 1961, in the case of VW. The climate effect on these indicators was, to some extent, offset by the cropland effect on rainfed crops and irrigated woody crops, and reinforced in the case of irrigated herbaceous crops. For its part, the cropland effect of the grand totals tended to worsen the climate change effects for these three indicators. The latter sheds light on the importance of structural changes (more irrigated and more woody crops) to explain such effects. Thus, the NPP-WI declined significantly in the case of all irrigated crops throughout the series, as well as for rainfed herbaceous crops from 1980 onwards, and increased significantly for rainfed woody crops and the total.

To summarise the evolution of the WPI, climate change tended to increase all of them for all the crop types under study (Fig. 3) over the period (1922–2016). The NPP of some crop types increased significantly (Fig. 2a) and this caused the cropland effect to decrease, in these cases, the NPP-WI (Fig. 3), offsetting the effects of climate change, except for rainfed woody crops and total woody crops. Regarding rainfed crops, cropland changes tended, to some extent, to offset the effect of climate change for the other indicators (CWR, AET and VW). On the other hand, in the cases of irrigated herbaceous crops and total irrigated crops, for these same indicators, both effects pushed in the same direction and in the opposite direction for irrigated woody crops. The patterns were less clear for the total herbaceous and woody crops depending on the variable studied (CWR, AET or VW). In the case of the grand totals, both effects joined forces to increase the three indicators. The interactions between cropland and climate effects (Fig. 3) are generally synergistic (since Actual > (Cropland effect + Climate effect)). The effects of AET, CWR and VW synergies were greater for the irrigated crops than for rainfed crops, and tended to increase the indicator in all cases, except for the VW of rainfed herbaceous crops, which was affected by the greatest synergistic interaction (−12.4%) of all cases under study.

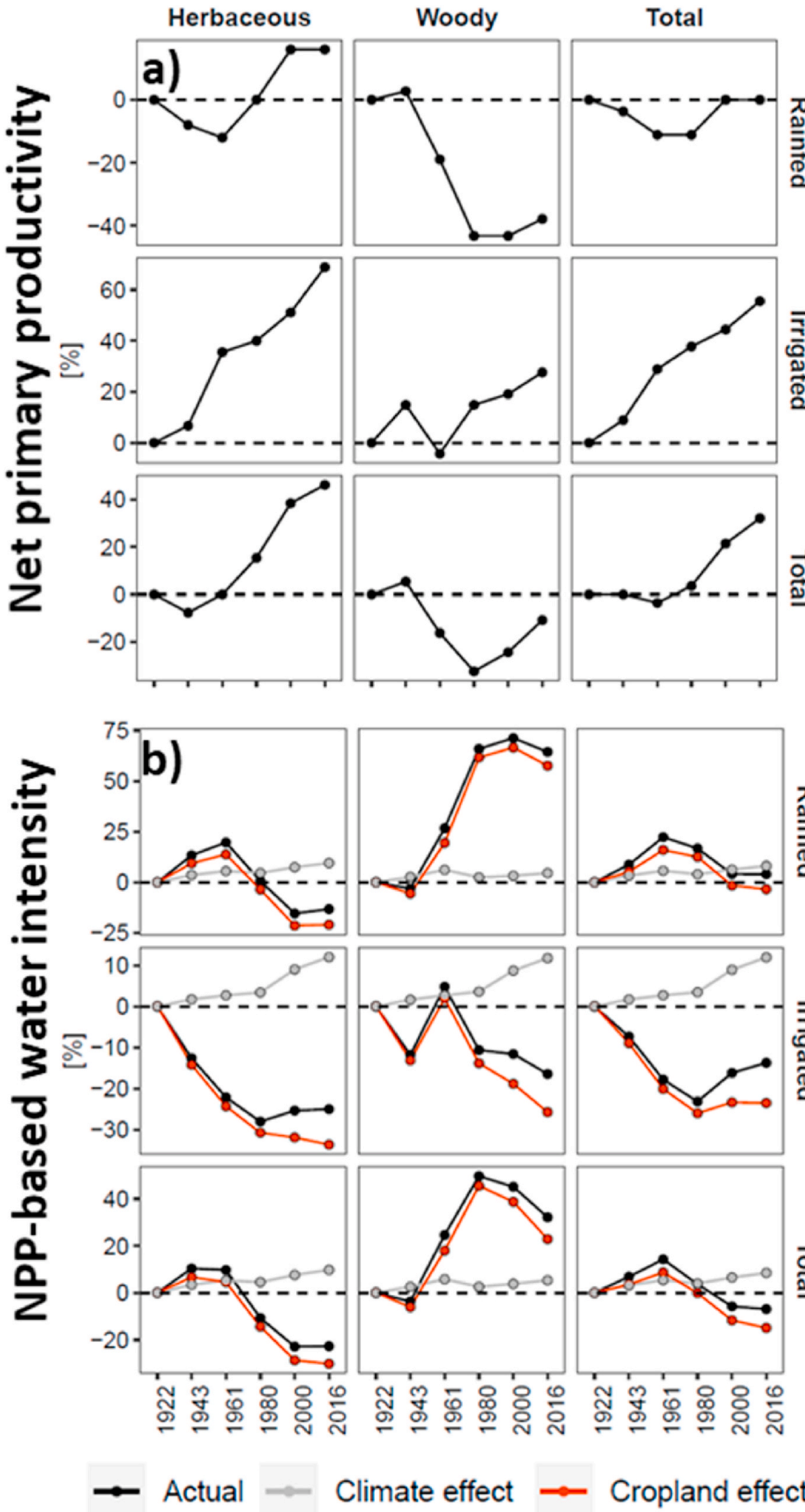

Fig. 2. Climate & Cropland effects and actual evolution (in percentages, over the year 1922) of water performance indicators for rainfed, irrigated crops and total cropland: a) Net primary productivity; and b), Net primary productivity-based water intensity. The effects were calculated based on the Net Primary Productivity expressed in Mg C ha^{-1} and on the NPP-based Water Intensity expressed in m^3 Mg C^{-1}.

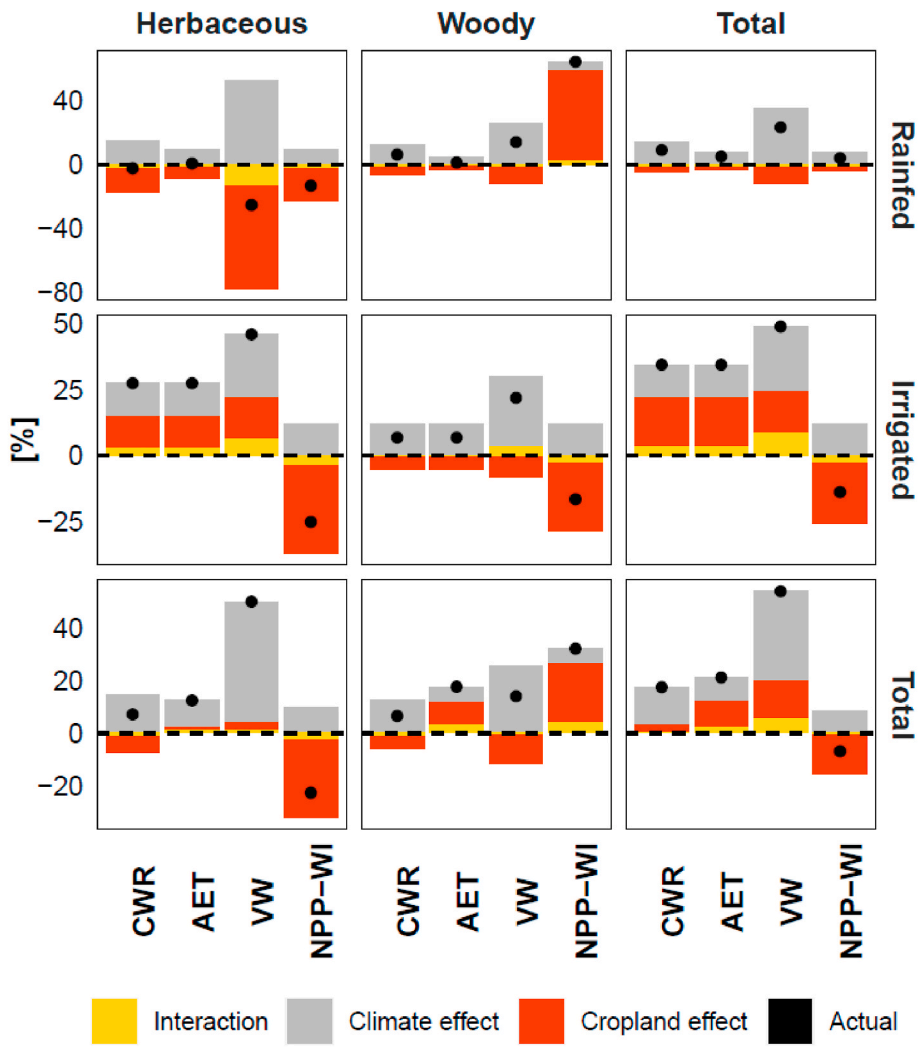

Fig. 3. Climate & Cropland effects, interaction between them and actual evolution (over the 1922–2016 period) of water performance indicators for rainfed, irrigated crops and total cropland. Interaction values other than zero reflect synergistic (>0) or antagonistic (<0) interactions between climate and cropland effects.

3.2. Regional patterns

The evolution of WPI, and the contribution of climatic effects and cropland were unevenly distributed across Spain's territory (Fig. 4). First, the geographical differences in the impact of climate change were unremarkable for the AET, NPP-WI and CWR and yet they presented an uneven distribution pattern in the case of VW, which rose to a much further extent in the northern part of the country. In absolute terms, however, the climate effect on the same region was similar to that of the rest of the country (Fig. A.3.13). The effect of cropland changes greatly determined the spatial distribution of the changes in the four WPI and led to greater geographical variations. Changes presenting opposite signs were found across different regions depending on the region and on whether the crops were rainfed or irrigated.

The effects of cropland on AET and CWR (Fig. 4a–c) showed very similar patterns. Cropland changes in rainfed systems had a reduction effect on both indicators in much of the central part and northwest of the country and had an opposite effect on a small part in the southwest. On the other hand, when combined with changes in climate, a much greater proportion of the territory under study saw a rise in CWR and AET. The changes in the irrigated croplands did not present such a clear spatial pattern, and opposite effects were found in different areas. In the same way, however, when combining the climate effects, the actual scenario presents increases over large sections of the area under study.

The NPP-WI of irrigated lands was reduced in most of the country by the cropland effect, as NPP production increased considerably, except in some points north and south of the country. In contrast, rainfed crops underwent the opposite effect, and a large part of the Eastern coast and central areas of the country increased the NPP-WI, requiring, in 2016, between 50% and 100% more volume of water per unit of carbon produced compared to 1922.

The effects of cropland on VW generated significant geographical differences. They led to a 50% reduction in some areas of the country, particularly in the case of irrigated crops, while bringing about notable increases (>100%) in other points, particularly in central eastern and central western parts for rainfed crops and in the north for irrigated crops, and in several areas in the central part of the country for the agriculture total.

Some of the patterns shown in Fig. 4 can be better understood through a more detailed analysis of the dynamic factors integrating the Climate and Cropland effects, and the evolution of these factors itself. The importance of the drivers varies, depending on the region and the agricultural type. Figures A.3.19-A.3.38 show the geographical correlations (R^2) between each WPI and their drivers. For example, the dropping of VW in the east-coast and in the centre of the country (Fig. 4) can be explained by the effect of kc reduction in those regions (Figure A.2.17), which, in turn, was the main driver affecting VW in those regions (Fig. 5). In the same way, NPP was the main driver of NPP-

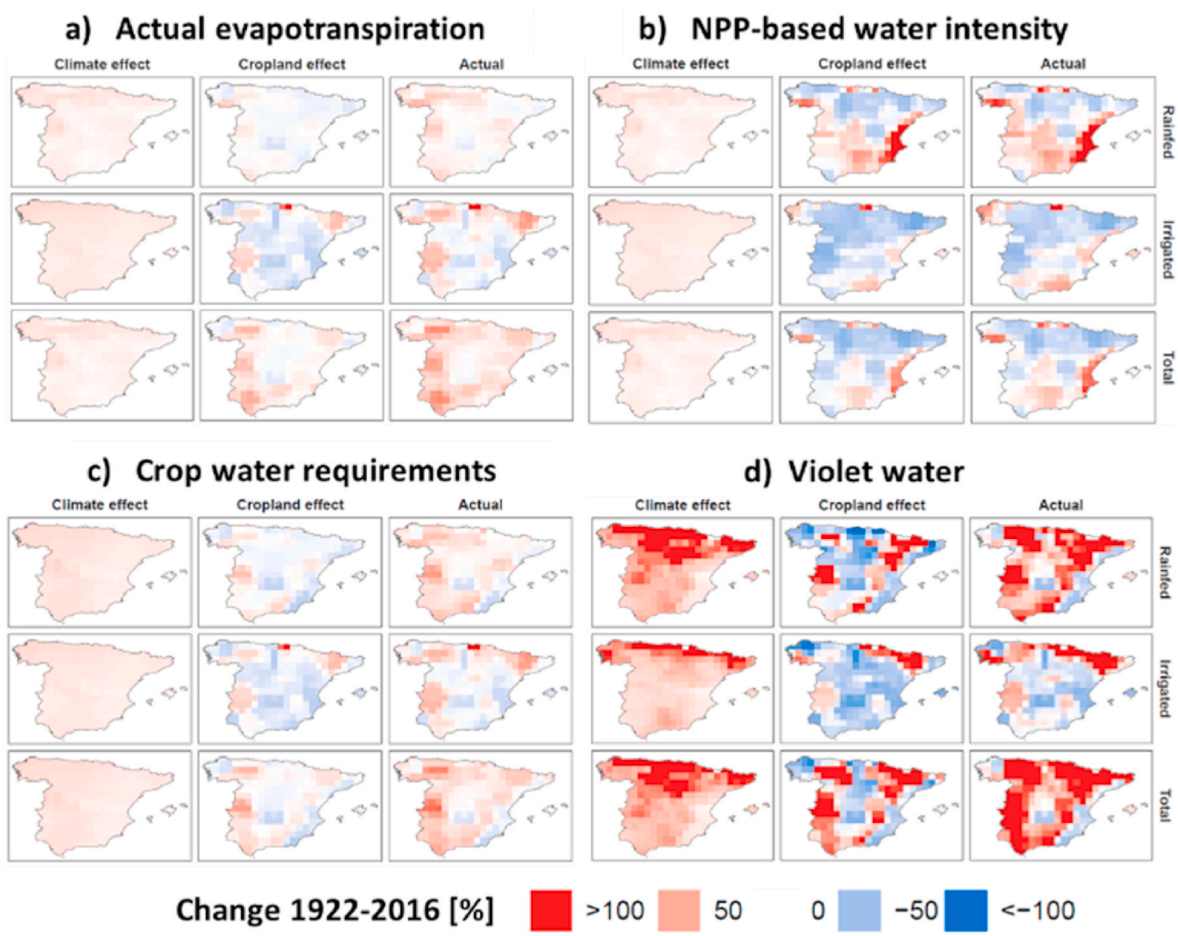

Fig. 4. Geographical distribution of Climate, Cropland effects and Actual scenario of water performance indicators, for rainfed, irrigated crops and total croplands: a) Actual evapotranspiration; b) Net primary productivity-based water intensity; c) Crop water requirements; and d), Violet water. The effects were calculated based on the indicators and expressed in mm $month^{-1}$ for actual ET, crop water requirements and violet water, and expressed in m^3 Mg C^{-1} for the NPP-based water intensity.

WI in almost every region (Fig. 5) but the NPP dropped principally in the east coast and south (A.2.16.), causing a growth on the NPP-WI in those particular regions (Fig. 4).

3.3. *The interrelation among water performance indicators*

The correlation among WPI have been empirically tested using our estimations, obtaining that CWR and VW are strongly correlated for all types of crops (Fig. 5-a). So are CWR and AET, except for rainfed-woody crops that present poor correlation, reflecting that increased CWR is frequently not accompanied by AET growth. As expected, AET-VW (Fig. 6) are well correlated for irrigated crops and show a clear inversely proportional relation for rainfed-woody crops, meaning that an increase in WS translates in a decrease in AET, but not for rainfed-herbaceous crops. The later means that in some of the cases water consumption (AET) and water stress (VW) grow simultaneously. Meanwhile, the correlation between the NPP-WI and the other WPI is generally weak.

4. Discussion

The results of the present work revealed highly complex patterns of change that were defined according to the parameters under study (temporal cross-section, location, month of the year, type of crop and water management). In this way, various interactions between climate and cropland effects arose across the four tested WPI, producing effects (the Actual scenario) of a different positive or negative sign based on those same parameters. The WPIs were selected based on their sensitivity to different aspects of climate change and cropland changes, as demonstrated in the results. In addition, by gathering the changes produced under two large categories only, i.e., climate and cropland, it was possible to analyse the effects more clearly. Indeed, we were able to identify which parts of the cropland adapted to climate change and which parts contributed to exacerbating its effects, and to what extent.

CWR, AET and VW grew over the 1922–2016 period, while the NPP-WI was the only indicator to have globally decreased. Climate change was partially responsible for these rises and generally, the cropland effect tended to accentuate the effects of climate change. This was even though in some of the subsectors under study, the cropland effect somewhat counteracted the effect of climate change. The fact that in certain cases, the WPI grew to a greater degree for total agriculture than for agricultural subsectors individually is due to the changes in the cropping patterns: indeed, there was a rise in woody and irrigated crops, which generally present higher values in these indicators (see Fig. A.3.9). For its part, the NPP-WI is a different case, since the cropland effect led to a reduction in the water cost of the NPP. The latter shows the NPP-WI is primarily driven by the NPP, coinciding with the findings of Niu et al. (2018) who detailed that crop water productivity (the inverse of water intensity) had a strong correlation with crop yields.

Separating the effects of climate and cropland changes on evapotranspiration is a necessary but difficult task, that involves dealing with high uncertainty (Zou et al., 2017). In the present study, there are some sources of uncertainty coming from both the inputs of the model (flaws in long-term cropland and climate data) and the model itself (NPP-kc

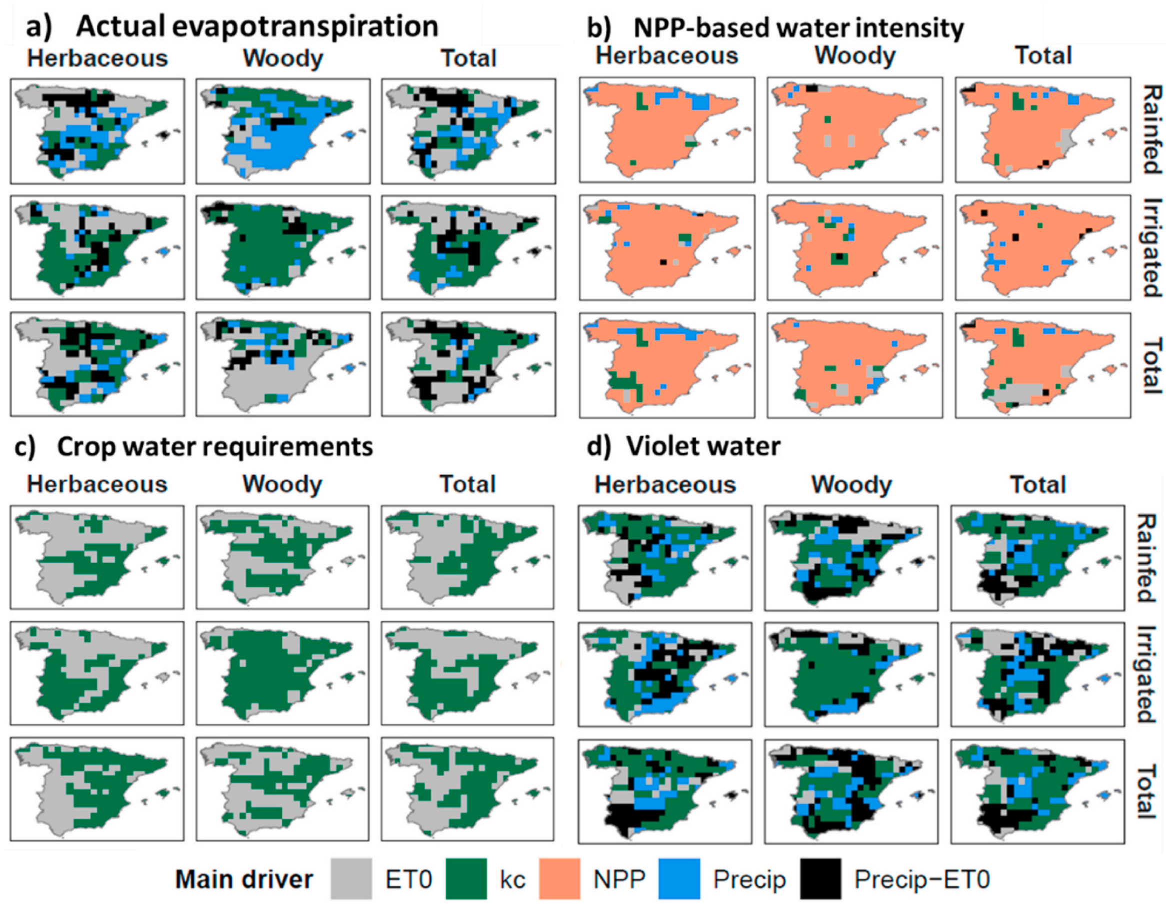

Fig. 5. Geographical distribution of the main drivers affecting water performance indicators in the Actual scenario, per crop type: a) Actual evapotranspiration; b) Net primary productivity-based water intensity; c) Crop water requirements; and d) Violet water.

adjusting, access to blue water not limited and CO_2 fertilization not explicitly considered) that are discussed in Appendix 5. The use of counterfactual scenarios implies the uncertain assumption that cropland changes could have happened independently of the climate changes and *vice versa*. However, in our opinion, the use of counterfactual scenarios prevents from further uncertainties related to the statistical analysis, as the attribution of the effects is done by running the model itself.

4.1. Should evapotranspiration be considered as an environmental impact?

To begin with, it is worth noting that studies that analyse the consumption of agricultural water (water footprint and related studies) usually consider that evapotranspiration is a loss for the basin in question. However, evapotranspiration is a major moisture flux that makes up the hydrological cycle and, as such, it provides a key ecosystem service, helping to generate rainfall elsewhere (Ellison et al., 2012; Keys et al., 2016; van der Ent et al., 2010); it also creates a moisture recycling mechanism that is particularly essential in Mediterranean environments (Millán et al., 2005; Millán, 2014). The increased evapotranspiration caused by irrigation modifies the lands' energy balance, increasing latent heat and reducing surface temperature (Chen et al., 2018). In fact, deforestation has caused global evapotranspiration to drop to a similar extent to the increase caused by the spread of irrigation, producing, however, a shift in regional evapotranspiration patterns (Gordon et al., 2005). Furthermore, the concept of water footprint has been criticised by Perry (2014), who stressed the need to contextualise the indicator and highlighted the importance of considering whether consumption takes place at moments or locations of major scarcity; indeed, unlike the carbon footprint, in the case of water, the geographical and temporal context is crucial (Tobarra et al., 2018). Finally, we must remember that in Spain, demand for blue water has considerably increased due to climate change, because of agricultural industrialization (Vila-Traver et al., 2021), and due to its role as a super-exporter of Mediterranean crops (Duarte et al., 2021). According to the estimates of Kummu et al. (2016), the blue water consumption-to-availability ratio in Spain has risen substantially (350%) over the last century, hand in hand with the rise in the consumption of blue water for irrigation (Fig. A.3.18). Therefore, we believe that increased evapotranspiration does not produce a negative impact *per se*, although it may do so, depending on the context. Hence, this interpretation will strongly depend on the local-regional context (Fulton et al., 2014) and the trade-offs with respect to other ecosystem services that derive from it. For example, it could be considered to have a negative impact in cases in which the degree of dependence on blue water does not allow to guarantee a good state of the related water bodies (Gerten et al., 2013) or if groundwater is unsustainably extracted, threatening adjacent ecosystems (Niu et al., 2019).

4.2. Climate change adaptation

Our results show how there are great opportunities for manoeuvre to modify the WPI by focusing the management options (historically captured in the cropland effect) on counteracting the effects of climate change on water consumption and by adapting activities to the resource's availability. The adaptation approach must be systemic because it includes measures to be taken in different fields. In this regard, the agroecological approach is ideal, since it considers the food system in its

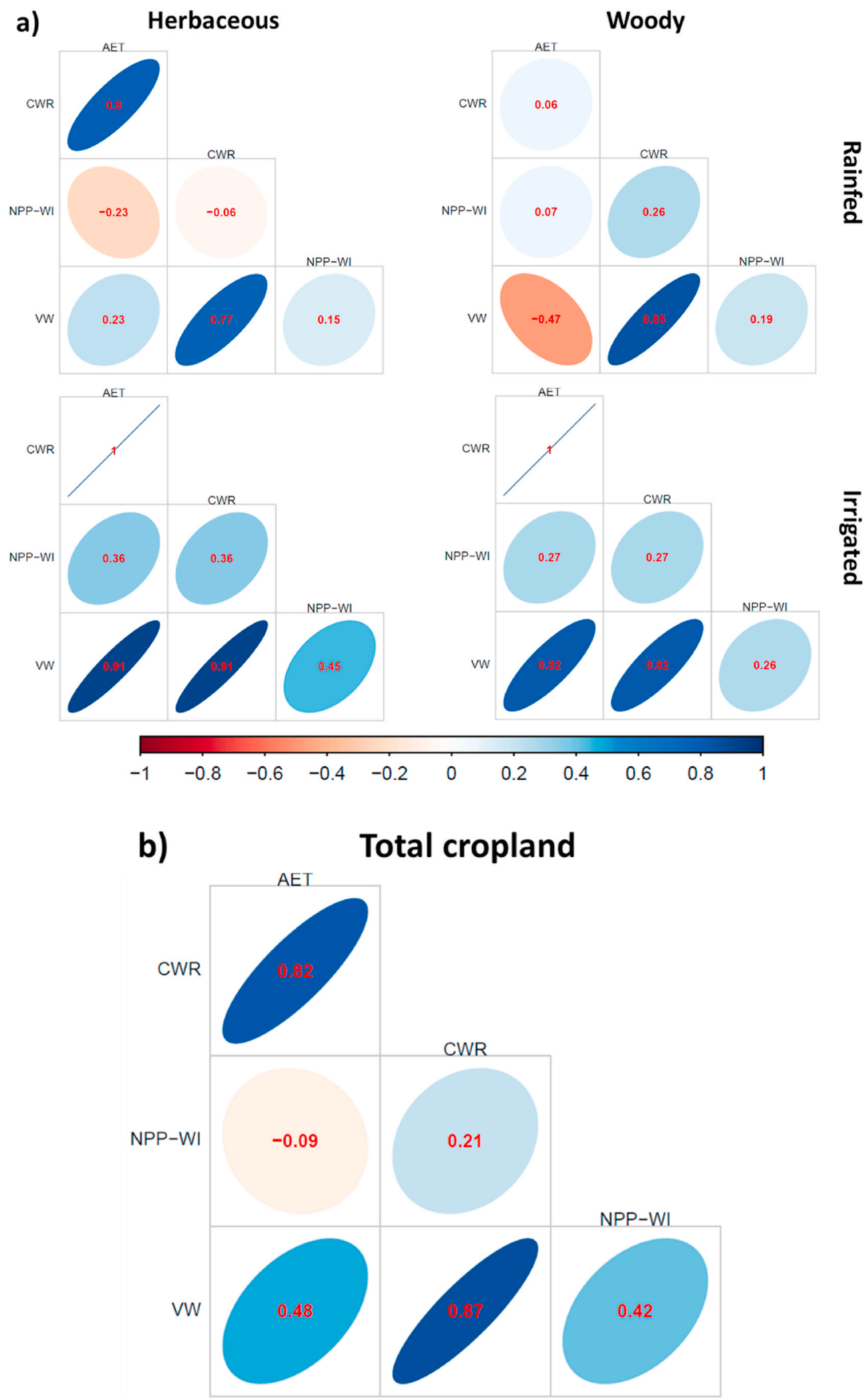

Fig. 6. Correlations (Pearson coefficient) among the water performance indicators, per agroecosystem type (a) and total cropland (b).

entirety, and encompasses environmental and socio-economic aspects (Aguilera et al., 2020). With respect to water scarcity measures, the lack of information about future changes in the socio-economic system leads to great uncertainties regarding the future agenda of adaptation measures (Iglesias and Garrote, 2015). In addition, because the impacts are specific, the measures must often be evaluated locally and per crop (Iglesias et al., 2010). At a European level, public policies must be based on scientific evidence, demonstration and training programmes need to be established, and the Water Framework Directive and the Common Agrarian Policy must address the issue more directly (Iglesias and Garrote, 2015).

Industrialization has led to a formidable increase in agricultural yields, largely due to the increased use of fertilizers (Aguilera et al., 2021), the expansion of irrigation and the sector's restructuring, allowing to plant crops in more arid spatiotemporal locations (Vila-Traver et al., 2021). In these cases, irrigation is used as a measure of adaptation to worse climatic conditions. However, the viability of future irrigation expansion is limited by ever-expanding water scarcity in Mediterranean environments (García-Ruiz et al., 2011). This is especially true in Spain, where substantial levels of water scarcity have been found (Kummu et al., 2016; Brauman et al., 2016; Fanning and O'Neill, 2016), and where resources have been used unsustainably, at the cost of reducing environmental flows (Wada and Bierkens, 2014). In addition, irrigated land expansion could prevent from accomplishing the conditions so that the improved efficiency of modern irrigation systems reduces the water consumption (Lopez-Gunn et al., 2012). In fact, there is evidence that the modernization of irrigation has increased water consumption at aggregate scales of analysis (Berbel et al., 2019; Perry et al., 2017). Moreover, irrigation growth in Spain has been possible thanks to the expansion of infrastructures and energy consumption that led to a considerable rising of greenhouse gas emissions (Aguilera et al., 2019). The migration of crops, together with the development of irrigation have globally reduced the impacts of climate change in recent decades (Sloat et al., 2020). The literature recommends such a measure to move the production of the most vulnerable regions (Iglesias et al., 2012). But according to our results, in Spain, the opposite has occurred: the shift in crops has worsened the effects of climate change on the climate in the cultivated areas. In addition, Sloat et al. (2020) recognise that this measure generates other impacts, associated with the expansion of agricultural frontiers (reduction of carbon stocks, lower water quality, lesser biodiversity, etc.) and such effects may render it undesirable as a global adaptation strategy. Therefore, more research is required to evaluate whether proposing new crop distribution shifts within Spain is appropriate in a context of climate change.

In the field of agronomy, Bodner et al. (2015) reviewed the available literature on water management under drought conditions and found that the most effective measures in a Mediterranean climate (storage driven conditions) are: the use of mulch cover to reduce losses due to evaporation; the use of varieties with a better root system to facilitate access to the resource; an increase in soil organic matter to increase the capacity for water retention; early planting to synchronise water supply and demand. In addition, adopting an agroecological approach (Aguilera et al., 2020), an emphasis has been placed on the potential of traditional knowledge to generate adaptation measures, such as: correcting land slopes through terracing to favour infiltration and to reduce runoff; the use of green roofs to reduce erosion and to increase the recharging of water in the soil; the use of landraces adapted to local agroclimatic conditions; diversification strategies to increase resilience and spread risks; stabilising the functionality and productivity of ecosystems; the introduction of tree species in arable systems (agroforestry) to enhance complementarity and increase yields; increasing soil organic matter to improve soil fertility and its hydric properties. Nevertheless, Aguilera et al. (2020) also warn about certain possible trade-offs that may be generated by the suggested measures, such as lower yields or economic productivity. The latter must be evaluated in detail. For their part, Iglesias and Garrote (2015) concluded that the most effective measures for farms to adapt to climate change are to improve drainage systems and to add small reservoirs on the farms.

To summarise, we believe that hydrological planning should seek to optimise the combination of services and activities provided by agroecosystems and trade-offs with natural ecosystems. Planning as well as agronomic measures should be combined, and static or conflicting stances (i.e., demonising the evapotranspiration of crops versus neglecting the impacts it produces on ecosystems) should be avoided. The most pressing needs should be made compatible with a long-term strategy to mitigate and to adapt to climate change.

4.3. Conclusions

Our findings show that climate change tended to increase actual evapotranspiration (9%), crop water requirements (14%) and net primary productivity-based water intensity (8%), its greatest impact being on violet water (increasing it by 34%). The cropland effect, in aggregated terms, pushed in the same direction as climate change, causing increases in actual evapotranspiration (11%), violet water (15%) and crop water requirements (3%), while reducing net primary productivity-based water intensity (−15%). That means, that structural changes, including the increase of woody and irrigated crops, and the spatio-temporal moving of the crops into more arid locations, have broadly contributed to exacerbating the effects of climate change, causing surges in three (CWR, AET and VW) of the four tested WPIs.

The importance of the cropland effect and its interactions with the climate effect remarks the great opportunities for manoeuvre to adapt agroecosystems to a changing climate, through water resources management and planning options. Therefore, in our opinion, croplands' adaptation to climate change and local water availability must be done opening the debate about whether it is necessary to reverse to some extent the restructuration occurred within the sector (i.e. Spain has become a super-exporter of Mediterranean crops) and the different kind of trade-offs that could arise from it (i.e. economic, food security, social, etc).

We must stress that the optimization of the water performance of agroecosystems, as a key measure of their resilience, must be made compatible with a broader framework of integrated action for mitigation and adaptation to climate change and food security. In our opinion, the combinations of measures that are necessary and possible in each case remain to be resolved in the literature. In this sense, the complex patterns of interaction between climate change and agriculture reflected in our results suggest the need to solve these combinations individually, depending on the location and type of agriculture considered.

CRediT authorship contribution statement

Jaime Vila-Traver: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Manuel González de Molina:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Juan Infante-Amate:** Investigation, Data curation, Writing – review & editing. **Eduardo Aguilera:** Conceptualization, Supervision, Validation, Investigation, Writing – review & editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.130811.

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