Identifying regions vulnerable to habitat degradation under future irrigation scenarios

2016 Environ. Res. Lett. 11 114025

(http://iopscience.iop.org/1748-9326/11/11/114025)

Environmental Research Letters

OPEN ACCESS

RECEIVED
30 April 2016

REVISED
25 October 2016

ACCEPTED FOR PUBLICATION
28 October 2016

PUBLISHED
17 November 2016

LETTER

Identifying regions vulnerable to habitat degradation under future irrigation scenarios

Marta Terrado[1,3], **Sergi Sabater**[1,2] **and Vicenç Acuña**[1]

[1] Catalan Institute for Water Research (ICRA), Emili Grahit 101, E-17003 Girona, Spain
[2] Institute of Aquatic Ecology, University of Girona, E-17071 Girona, Spain
[3] Author to whom any correspondence should be addressed.

E-mail: marta.terrado@bsc.es, ssabater@icra.cat **and** vicenc.acuna@icra.cat

Keywords: habitat quality, biodiversity, irrigation, global change scenarios, water scarcity, threats

Supplementary material for this article is available online

Abstract

The loss and degradation of natural habitats is a primary cause of biodiversity decline. The increasing impacts of climate and land use change affect water availability, ultimately decreasing agricultural production. Areas devoted to irrigation have been increased to compensate this reduction, causing habitat and biodiversity losses, especially in regions undergoing severe water stress. These effects might intensify under global change, probably contributing to a decrease in habitat quality. We selected four European river basins across a gradient of water scarcity and irrigation agriculture. The habitat quality in the basins was assessed as a function of habitat suitability and threats under current and future global change scenarios of irrigation. Results revealed that the most threatened regions under future scenarios of global change were among those suffering of water scarcity and with bigger areas devoted to irrigation. Loss of habitat quality reached 10% in terrestrial and 25% in aquatic ecosystems under climate change scenarios involving drier conditions. The aquatic habitats were the most degraded in all scenarios, since they were affected by threats from both the terrestrial and the aquatic parts of the basin. By identifying in advance the regions most vulnerable to habitat and biodiversity loss, our approach can assist decision makers in deciding the conservation actions to be prioritized for mitigation and adaptation to the effects of climate change, particularly front the development of irrigation plans.

1. Introduction

Biodiversity is under threat at the global scale mostly because of habitat loss and degradation and over-exploitation through hunting and fishing, but also as a result of climate change (Sala *et al* 2000, Vörösmarty *et al* 2010). Between 1970 and 2010 the population size of worldwide terrestrial species declined by 39% whereas those of freshwater species declined by 76% (WWF 2014). In Europe, this trend could be associated to habitat degradation. The assessment of the European Habitats Directive (EEC 1992) showed that only 16% of habitat types were in favorable conservation status during the period 2007–2012 (EEA 2015). This percentage was higher in terrestrial than in freshwater and marine ecosystems. While habitat loss in favor of agriculture, urban development and energy production threatens terrestrial species (Alkemade *et al* 2009), freshwater species are affected by habitat loss and fragmentation, pollution and invasive species (EEA 2012, Janse *et al* 2015).

At the global scale, several studies have recently identified areas vulnerable to habitat degradation and biodiversity loss, both for current (Halpern *et al* 2008, Vörösmarty *et al* 2010) and future global change scenarios (Sala *et al* 2000, van Vuuren *et al* 2006, Jetz *et al* 2007, Alkemade *et al* 2009, Janse *et al* 2015). Global change scenarios have also been used in Europe to predict changes in ecosystem services and biodiversity (EEA 2005, Metzger *et al* 2005, Schröter *et al* 2005, Verboom *et al* 2007). These analyses coincide on the relevance of climate and land use change as future causes for habitat loss across Europe, and identify the Mediterranean region as the most vulnerable in relation to water stress.

Approaches to quantify the potential impact of human threats on biodiversity are varied. For example, human footprint mapping has been used to assess spatial patterns of threats (Sanderson *et al* 2002, Woolmer *et al* 2008), and other approaches mapping the cumulative impact of threats to ecosystems have followed (Araújo *et al* 2008, Halpern *et al* 2008, Evans *et al* 2011, Schinegger *et al* 2012). More recently, studies addressing biodiversity impacts on life cycle assessment (LCA) have emerged, either based on habitat suitability models (de Baan *et al* 2015) or on the combined biodiversity impacts of different stressors (Verones *et al* 2015). Impacts on biodiversity have also been estimated using indicators such as the mean species abundance (MSA, Alkemade *et al* 2009, Janse *et al* 2015) and the biodiversity intactness index (Biggs *et al* 2008). Other models have used a score of habitat quality as biodiversity indicator (Nelson *et al* 2009, Terrado *et al* 2016b). In this context, many predictions have been obtained at large spatial scales using coarse spatial resolutions, yet the role of more local scale effects remains poorly explored (Randin *et al* 2009). Although local studies assessing fine scale impacts at the river basin or sub-basin scale exist (Biggs *et al* 2008, Nelson *et al* 2009), they are usually applied to particular areas and often provide non-comparable results because formatting of model inputs and outputs differs. As such, the choice of an appropriate spatial resolution for large scale habitat quality and biodiversity is of outmost importance (del Barrio *et al* 2006, Metzger *et al* 2008, Bellard *et al* 2012).

Irrigation agriculture has been identified as one of the main threats to habitat and biodiversity (Reidsma *et al* 2006). This is particularly true in areas where precipitation is insufficient to sustain crop yields and irrigation is unavoidable to attain crop production objectives. Irrigated agriculture is a major user of freshwater resources (Schaldach *et al* 2012, Boithias *et al* 2014), estimations indicating that water for irrigation constitutes 70% of all freshwater withdrawals (UNESCO 2009). It is obvious that climate change may affect the intensity of irrigation agriculture (Macleod and Haygarth 2010) and this will have significant implications for agricultural adaptation and mitigation in Europe. In this area, the success of management strategies will depend on the balance between human needs of natural resources and ecosystem protection.

We aim to determine the current and future effects of irrigation on terrestrial and aquatic habitat quality of river basins distributed across a gradient of water scarcity under different scenarios of climate change. To do so, we apply the InVEST habitat quality model (*Integrated Valuation of Environmental Services and Tradeoffs*, Kareiva *et al* 2011, Terrado *et al* 2016b), which assesses habitat quality as a biodiversity indicator. Various studies have already considered climate and land use changes in predicting variations of habitat quality (Schröter *et al* 2005, van Vuuren *et al* 2006, Jetz *et al* 2007, Nelson *et al* 2009), but only a few have considered the simultaneous variation of other threats together with climate and land uses, both in terrestrial and freshwater ecosystems (Verones *et al* 2015, Terrado *et al* 2016b). Here we aim to identify the characteristics that make a region more vulnerable to habitat degradation and biodiversity loss with respect to other regions. This can provide additional criteria to decision-makers when applying management actions for adaptation to climate change, that account simultaneously for terrestrial and aquatic habitats.

2. Methods

2.1. Description of the study basins

We selected four river basins distributed across a gradient of water scarcity and irrigation agriculture (figure 1). Two of the basins (Ebro—Spain and Evrotas—Greece), presented a mean precipitation-to-evapotranspiration ratio (P/ET) around 2, with 14% and 7% of their surfaces occupied by irrigated crops in the Ebro and the Evrotas basins respectively. Many sub-basins in the Ebro and the Evrotas have a P/ET ratio close to 1 and host important irrigation areas. A P/ET ratio approaching one indicates that serious problems of water scarcity might occur. The two other basins showed a mean P/ET ratio close to 3 (Sava, transboundary—Slovenia, Croatia, Bosnia and Herzegovina, and Serbia) and to 5 (Adige—Italy). The percentage of area occupied by typically irrigated crops also differed among them, being 17% in the Sava basin and 5% in the Adige basin. The four selected basins encompass a rich set of socio-ecological conditions (forested mountainous areas, highly populated regions relying on water transfers or agricultural areas) and a wide geographic coverage (figures 1 and 2). All basins are affected by different levels of multiple anthropogenic threats deriving in different problems (figure 3).

2.2. Description of the habitat quality model

The spatially-explicit habitat quality model InVEST (v. 2.4.4, Kareiva *et al* 2011, Tallis *et al* 2011) was applied. This model combines information on land use/land cover (LU/LC) suitability and threats to biodiversity in order to produce maps of habitat quality. The model is based on the assumption that areas of higher habitat quality can support higher richness of native species, and that decreases in habitat extent and quality lead to species decline. The model was initially developed for terrestrial ecosystems and later extended to aquatic ecosystems (Terrado *et al* 2016b). This approach generates information on the relative extent and degradation of different habitat types in a region, providing an initial assessment of conservation needs.

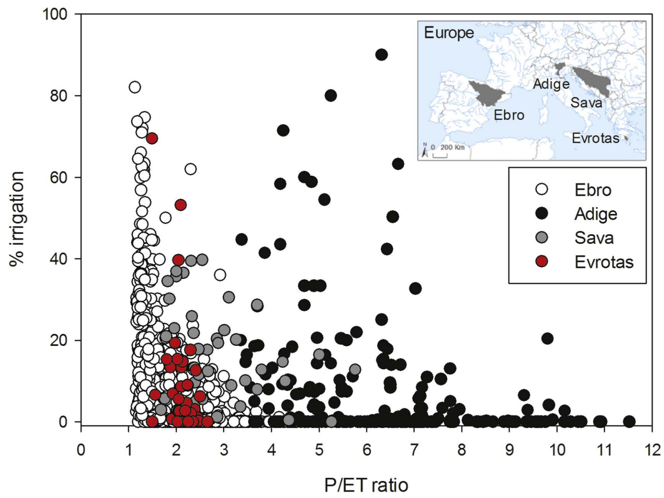

Figure 1. Graph of water scarcity represented as the ratio between precipitation and evapotranspiration (P/ET) against the relative abundance of irrigation in the study basins. Points refer to the results per sub-basin; sub-basins defined according to the water bodies defined within the Water Framework Directive.

We used as model inputs geographical data sets obtained at a broad spatial scale (i.e. European scale) in order to incorporate within- and across-region variations. Thus, we used the CORINE LU/LC map obtained from the European Environment Agency at 100 m resolution for year 2006 (year 2000 in the case of Greece) and we aggregated the land uses in 10 different categories corresponding to habitat types (figure 2). A relative habitat suitability score (H_j) from 0 to 1, where 1 indicates the highest suitability for species, was assigned to each habitat type. We considered eight different threats, 4 terrestrial threats corresponding to agriculture, urbanization, mining and roads, and 4 aquatic threats, corresponding to urban wastewater discharges, water abstraction, dams and channeling (see description in table 1). We mapped the source of each threat on a raster in which the value of the grid cell, normalized between 0 and 1, indicated the intensity of the threat (figure 3). We applied this normalization by taking into account the intensity of threats across the four river basin territories. A maximum of four different categories were established for the representation of each threat according to the range of its measurement (table 1). The impacts of threats on habitat were mediated in a grid cell by three factors: (1) the distance between the cell and the threat's source, where a maximum distance over which the threat affects habitat quality was defined (Max D); (2) the relative weight of each threat, where the importance of one threat compared to the others was established (W_r); and (3) the relative sensitivity of each habitat type to the threat (S_{jr}). Terrestrial threats were considered to extend in all directions of the landscape, but the impacts of aquatic threats were only considered downstream of the threat source. This caused the effect of dams on hydrological regulation to affect habitat connectivity downstream, but to disregard their barrier effect on species migration upstream. In the case of channeling, its effect was only considered in the channelized area (no affectation up- or downstream). Input model parameters H_j and S_{jr} were not considered site-specific and we used values from a previous study in the Llobregat River basin (NE Iberian Peninsula), where the model was calibrated and validated (Terrado *et al* 2016b). These parameters depend on the characteristics of land use categories, which were assumed to be constant no matter the basin's characteristics. Because they depend on the specific characteristics of the study basin, the values for the parameters Max D and W_r were obtained using expert opinion (Kuhnert *et al* 2010). The sum of the total threat's level in a grid cell provided a degradation score that was then used along with habitat suitability to compute a score of habitat quality for both terrestrial and aquatic ecosystems. Values obtained for habitat quality range from 0 to 1, with 1 meaning the highest habitat quality.

2.3. Elucidation of expert opinion

We elucidated expert opinion using an on-line survey directed to scientists from several research institutions and managers from each of the study basins. A total of 43 experts responded to the survey (13 for the Ebro, 8 for the Adige, 9 for the Evrotas and 13 for the Sava) and provided values for W_r and Max D in each of the basins. For the latter parameter, the experts could decide on different categories of distance intervals or provide specific distance values. We used expert judgments as a measure of uncertainty that could be incorporated into the model. Experts were requested to provide a confidence weight (CW) to their answers, from low to very high. We used the CW to weight their responses in order to obtain a mean weighted value, mean_w (equation (1)), for each of the parameters,

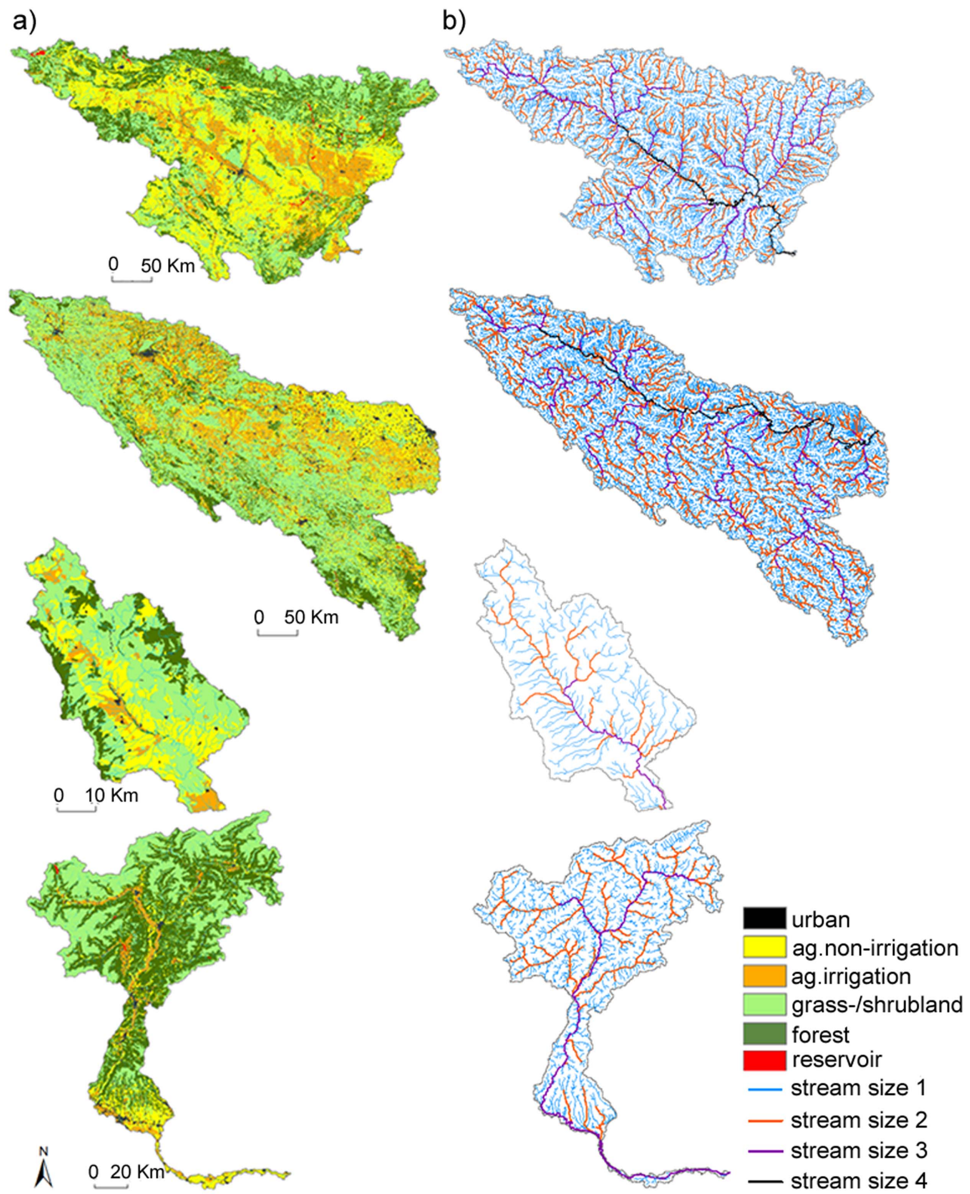

Figure 2. Maps of (a) habitat types in the four study basins and (b) detail of habitat types defined as stream size 1 to 4 according to stream order.

which was used as model input (figure 4). Note that x_i in equation 1 corresponds to each of the parameter values provided by experts.

$$\text{mean}_w = \frac{\sum_{i=0}^{n} x_{\ i} \times \text{CW}}{\sum \text{CW}}. \quad (1)$$

2.4. Uncertainty analysis of the habitat quality model

We consider that our analysis was affected by three types of uncertainty: (i) the uncertainty from parameters obtained by expert knowledge, (ii) the uncertainty of the threat maps used in the model, and (iii) the uncertainty coming from the irrigation scenarios. In this analysis, we cannot take into account the uncertainty from the threat maps and the scenarios of irrigation because we lack the information for them. The irrigation scenarios were obtained from Schaldach *et al* (2012), whereas the threat maps came from different environmental agencies, water management authorities and governments. For this reason, here we focus in assessing the uncertainty associated to the parameters obtained by expert knowledge. In order to quantify this uncertainty, for each of the basins we performed five different runs changing randomly the value of the input parameters: W_r, Max D, H_j and S_{ij}. The values assigned to these parameters were always within the range defined by the mean +/− the standard deviation of the values provided by experts. From the habitat quality maps obtained from the five runs, we calculated a coefficient of variation per pixel. Individual pixels were then averaged by habitat type (land use/land cover), ecosystem type (terrestrial and aquatic) and at the basin's level.

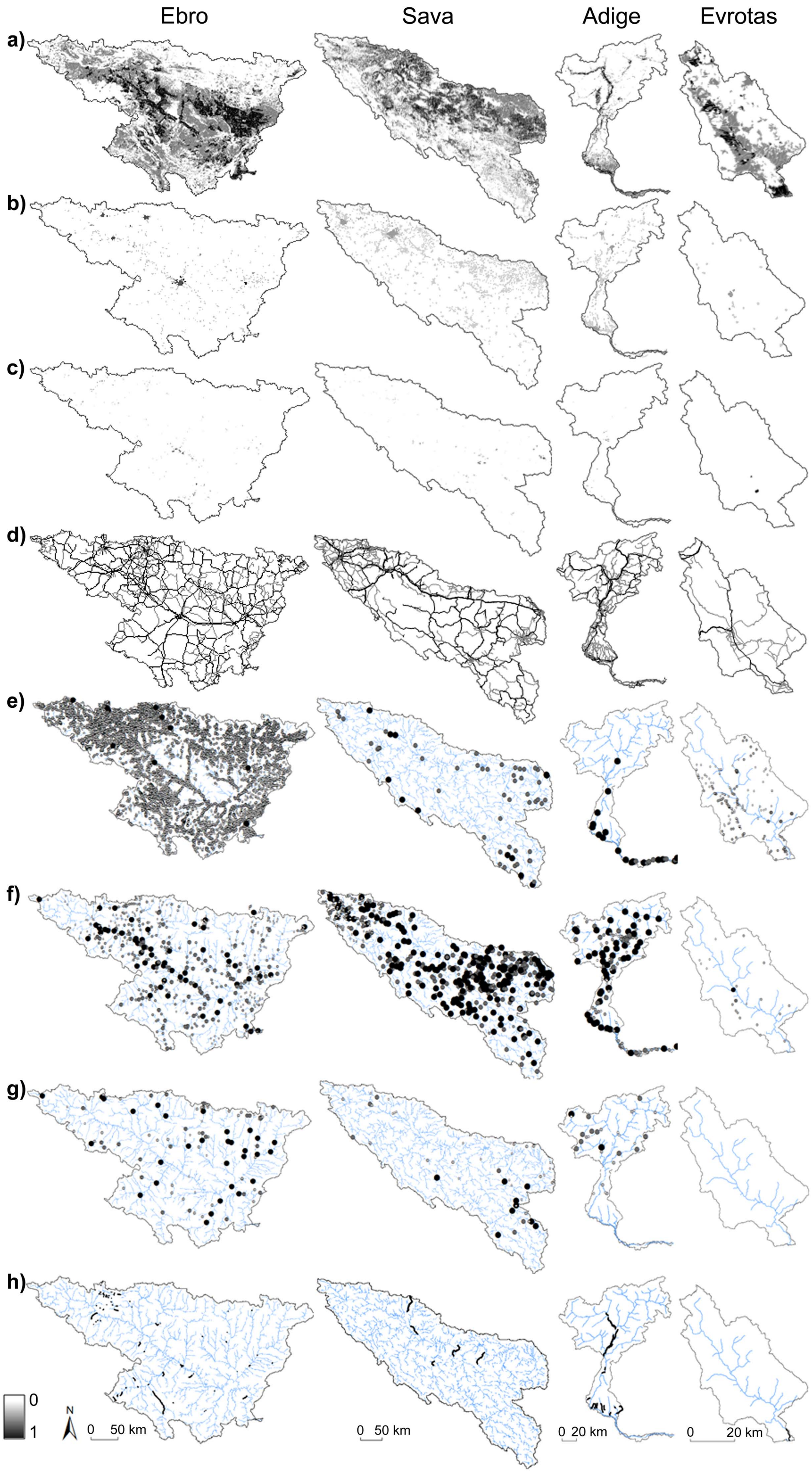

Figure 3. Distribution and intensity of threats in the four study basins: (a) agriculture, (b) urbanization, (c) mining, (d) roads, (e) water abstraction, (f) urban discharge, (g) dams, and (h) channeling. For aquatic threats (e) to (h) the represented hydrological network starts at third-order streams.

Table 1. Threats considered, data sources and threat representation in the habitat quality model.

Threat	Data source				Threat representation
	Adige	Ebro	Evrotas	Sava	
Agriculture	CORINE 2006 from the European Environment Agency (EEA) at 100 m grid resolution (CORINE 2000 for Evrotas)				Irrigation agriculture, 1 Non-irrigation agriculture, 0.5
Urbanization	Population distribution in 2001 from the EEA				Range of population density[4]: 1–35 inh ha^{-1}, 0.25 36–70 inh ha^{-1}, 0.5 71–105 inh ha^{-1}, 0.75 $>$ 105 inh ha^{-1}, 1
Mining	CORINE 2006 from the EEA at 100 m grid resolution (CORINE 2000 for Evrotas)				Mining, 1
Roads	OpenStreetMap data from 2014 in shapefile format, courtesy of Geofabrik				Motorway/ primary road/ trunk, 1 Secondary road/ tertiary road, 0.5[5]
Water abstraction	*Confederación Hidrográfica del Ebro*, CHE (river basin managing authority), 2015	*Autorità di Bacino del Fiume Adige* (river basin managing authority), 2008	Prefecture of Pelloponese and LIFE Project 2005–09 (location of abstractions). Volumes assigned using water demands in the neighboring settlements from abstraction points obtained from the Evrotas River Basin Management Plan, 2011	International Sava River Basin Commission, 2012	Range according to the annual volume of water abstracted. A different weight factor applied to surface and groundwater: water volume multiplied by 1 for surface water abstraction and by 0.5 for groundwater abstraction. Range: 0–0.13 Hm^3 y^{-1}, 0.25 0.14–0.27 Hm^3 y^{-1}, 0.5 0.28–10 Hm^3 y^{-1}, 0.75 $>$10 Hm^3 y^{-1}, 1
Urban discharges	CHE, 2015	*Repartizione Agenzia Provinciale per l'Ambiente -Bolzano, Agenzia per la Depurazione - Trento, Agenzia Regionale per la Prevenzione e Protezione Ambientale—Veneto* (ARPAV), 2015	Evrotas River Basin Management Plan, 2011	International Sava River Basin Commission, 2007	Range according to the person equivalents (PEs). For treated effluents, PEs from the wastewater treatment plant considered. For non-treated effluents, 1 inh = 1 PE considered. A different weight factor applied to treated and non-treated discharges: PEs multiplied by 0.5 for

Table 1. (Continued.)

Threat	Data source				Threat representation
	Adige	Ebro	Evrotas	Sava	
					treated urban discharges and by 1 for non-treated urban discharges. Ranges: 0–250 PEs, 0.25 251–2000 PEs, 0.5 2001–4500 PEs, 0.75 >4500 PEs, 1
Dams	CHE and EEA reservoirs and dams database for Europe, European catchments and river network system (EEA-Ecrins, 2012)	EEA-Ecrins, 2012	Non-regulated	EEA-Ecrins, 2012	Range of reservoir volume: 0.1–2 Hm^3, 0.25 2.1–10 Hm^3, 0.5 11–50 Hm^3, 0.75 >50 Hm^3, 1
Channeling	CHE, 2014[6]	*Alpi Orientali* River Basin Management Plan, 2010	*Personal communication*	International Sava River Basin Commission, 2012	Channeling, 1

[4] Cities without population records (only in the case of the Sava River basin) were set to the average population density of the basin.
[5] Only the category 'roads' from OpenStreetMap data was considered. Categories designed as 'special', 'paths' and 'sidewalks' were not included.
[6] When the channelized length was <50 m (half a pixel) it was not represented in the map (not considered).

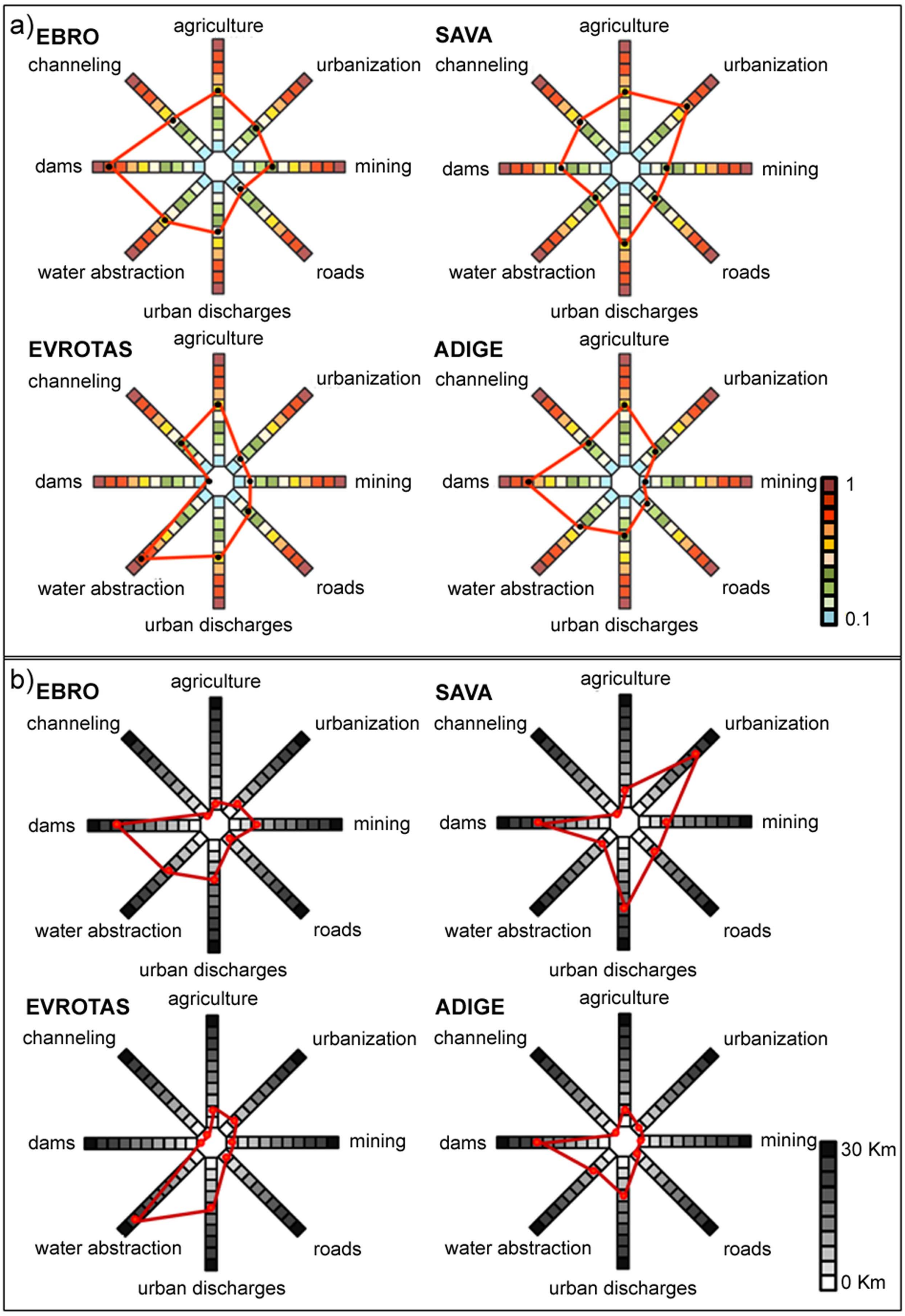

Figure 4. Mean weighted value assigned by expert opinion to each study basin for the parameters: (a) threat weights and (b) maximum distance of threat affectation.

2.5. Future irrigation and habitat quality scenarios

To predict the habitat quality for the year 2050, we used the scenarios of irrigated areas obtained by the EU FP-6 project SCENES (Schaldach *et al* 2012), that were kindly provided by their authors for the purpose of our work. In the mentioned study, changes in irrigation were calculated on a uniform raster with a cell size of 5 arc-minutes using the LandSHIFT land-use model (Schaldach *et al* 2011). Simulations using LandSHIFT were performed taking into account the respective combination of socio-economic scenarios and the climate change data from two General Circulation Models (GCMs). Among the different available socio-economic scenarios developed by means of a participatory scenario development process involving a group of stakeholders, we selected the 'Economy First' (EcF). EcF was classified as a reference (non-policy) scenario, and therefore, one of the worst-case scenarios in conservation terms (see description in the appendix A.1). This scenario was combined with the IPCC SRES A2 emission scenario (IPCC 2007) to account for the effect of climate change. The two

Table 2. Average of the coefficient of variation of the predicted habitat quality values in the four study basins at the scale of habitat type (land use/land cover), ecosystem type (terrestrial and aquatic) and entire basin.

	Adige			Ebro			Evrotas			Sava		
LULC	Habitat	Ecosystem	Basin	Habitat	Ecosystem	Basin	Habitat	Ecosystem	Basin	Habitat	Ecosystem	Basin
Urban	1.3			1.9			2			1.7		
Agric—NI	0.1			0.2			0.1			0.6		
Agric—I	0.7	0.9		0.8	1.1		1.1	0.6		1.4	1.4	
Grass-/Shrubland	0.8			1.7			0.7			1.6		
Forest	1			1.6			1			1.6		
			0.9			1.1			0.6			1.4
Reservoirs	1.3			1.9			—			1.6		
Stream size 1	1.2			1			1.4			1.6		
Stream size 2	1.2	1.2		1.8	1.9		1.2	1.4		1.6	1.6	
Stream size 3	1.8			2			1			1.7		
Stream size 4	—			2			—			1.6		

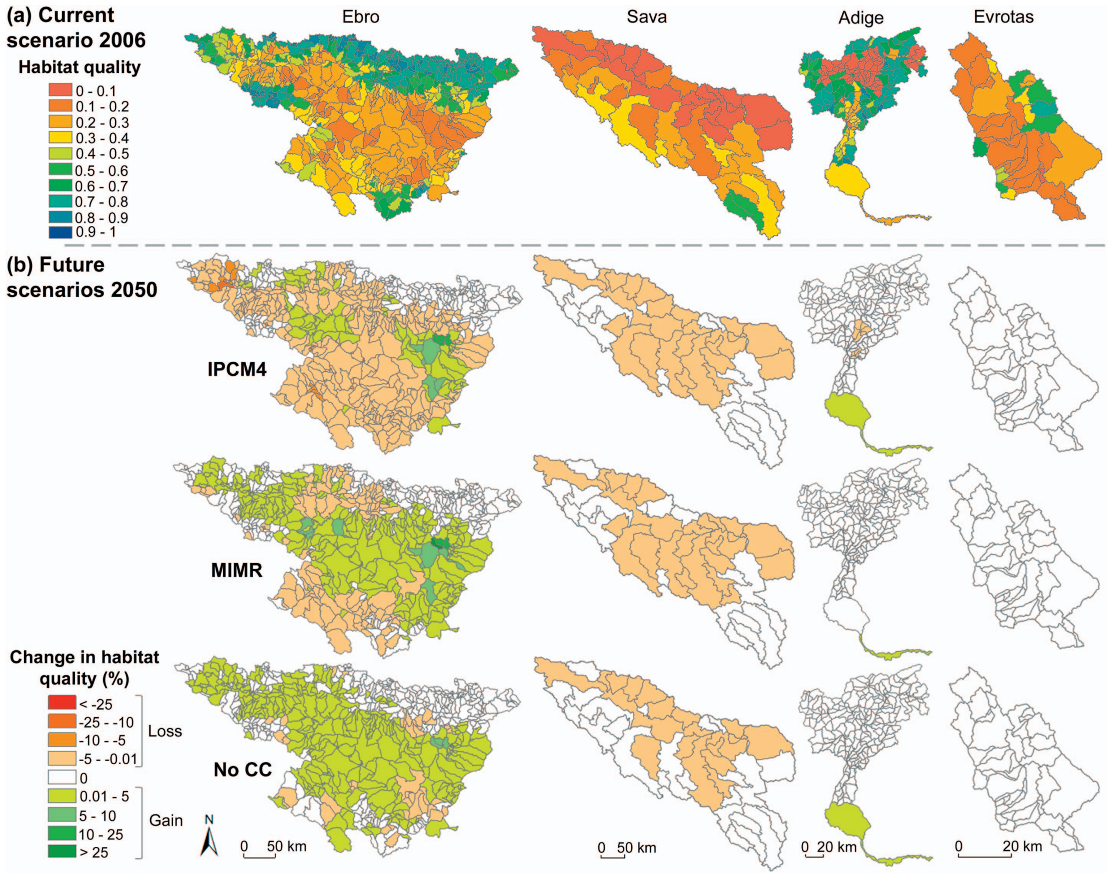

Figure 5. Terrestrial habitat quality in the four studied river basins (a) under current conditions and (b) change of habitat quality under the future Economy First scenario with different assumptions for climate change for year 2050: IPCM4 or 'dry' scenario, MIMR or 'wet' scenario and no climate change or 'no CC' scenario.

GCMs were chosen to represent the variability between global climate models. Both GCMs selected showed a high increase of temperature but had large differences in precipitation, representing 'dry' (IPCM4 scenario) and 'wet' (MIMR scenario) climate conditions for Europe. In addition, a scenario without the effects of climate change was considered ('no CC' scenario), which only took into account the socio-economic drivers. See more details in the appendix A.1.

New maps of future habitat types in the study basins were generated by considering the future global change scenarios of irrigation. Apart from the differences in habitat types, the new irrigation scenarios also involved changes in the threats agriculture and water abstraction (see more details in the appendix A.2). We calculated the difference in habitat quality between the current and the future global change scenarios at the sub-basin scale; sub-basins established according to the water bodies defined in the Water Framework Directive (WFD, EC 2000), that is 715 for the Ebro, 306 for the Adige, 46 for the Evrotas and 39 for the Sava. Due to model assumptions, areas where irrigated agriculture was projected to increase in the future will tend to suffer habitat quality losses, whereas areas where irrigated agriculture was projected to decrease will tend to experience habitat quality gains.

3. Results

3.1. Threats affecting habitat quality

The mean weighted values (mean$_w$) of W_r and Max D (figure 4) show specific patterns in the different basins. Experts identified dams, followed by agriculture and water abstraction, as the most important threats in the Ebro and Adige basins (figure 4(a)). In the Sava basin experts assigned the highest weight to urbanization, followed by agriculture and urban discharges. Dams had lower importance in that basin. Water abstraction was identified as the most important threat in the Evrotas basin, while dams received a zero weight because of the non-regulated character of the basin. The highest distances of affectation (Max D) were assigned to dams, urban discharges, and water abstraction (figure 4(b)), meaning that the effects of these threats were the ones persisting the most further away from where they were originated. Only in the case of the Sava basin the urbanization threat received a higher Max D value. The expert values for W_r and Max D, and the associated CWs of their responses are available in the

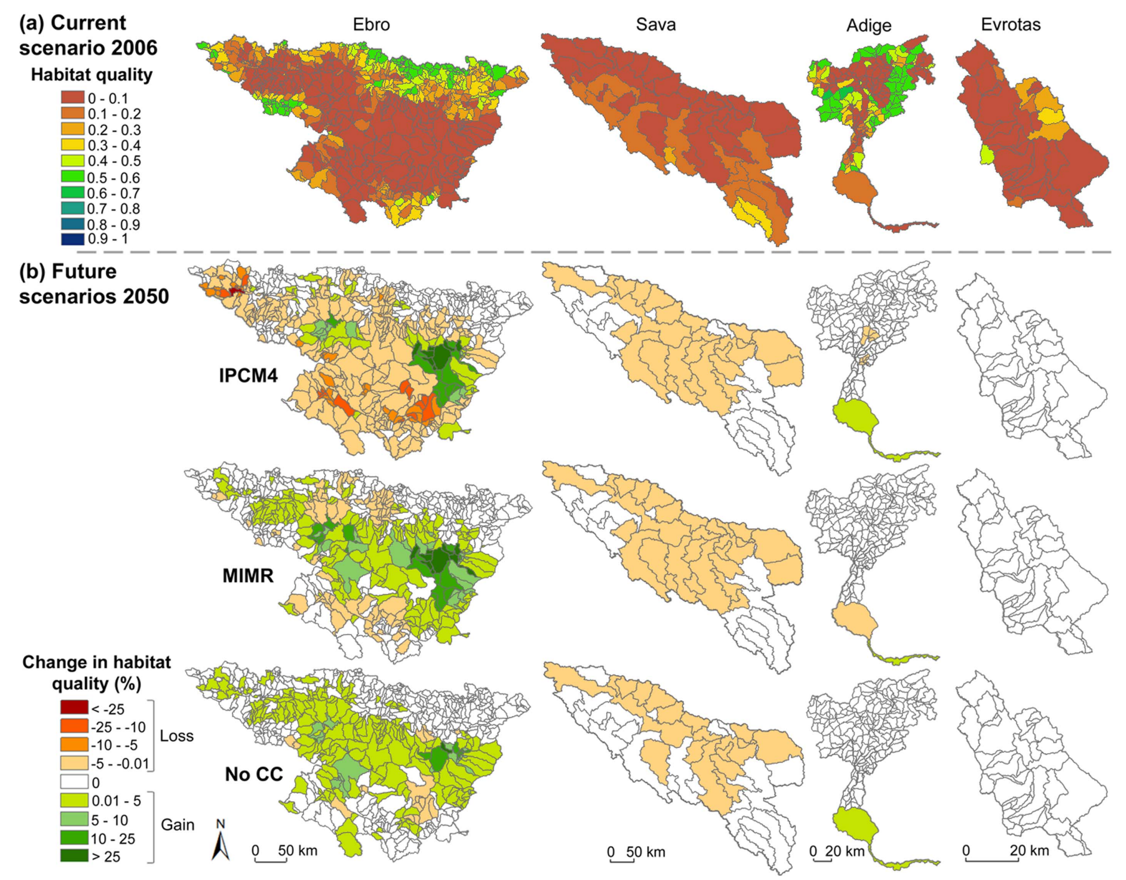

Figure 6. Aquatic habitat quality in the four studied river basins (a) under current conditions and (b) change of habitat quality under the future Economy First scenario with different assumptions for climate change for year 2050: IPCM4 or 'dry' scenario, MIMR or 'wet' scenario and no climate change or 'no CC' scenario.

appendix (tables A.1 and A.2, and figure A.1). Likewise, the values used for the parameters H_j and S_{jr} are available in table A.3 from the appendix.

3.2. Habitat quality

We used a relative scoring for the estimation of the current habitat quality, where values close to zero indicated the lowest habitat quality, and values approaching one corresponded to the highest habitat quality. This scoring included all the different sub-basins in the study basins to reach a common consideration of the degree of habitat affectation due to threats. The terrestrial and aquatic habitat quality in the four study basins always decreased in the downstream direction (figures 5(a) and 6(a)). The highest values of terrestrial habitat quality were in the northern part of the Ebro basin, in the northern part of the Adige basin and in north-eastern parts of the Evrotas basin (figure 5(a)). The lowest terrestrial habitat quality was around the main course of the Sava basin and north of the main course of the Adige. The patterns of habitat quality identified in aquatic ecosystems (0.21 ± 0.21) were lower and more variable than those in the terrestrial ecosystems (0.43 ± 0.26; figure 6(a)).

The threat agriculture, involving irrigation and rain fed crops, was the main responsible of habitat degradation in the four study basins. Agriculture had its lowest contribution to habitat degradation in the Sava basin, whereas the highest contribution was found in the Evrotas basin. Irrigation was responsible of around 40% habitat degradation in the Sava and Adige basins, 31% in the Ebro and 27% in the Evrotas. The relative contribution of the other threats to habitat degradation was dependent on the basin. Urbanization was important in the Sava and Adige basins (28% and 10% relative contribution respectively), whereas mining was only relevant in the Ebro basin (2.2% relative contribution). Roads mainly contributed to the habitat degradation of the Ebro, Adige and Sava basins (around 4% relative contribution). The contribution of aquatic threats was much lower than the contribution of the terrestrial ones, due to the lower proportion of aquatic habitat when compared to terrestrial. While water abstraction was important in the Ebro and Evrotas basins, urban water discharges were more relevant in the Adige basin, and dams in the Ebro and the Adige. The contribution of channeling to habitat degradation was estimated to be lower than other threats in all the study basins.

In terms of uncertainty, the basin presenting the highest coefficient of variation was the Sava (CV = 1.4, which results from averaging the coefficient of variation of all the pixels in the basin), whereas the Evrotas had the lowest coefficient of variation at the basin scale (CV = 0.6; table 2). In all basins, aquatic ecosystems presented higher uncertainty than terrestrial ecosystems. In this case, the CV per ecosystem type was obtained from averaging the coefficient of variation of all aquatic and all terrestrial habitats, respectively. While all aquatic habitats had a similar level of uncertainty, the urban habitat type presented the highest uncertainty in terrestrial ecosystems.

3.3. Future changes of irrigated area and habitat quality

The predicted changes of irrigated area varied depending on the basin considered (figure A.2). Decrease of irrigated areas in the Ebro River basin was mainly predicted in the Ebro River main course, especially for the 'wet' and the 'no CC' scenario. Increases were more important north and south from the Ebro River main course and close to the river source, particularly for the 'dry' scenario. In the Sava basin, there was a generalized increase of irrigated area in all climate change scenarios, although this increase was much lower than in the Ebro basin. In the Adige basin, a decrease of irrigated area always dominated the lower river course. No change in irrigated area could be assessed for the Evrotas basin because of its small size, taking into account the resolution of the irrigation scenarios used. Nevertheless, the basin is expected to continue experiencing local changes in irrigation in the future based on a historical scenario analysis (Cazemier *et al* 2011).

Changes of habitat quality under future irrigation scenarios were higher for aquatic than for terrestrial habitats (figures 5(b) and 6(b)). Losses of habitat quality were higher under the 'dry' scenario followed by the 'wet' scenario, and they were minimized under the 'no CC' scenario. Higher changes in habitat quality were obtained in the Ebro River sub-basins than in the sub-basins of the other three study basins. In the 'dry' scenario, habitat quality losses in the Ebro sub-basins reached −19% in terrestrial habitats and −28% in aquatic habitats. The highest losses were located close to the river source and in the southern part of the basin. Conversely, some gains of habitat quality also occurred in particular Ebro sub-basins in the 'wet' scenario. Habitat quality losses occurred in the Sava basin in all irrigation scenarios, and especially in the center of the basin and close to the junction with the Danube River. The highest change occurred under the 'dry' scenario, with decreases of −2% per sub-basin in the terrestrial habitats and −3% in the aquatic habitats. Minor losses of terrestrial and aquatic habitat quality occurred in the north of the Adige basin, only under the 'dry' scenario. Habitat quality increased at the outlet of the Adige River in all global change scenarios, mainly under the 'no CC' scenario (increases were 1% and 2% in terrestrial and aquatic ecosystems, respectively). Since we could not assess the change of irrigated areas in the Evrotas basin, no change of habitat quality could be predicted.

4. Discussion

Our analysis allows for a spatially-explicit assessment of habitat quality in humanized river basins distributed across a gradient of water scarcity and irrigation agriculture. Using a simple approach that combines available information in a reproducible and transparent manner, our analysis produces results that are comparable among different regions. The analysis identified the sub-basins characterized by higher water scarcity (P/ET ratios between 1.1 and 3) and larger areas devoted to irrigation (around 14% of the sub-basin area) to be the most threatened under future scenarios of land use and climate change. The sub-basins having less water scarcity (P/ET ratios up to 7) but still important irrigation areas (around 9%) were also vulnerable to habitat degradation, although less pronouncedly. The lowest risk of habitat degradation corresponded to regions with small irrigation areas and not suffering from water scarcity. Aquatic habitat quality was lower than terrestrial, reflecting the degradation of aquatic habitats by threats occurring within the freshwater environment but also as a consequence of terrestrial threats upstream. Aquatic habitat was also predicted to suffer more degradation than terrestrial habitat under global change scenarios, indicating that differences between terrestrial and aquatic habitat quality are expected to become larger in the future. In all cases, the loss of habitat quality was exacerbated under dry climate scenarios.

4.1. Considerations about the approach

The approach used in this paper was based on data elicited from expert opinion and global change scenarios of irrigation obtained in a previous study (Griffiths *et al* 2007, Schaldach *et al* 2012). This has an associated uncertainty, amplified by the fact that current conditions relied on the model validation previously performed in the Llobregat River basin (NE Iberian Peninsula, Terrado *et al* 2016b), but were not directly assessed in the four study basins. Maps of animal and plant species of interest in the European Member States (listed in the Habitats Directive, Art. 17) were available from the European Environment Agency (EEA, www.eea.europa.eu), but they focused on particular species and excluded parts of the basins that were not within the EU (i.e. major part of the Sava basin). Species data from the Global Biodiversity Information Facility (GBIF, www.gbif.org/) could neither be used for habitat quality validation because information on biodiversity was not homogeneously captured. The use of maps of species occurrence from the International Union for Conservation of Nature (IUCN, www.iucnredlist.org/) was also attempted, although data resolution (at the basin and supra-basin level) did not match the resolution of the predicted habitat quality maps (water body level); this resulting in non-consistent relationships throughout the four study basins.

The obtained results could be affected by the lack of consideration of some particular threats that could be of importance. As an example, invasive species, thermal pollution from nuclear or thermal power plants, navigation, or fishing can have an impact on the study basins, but information on them is scanty. Furthermore, interactions between drivers have been disregarded, although climate change will probably interact with and accelerate ongoing threats to biodiversity such as habitat degradation (Brook *et al* 2008). Species may persist and tolerate the assault of one threat, but the additive or synergistic impacts of threats such as irrigation and the resulting habitat fragmentation and degradation, can completely decimate them. Even though in our model habitat quality has been considered to be linear ecological models tend to predict that the fraction of extinct species will increase faster than linearly. There are many situations in which a small or intermediate-size threat to a system generates little or no impact, but when the threat exceeds a certain level, the impact increases dramatically (Harte 2007).

For the sake of homogeneity, threats' representation in the habitat quality model has been done in absolute rather than relative terms. Nevertheless, the impact of some threats will be different according to the characteristics of a particular region. For instance, the same water use in drier conditions creates more stress than in wetter conditions because a greater fraction of available water is being used, or the effects of the same or higher mining and urban discharges would be worse in areas with lower dilution capacity.

Each source of data and model prediction comes with inherent uncertainty, which may be propagated in the analysis and lead to overly confident estimations. An assessment of the applied habitat quality model reports an uncertainty of 23% across the whole basin, being higher for aquatic (34%) than for terrestrial ecosystems (23%) (Terrado *et al* 2016b). The uncertainty of results was also affected by the future irrigation scenarios used in the model. These scenarios were projections originally obtained for all Europe, not particularly representative of Southern Europe, and this constituted a drawback for small basins such as the Evrotas. Another source of uncertainty in the obtained scenarios of habitat quality arises from the transformation of the percentage of irrigation in a grid cell (5 arc-minutes size, ~6 × 9 km in central Europe) into entire cells of 100 × 100 m size which are classified as irrigation or non-irrigation. It is also possible that different results could be obtained using different scenarios such as the sustainability eventually scenario (SuE, Schaldach *et al* 2012), a policy scenario oriented to a more environmentally-sustainable society (see description in the appendix A.1). In fact, major sources of uncertainty on the input data are the assumptions about the future socio-economic and climatic developments. Whereas irrigated area was shrinking under the 'wet' climate scenario for both EcF and SuE, under the 'dry' scenario for EcF, irrigated area increased 45% in Southern Europe and it showed a decreasing trend under the SuE scenario.

4.2. Trends in habitat quality

In the four study basins, habitat degradation due to irrigation mainly concentrated around the main river flow. In the Sava, the middle reaches were particularly affected by agricultural activities and eutrophication. In the Adige, degradation due to irrigation concentrated in the upper course, which has a severely altered hydrology due to the high number of reservoirs. Reservoirs, dams and water diversions, endanger freshwater species by creating physical barriers to the normal movement and migration of biota (Leadley *et al* 2010). Diffuse pollution by agriculture in the central and lower course represents a relevant threat in the Adige basin. In the Ebro, abstraction of ground and surface water together with agricultural activities has deteriorated soil and water quality in some areas, especially in the central and lower parts of the basin. Pollution due to pesticides is also relevant in some parts of this river (Terrado *et al* 2010). Finally, the Evrotas basin was affected by overexploitation of water resources for irrigation, agro-industrial wastes (mainly oil mills) and agrochemical pollution (Navarro-Ortega *et al* 2015). Overexploitation of groundwater aquifers and abstraction from surface water results in the artificial desiccation of parts of the main stream and a number of tributaries, which may pose a risk to groundwater-dependent ecosystems (Skoulikidis *et al* 2011).

The Ebro River basin appeared to be the most vulnerable to habitat degradation under global change. This is a Mediterranean basin with a strong water scarcity and a high pressure for irrigation (Boithias *et al* 2014). The vulnerability to climate change of those areas suffering from water deficit has been already discussed (Vörösmarty *et al* 2010, Schröter *et al* 2005). For example, Boithias *et al* (2014) analyzed the sensitivity of the supply:demand ratio to climate extremes in the Ebro River basin, and could identify serious problems in the near future if the current demand is increased because of irrigation. The Evrotas River basin is also a Mediterranean basin characterized by high water scarcity (figure 1), and it is therefore likely that habitat vulnerability becomes close to that in the Ebro. The Mediterranean region has been indicated as one of the most vulnerable areas to climate change (Schröter *et al* 2005, Reidsma *et al* 2006, Markovic *et al* 2014). Mediterranean ecosystems are expected to experience a large biodiversity loss because of their sensitivity to all drivers of biodiversity change, especially land use change (Sala *et al* 2000).

Regarding the future irrigation scenarios, those involving drier conditions have a much stronger impact on the extent of irrigated areas than scenarios involving wetter conditions. The rationale behind that is that climate impacts under dry conditions lead to negative influences on crop yields and, in turn, this leads to an increasing demand for irrigated area to fulfill the crop production goals (Schaldach *et al* 2012). This higher increase of irrigation areas under drier conditions is also responsible for the higher habitat degradation obtained under 'dry' scenarios. Note that the resulting habitat degradation under drier conditions could be probably lower if more moderate scenarios of irrigation, such as the SuE scenario, had also been assessed (see section 4.1).

4.3. Implications of the results obtained

Our work highlights water-stressed basins as the most prone to be impacted by irrigation, especially under global change scenarios involving drier conditions. Ecosystems under stress are the ones to show quicker and more acute reactions to climate change (Staudt *et al* 2013). For example, an analysis of different empirical studies determined that biodiversity was more likely to be negatively affected by habitat loss in areas where precipitation rates had been modified (Mantyka-Pringle *et al* 2012). These results reflect the need for effective adaptation in regions identified as most vulnerable (Motha 2007, Falloon and Betts 2010, Lal *et al* 2011). Particularly in these regions, it will be useful to understand how multiple threats interact as the magnitude of climate change increases. Agriculture has been identified as the main driver of biodiversity loss and a major contributor to climate change and pollution. Agricultural expansion is therefore undesirable (Foley *et al* 2011, Bajzelj *et al* 2014), particularly if it involves an increase of irrigation areas, that directly impacts habitat quality and biodiversity (Reidsma *et al* 2006, Alkemade *et al* 2009, Pfister *et al* 2011, Verones *et al* 2012, Terrado *et al* 2016b). Hydrological planning can be regarded as a tool to help reduce the basins' vulnerability to climate change (García-Vera 2013, Grantham *et al* 2013). Farmers are one of the collectives that will need to adapt their crop production systems to the changing temperature and precipitation regimes. Different strategies for increasing water use efficiency in agriculture have been already identified. For instance, a decrease in evapotranspiration could be achieved by soil preparation (i.e. mulching) or by adaptation of crop selection (i.e. crop tolerant varieties) and management (Falkenmark and Rockström 2006). Other measures are the introduction of pricing mechanisms to avoid a waste of irrigation water (Thomas 2008) and a more efficient irrigation scheduling, consisting in adaptation measures such as moving sowing dates (Schaldach *et al* 2012). In the particular case of the Ebro River basin, water resources can decrease by 15%–35% by 2050, mainly during spring and summer, involving severe water shortages for irrigation agriculture (Milano *et al* 2013). A substantial decrease in irrigated land (up to 30%) has been predicted to result only in moderate losses of crop production (Quiroga *et al* 2011). Therefore, decreases of irrigated land have already been suggested as a mitigation and adaptation strategy to the effects of climate change (Quiroga *et al* 2011, Boithias *et al* 2014).

Unlike studies performed at the scale of major river basins, countries or biomes, the identification of threat sources and the assessment of habitat quality at a scale that matches environmental management objectives (i.e. the water body, management unit in the EU WFD) is advisable. Vulnerable areas present higher threats to water availability and their management may lead to a conflict among different socio-economic actors, aggravated by climate change impacts on ecological, economic and social components of human-environment systems. Providing assessments on habitat quality can assist decision-makers to prioritize management actions for biodiversity conservation.

Although these results have been obtained for the basins analyzed in our study, they can be extrapolated to other systems of the global south, where this type of message is urgently needed. In fact, the negative effects derived from the increase of irrigation in water-stressed areas will also be observed in any river basin where an increase of irrigation area will be planned. Thus, coping with food demand of an increased population while minimizing the impacts of crop production (i.e. through the mentioned strategies of water use efficiency), is therefore an upcoming challenge. One major suggestion is to promote crop installations where they have the greatest impact on productivity and are more environmentally efficient, but to limit them where they produce the highest affectation on habitat quality (Tulloch *et al* 2015, Terrado *et al* 2016a). Proceeding that way would be a major step towards balancing food security and biodiversity protection in vulnerable areas.

Acknowledgments

This research was supported by the EC 7th Framework Programme (GLOBAQUA; 603629-ENV-2013-6.2.1) and from a Juan de la Cierva fellowship from the MINECO (MT). The authors acknowledge Laura Vergonyós from the Catalan Institute for Water Research for helping with GIS and data collection, Dr Rüdiger Schaldach from the University of Kassel for providing the rasters with irrigation scenarios used in the analysis and Dr Louis Vardakas from the Hellenic Center for Marine Research and Dr Momir Paunović from the University of Belgrade for facilitating data for the Evrotas and Sava basins respectively. The Hydrological Confederation from the Ebro basin and the Sava Commission are also acknowledged for data sharing. Finally, we are grateful to all the anonymous survey respondents for the information provided.

Appendix

A.1. Maps of future irrigation scenarios

We used the scenarios of irrigated areas obtained by the EU FP-6 Project SCENES (Schaldach *et al* 2012). In the mentioned study, four socio-economic scenarios were created involving a group of stakeholders within a participatory scenario development process. From those scenarios, we selected the 'EcF' scenario for our work. In the EcF scenario the economy develops toward globalization and liberalization, so innovations spread but income inequality, immigration and urban sprawl cause social tensions. Global demand for food and bio-fuels from Europe drives the further industrialization of agriculture with large farm units. As the Common Agricultural Policy (CAP) is weakened and subsidy payments are drastically cut-off, farms are abandoned where crop production is uneconomic. Until 2050 inequalities between regions predominate and represent a rather pessimistic view on future crop yield developments. Nevertheless, total crop production is growing by 29%. While the EU is exporting agricultural goods to the world market, the other countries (Eastern Europe, Northern Africa and Western Asia) predominantly aim at fulfilling their domestic food demand. The economic activity continues to grow over the whole scenario period.

The EcF scenario was combined with the IPCC SRES A2 emission scenario to account for the effect of climate change until 2050. Under this emission scenario, the atmospheric CO_2 concentration increases up to 492 ppm. In order to represent the variability between different global climate models, Schaldach *et al* (2012) selected the climate output from two Global Circulation Models (GCMs): IPCM4 and MIMR. Both selected scenarios show a high increase of temperature but have large differences in precipitation thus representing 'dry' and 'wet' climate conditions. The authors also improved the spatial information density of the coarse resolution GCM outputs by scaling the values with another high resolution dataset developed by the Climate Research Unit of the University of East Anglia, UK. Simulations using LandSHIFT were performed taking into account the respective combination of socio-economic scenarios and the climate change data from the two GCM models. In the case of

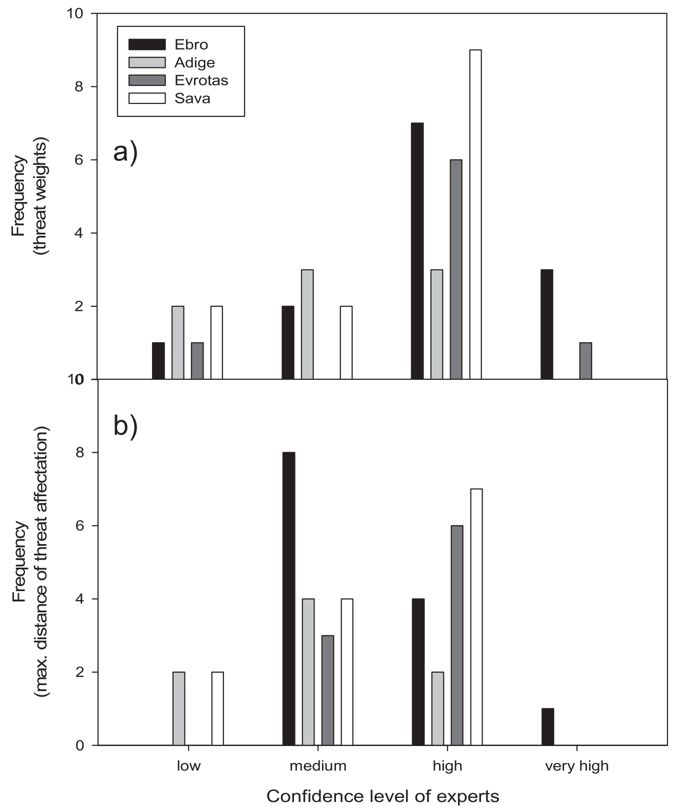

Figure A.1. Level of confidence of the parameters obtained by expert knowledge: (a) threat weights and (b) maximum distance of threat affectation for each of the river basins.

Table A.1. Values provided by experts for the relative weight (W_r) of the threats considered in the four study basins and level of confidence on the values provided (CW). Threats: Agr-agriculture, Urb-urbanization, Min-mining, Road-roads, Abs-water abstraction, Disch-wastewater discharges, Dam-dams, Chan-channeling.

		W_r [0–1]								
Basin	Respondent	Agr	Urb	Min	Road	Abs	Disch	Dam	Chan	CW
Ebro	R1	0.4	0.3	0.4	0.2	0.5	0.7	0.4	0.2	2
	R2	0.5	0.4	0.3	0.3	0.8	0.8	0.9	0.6	5
	R3	0.2	0.2	0.9	0.3	0.8	0.5	0.9	0.9	5
	R4	0.6	0.5	0.1	0.1	0.6	0.2	1	0.4	5
	R5	0.5	0.5	0.8	0.1	0.3	0.2	0.8	0.3	3
	R6	0.5	0.2	0.1	0.1	0.4	0.3	—	0.7	4
	R7	0.5	0.2	0.2	0.1	0.6	0.7	0.8	0.5	4
	R8	0.8	0.4	0.6	0.4	0.8	0.6	0.8	0.2	4
	R9	0.6	0.8	0.2	0.3	0.2	0.4	0.6	0.3	4
	R10	0.9	0.9	0.8	0.3	0.7	0.9	1	0.3	3
	R11	0.8	0.6	0.4	0.2	0.4	0.6	0.9	0.5	4
	R12	0.8	0.3	0.8	0.1	1	0.3	1	0.8	4
	R13	—	0.2	0.1	0.2	0.8	0.4	0.9	—	4
Adige	R1	0.6	0.5	0.2	0.2	0.2	0.4	0.7	0.8	3
	R2	0.5	—	—	—	—	0.1	0.8	—	4
	R3	0.5	0.1	0	0.3	0.5	0.5	1	0.4	4
	R4	0.9	0.7	0.1	0.5	0.6	0.8	0.7	0.6	3
	R5	0.4	0.1	0.2	0	0.5	0.4	0.8	0.1	4
	R6	0.2	0.2	0	0.1	0.3	0.2	0.3	0.3	2
	R7	1	0.7	0.2	0.3	0.6	0.8	1	0.6	3
	R8	0.3	0.2	0.1	0.1	0.5	0.5	0.5	0.2	2
Evrotas	R1	0.6	0.3	0.5	0.4	0.9	0.5	0.2	0.4	4
	R2	0.7	0.4	0	0.2	0.9	1	0	0.3	5
	R3	0.8	0.2	0	0.4	1	0.9	0	0.5	4
	R4	0.8	—	—	—	0.8	0.8	—	—	2
	R5	0.4	0.1	0	0.2	0.8	0.2	0	0.4	4
	R6	0.9	0.3	0.1	0.1	0.9	0.4	0.1	0.2	4
	R7	0.7	0.1	0.7	0.8	1	0.2	0.7	0.9	4
	R8	0.4	0.3	0.1	0	0.6	0.7	0	0.2	3
	R9	0.5	0.3	0.1	0	—	—	0	0.2	4
Sava	R1	0.6	0.8	0.3	0.2	0.3	0.8	0.6	0.5	4
	R2	0.6	0.8	0.3	0.2	0.2	0.8	0.6	0.5	4
	R3	0.6	0.6	0.4	0.3	0.5	0.5	0.7	0.7	4
	R4	0.6	0.8	0.5	0.3	0.4	0.3	0.8	0.6	4
	R5	0.9	0.8	0.4	0.3	0.4	0.5	0.6	0.5	3
	R6	0.9	0.8	0.4	0.3	0.4	0.5	0.6	0.5	3
	R7	0.4	0.9	0.6	0.4	0.5	0.7	0.9	0.7	4
	R8	0.2	0.4	0	0.4	0.1	0.1	0.2	0.4	4
	R9	0.8	0.7	0.2	0.1	0.3	0.7	0.7	0.6	4
	R10	0.9	0.8	0.5	0.2	0.1	1	0	0.2	2
	R11	0.8	0.6	0.5	0.4	0.2	0.8	0.4	0.4	2
	R12	0.3	0.4	0.5	0.3	0.3	0.9	0.4	0.3	4
	R13	0.4	0.3	0.1	0.1	0	0.3	0	0.5	4

the scenario without climate change (no CC) the simulation only took into account the socio-economic drivers from the EcF scenario in form of irrigated crop production and technological change, while climate data was taken from the reference period (1961–1990). In the 'dry' and 'wet' scenarios, the runs were performed combining the socio-economic scenario with the two climate change scenarios provided by the IPCM4 and MIMR GCMs.

Apart from the reference scenario EcF, a policy scenario called Sustainability Eventually (SuE) was developed in SCENES, which reflects a different view of the future. This scenario was not used in the analysis presented in this work, but we need to be aware of the wide range of potential future development pathways in the agricultural sector. Under SuE, Europe transforms from a globalized, market-oriented to an environmentally sustainable society. Land-use changes in general promote greater biological diversity. Total crop production is increasing by 6.9% with large regional differences. A decrease of population is projected for Europe.

A.2. Maps of future habitat types

Maps of future habitat types in the study basins were generated using the future global change scenarios of irrigation. Thus, current areas of irrigation agriculture in the CORINE LU/LC map were adjusted according to the predictions of the global change scenarios of irrigation. Note that irrigation agriculture was initially defined as the aggregation of different crops presenting higher water requirements to grow than other crops. However, these crops may be rain fed in particular areas characterized by higher precipitation during the crop growing period, and these differences have not been taken into account in our analysis. Variation in irrigation areas was implemented contiguous to the current irrigated areas. Non-irrigation agriculture, grassland/shrubland and forest habitat types could be transformed from or into irrigation agriculture. We also considered changes in threats related to irrigation, namely agriculture and water abstraction, because changes in the relative area of irrigation and non-irrigation agriculture occurred together with variations in the required volume of water for irrigation.

In the Ebro River basin, both increases and decreases were predicted depending on the location of the different sub-basins and the climate scenarios. The IPCM4 scenario was dominated by an increase of the irrigated area, especially in sub-basins close to the river source (North-West) and in the central part of the basin, although a decrease of irrigated area was also observed in some sub-basins. Increases in irrigation were lower in the MIMR than in the IPCM4 scenario and concentrated in sub-basins located in the center of the basin, North and South from the river main course. A generalized decrease of the irrigated area was predicted for the scenario without climate change. In the Sava basin, a generalized increase of irrigated area was predicted in all climate scenarios, although this decrease was much lower than in the Ebro basin. In the Adige basin, a decrease of irrigated area dominated at the lower river course. The highest decrease occurred in the scenario without climate change. Only in the IPCM4 scenario a slight increase of irrigated area was predicted in some northern areas. In the Evrotas basin, no change of irrigated areas could be assessed due to

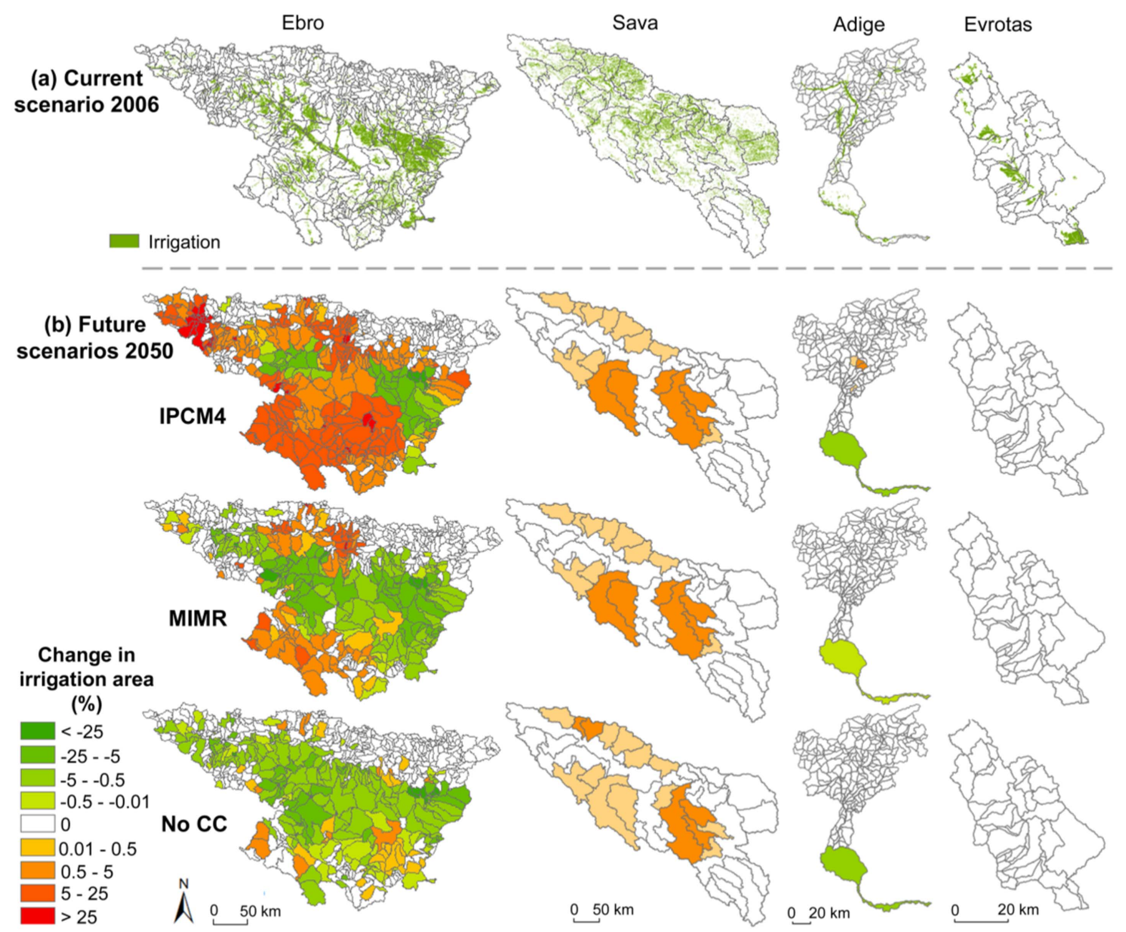

Figure A.2. Irrigated area in the four study basins (a) under current conditions and (b) change in the irrigated area under the future Economy First scenario (EcF) projected for year 2050 for Europe. Future scenarios are presented in combination with different assumptions for climate change: IPCM4 or 'dry' scenario, MIMR or 'wet' scenario and no climate change or 'no CC' scenario.

Table A.2. Values provided by experts for the maximum distance of affectation (Max*D*) of the threats considered in the four study basins and level of confidence on the values provided (CW). Threats: Agr-agriculture, Urb-urbanization, Min-mining, Road-roads, Abs-water abstraction, Disch-wastewater discharges, Dam-dams, Chan-channeling.

		Max*D* (Km)								
Basin	Respondent	Agr	Urb	Min	Road	Abs	Disch	Dam	Chan	CW
Ebro	R1	3–5	0–3	5–10	0	0–3	3–5	10–15	0	3
	R2	15–30	0–3	3–5	0–3	15–30	10–15	30		4
	R3	0–3	0–3	15–30	0–3	30	30	30		5
	R4	5–10	0–3	0	0	3–5	0–3	15–30		4
	R5	—	—	—	—	—	—	—		3
	R6	3–5	0–3	5–10	0–3	3–5	5–10	15–30		3
	R7	30	15–30	—	5–10	30	10–15	30		3
	R8	5–10	5–10	5–10	5–10	10–15	10–15	15–30		3
	R9	15–30	5–10	3–5	3–5	3–5	3–5	30		4
	R10	30	30	15–30	—	—	30	15–30		3
	R11	15–30	5–10	5–10	0–3	30	10–15	30		4
	R12	30	15–30	15–30	0–3	30	5–10	30		3
	R13	15–30	5–10	3–5	0–3	10–15	5–10	15–30		3
Adige	R1	15–30	3–5	3–5	0–3	15–30	15–30	15–30	0	3
	R2	15–30	—	—	—	—	—	15–30		4
	R3	15–30	3–5	0	0–3	3–5	5–10	30		4
	R4	15–30	5–10	0	0–3	0–3	10–15	15–30		3
	R5	5–10	0–3	0–3	0	5–10	15–30	30		3
	R6	0–3	0–3	0	0–3	0	0	0		2
	R7	30	10–15	0	0–3	15–30	15–30	15–30		3
	R8	3–5	3–5	0–3	0–3	0	0	0		2
Evrotas	R1	30	10–15	15–30	10–15	30	15–30	10–15	0	4
	R2	5–10	0–3	0	0–3	30	10–15	0		4
	R3	15–30	15–30	0	0–3	15–30	15–30	0		4
	R4	10–15	—	—	—	3–5	10–15	—		3
	R5	30	0–3	0	0–3	30	3–5	0		4
	R6	30	0–3	0–3	0–3	30	10–15	0–3		3
	R7	30	0	0–3	0	30	3–5	3–5		3
	R8	30	10–15	0	0	30	15–30	0		4
	R9	30	10–15	0	0	30	30	0		4
Sava	R1	30	30	5–10	0	0	30	30	0	4

Table A.2. (Continued.)

Basin	Respondent	MaxD (Km)								
		Agr	Urb	Min	Road	Abs	Disch	Dam	Chan	CW
	R2	30	30	5–10	0–3	0–3	30	30		4
	R3	30	30	10–15	30	10–15	30	30		4
	R4	5–10	15–30	10–15	0–3	30	10–15	30		4
	R5	—	—	3–5	5–10	5–10	10–15	10–15		3
	R6	30	30	3–5	5–10	5–10	10–15	10–15		3
	R7	0	0–3	0–3	0	0	0–3	0		3
	R8	10–15	30	0	5–10	3–5	3–5	10–15		3
	R9	30	30	5–10	3–5	5–10	30	30		4
	R10	30	30	0	—	0	0	—		2
	R11	30	30	15–30	10–15	10–15	30	10–15		2
	R12	5–10	10–15	30	3–5	10–15	30	30		4
	R13	30	15–30	0	30	0	30	0		4

Table A.3. Mean values for habitat suitability (H_j) and relative sensitivity of habitat types to threats (S_{jr}). Values obtained from Terrado *et al* (2016b) using expert knowledge.

		Relative sensitivity of habitat types to threats (S_{jr})							
Habitat type	H_j [0–1]	Agr	Urb	Min	Road	Abs	Disch	Dam	Chan
Urban	0.15	0.16	0.01	0.19	0.10	—	—	—	—
Agric-NI	0.55	0.01	0.72	0.63	0.58	—	—	—	—
Agric-I	0.40	0.03	0.69	0.65	0.59	—	—	—	—
Grass-/Shrubland	0.72	0.67	0.75	0.68	0.70	—	—	—	—
Forest	0.93	0.70	0.85	0.72	0.78	—	—	—	—
Reservoirs	0.33	0.61	0.42	0.64	0.29	0.60	0.72	0.06	0.14
Stream size1	0.66	0.94	1.00	0.96	0.88	1.00	1.00	1.00	1.00
Stream size2	0.70	0.84	1.00	0.89	0.78	0.96	0.97	1.00	0.94
Stream size3	0.76	0.79	0.96	0.82	0.70	0.84	0.86	0.90	0.85
Stream size4	0.80	0.71	0.91	0.76	0.65	0.73	0.76	0.80	0.77

the resolution of the future scenarios used for year 2050.

References

Alkemade R, van Oorschot M, Miles L, Nellemann C, Bakkenes M and ten Brink B 2009 GLOBIO3: a framework to investigate options for reducing global terrestrial biodiversity loss *Ecosystems* **12** 374–90

Araújo M B, Nogués-Bravo D, Reginster I, Rousenvell M and Whittaker R J 2008 Exposure of European biodiverstiy to changes in human-induced pressures *Environ. Sci. Policy* **11** 38–45

Bajzelj B, Richards K S, Allwood J M, Smith P, Dennis J S, Curmi E and Gilligan C A 2014 Importance of food-demand management for climate mitigation *Nat. Clim. Change* **4** 924–9

Bellard C, Bertelsmeier C, Leadley P, Thuiller W and Courchamp F 2012 Impacts of climate change on the future of biodiversity *Ecol. Lett.* **15** 365–77

Biggs R, Simons H, Bakkenes M, Scholes R J, Eickhout B, van Vuuren D and Alkemade R 2008 Scenarios of biodiversity loss in southern Africa in the 21st century *Glob. Environ. Change—Hum. Policy Dimens.* **18** 296–309

Boithias L, Acuña V, Vergoñós L, Ziv G, Marcé R and Sabater S 2014 Assessment of the water supply:demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives *Sci. Total Environ.* **470–471** 567–77

Brook B W, Sodhi N S and Bradshaw C J A 2008 Synergies among extinction drivers under global change *Trends Ecol. Evol.* **23** 453–60

Cazemier M M, Querner E P, van Lanen H A J, Gallart F, Prat N, Tzoraki O and Froebrich J 2011 Hydrological analysis of the Evrotas basin, Greece. Low flow characterization and scenario analysis *Alterra Report* 2249 Wageningen

De Baan L, Curran M, Rondinini C, Visconti P, Hellweg S and Koellner T 2015 High-resolution assessment of land use impacts on biodiversity in life cycle assessment using species habitat suitability models *Environ. Sci. Technol.* **49** 2237–44

Del Barrio G, Harrison P A, Berry P M, Butt N, Sanjuan M, Pearson R G and Dawson T P 2006 Integrating multiple modelling approaches to predict the potential impacts of climate change on species' distributions in contrasting regions: comparison and implications for policy *Environ. Sci. Policy* **9** 129–47

EC 2000 Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy, Official Journal of the European Communities, Luxembourg

EEA 2005 *European Environment Outlook* (Copenhagen: European Environment Agency)

EEA 2012 *The Impacts of Invasive Alien Species in Europe* (Copenhagen: European Environment Agency)

EEA 2015 The European environment *State and Outlook 2015: Synthesis report* (Copenhagen: European Environment Agency)

EEC 1992 Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. The Council of the European Communities, Brussels

Evans M C, Watson J E M, Fuller R A, Venter O, Bennett S C, Marsack P R and Possingham H P 2011 The spatial distribution of threats to species in Australia *BioScience* **61** 281–9

Falkenmark M and Rockström J 2006 The new blue and green water paradigm: breaking new ground for water resources planning and management *J. Water Resour. Plan. Manage.* **132** 129–32

Falloon P D and Betts R A 2010 Climate impacts on European agriculture and water management in the context of adaptation and mitigation—the importance of an integrated approach *Sci. Total Environ.* **408** 5667–87

Foley J A *et al* 2011 Solutions for a cultivated planet *Nature* **478** 337–42

García-Vera M A 2013 The application of hydrological planning as a climate change adaptation tool in the Ebro basin *Int. J. Water Resour. Dev.* **29** 219–36

Grantham T E, Figueroa R and Prat N 2013 Water management in mediterranean river basins: a comparison of management frameworks, physical impacts and ecological responses *Hydrobiologia* **719** 451–82

Griffiths S P, Kuhnert P M, Venables W N and Blaber S J M 2007 Estimating abundance of pelagic fishes using gillnet catch data in data-limited fisheries: a Bayesian approach *Can. J. Fisheries Aquatic Sci.* **64** 1019–33

Halpern B S *et al* 2008 A global map of human impact on marine ecosystems *Science* **319** 948–52

Harte J 2007 Human population as a dynamic factor in environmental degradation *Population Environ.* **28** 223–36

IPCC 2007 Climate change 2007: the physical science basis *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge, UK

Janse J H, Kuiper J J, Weijters M J, Westerbeek E P, Jeuken M H J L, Bakkenes M, Alkemade R, Mooij W M and Verhoeven J T A 2015 GLOBIO-aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems *Environ. Sci. Policy* **48** 99–114

Jetz W, Wilcove D S and Dobson A P 2007 Projected impacts of climate and land-use change on the global diversity of birds *PLoS Biol.* **5** e157

Kareiva P, Tallis H, Ricketts T, Daily G C and Polasky S 2011 *Natural Capital: Theory and Practice of Mapping Ecosystem Services* (New York: Oxford University Press)

Kuhnert P M, Martin T G and Griffiths S P 2010 A guide to eliciting and using expert knowledge in Bayesian ecological models *Ecol. Lett.* **13** 900–14

Lal R, Delgado J A, Groffman P M, Millar N, Dell C and Rotz A 2011 Management to mitigate and adapt to climate change *J. Soil Water Conservation* **66** 276–85

Leadley P, Pereira H M, Alkemade R, Fernandez-Manjarrés J F, Proença V, Scharlemann J P W and Walpole M J 2010 Biodiversity scenarios: projections of 21st century change in biodiversity and associated ecosystem services *Technical Series* No.50 Secretariat of the Convention on Biological Diversity, Montreal

Macleod C J A and Haygarth P M 2010 Integrating water and agricultural management under climate change *Sci. Total Environ.* **408** 5619–22

Mantyka-Pringle C S, Martin T G and Rhodes J R 2012 Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis *Glob. Change Biol.* **18** 1239–52

Markovic D, Carrizo S, Freyhof J, Cid N, Lengyel S, Scholz M, Kasperdius H and Darwall W 2014 Europe's freshwater biodiversity under climate change: distribution shifts and conservation needs *Diversity Distrib.* **20** 1097–107

Metzger M J, Bunce R G H, Leemans R and Viner D 2008 Projected environmental shifts under climate change: European trends and regional impacts *Environ. Conservation* **35** 64–75

Metzger M J, Leemans R and Schröter D 2005 A multidisciplinary multi-scale framework for assessing vulnerabilities to global change *Int. J. Appl. Earth Obs. Geoinf.* **7** 253–67

Milano M, Ruelland D, Dezetter A, Fabre J, Ardoin-Bardin S and Servat E 2013 Modeling the current and future capacity of water resources to meet water demands in the Ebro basin *J. Hydrol.* **500** 114–26

Motha R P 2007 Development of an agricultural weather policy *Agric. Forest Meteorol.* **142** 303–13

Navarro-Ortega A *et al* 2015 Managing the effects of multiple stressors on aquatic ecosystems under water scarcity. The GLOBAQUA project *Sci. Total Environ.* **503–504** 3–9

Nelson E *et al* 2009 Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales *Frontiers Ecol. Environ.* **7** 4–11

Pfister S, Bayer P, Koehler A and Hellweg S 2011 Projected water consumption in future global agriculture: scenarios and related impacts *Sci. Total Environ.* **409** 4206–16

Quiroga S, Fernández-Haddad Z and Iglesias A 2011 Crop yields response to water pressures in the Ebro basin in Spain: risk and water policy implications *Hydrol. Earth Syst. Sci.* **15** 505–18

Randin C F, Engler R, Normand S, Zappa M, Zimmermann N E, Pearman P B, Vittoz P, Thuiller W and Guisan A 2009 Climate change and plant distribution: local models predict high-elevation persistence *Glob. Change Biol.* **15** 1557–69

Reidsma P, Tekelenburg T, van den Berg M and Alkemade R 2006 Impacts of land-use change on biodiversity: an assessment of agricultural biodiversity in the European Union *Agric. Ecosyst. Environ.* **114** 86–102

Sala O E *et al* 2000 Global biodiversity scenarios for the year 2100 *Science* **287** 1770–4

Sanderson E W, Jaiteh M, Levy M A, Redford K H, Wannebo A V and Woolmer G 2002 The human footprint and the last of the wild *BioScience* **52** 891–904

Schaldach R, Alcamo J, Koch J, Kölking C, Lapola D M, Schüngel J and Priess J A 2011 An integrated approach to modelling land use change on continental and global scales *Environ. Modelling Softw.* **26** 1041–51

Schaldach R, Koch J, aus der Beek T, Kynast E and Flörke M 2012 Current and future irrigation water requirements in pan-Europe: an integrated analysis of socio-economic and climate scenarios *Glob. Planet. Change* **94–95** 33–45

Schinegger R, Trautwein C, Melcher A and Schmutz S 2012 Multiple human pressures and their spatial patterns in European running waters *Water Environ. J.* **26** 261–73

Schröter D *et al* 2005 Ecosystem service supply and vulnerability to global change in Europe *Science* **310** 1333–7

Skoulikidis N T, Vardakas L, Karaouzas I, Economou A N, Dimitriou E and Zogaris S 2011 Assessing water stress in Mediterranean lotic systems: insights from an artificially intermittent river in Greece *Aquatic Sci.* **73** 581–97

Staudt A, Leidner A K, Howard J, Brauman K A, Dukes J S, Hansen L J, Paukert C, Sabo J and Solórzano L A 2013 The added complications of climate change: understanding and managing biodiversity and ecosystems *Frontiers Ecol. Environ.* **11** 494–501

Tallis H *et al* 2011 InVEST 2.4.4 User's Guide. The Natural Capital Project, Stanford

Terrado M, Barceló D and Tauler R 2010 Multivariate curve resolution of organic pollution patterns in the Ebro River surface water-groundwater-sediment-soil system *Anal. Chim. Acta* **657** 19–27

Terrado M, Momblanch A, Bardina M, Boithias L, Munné A, Sabater S, Solera A and Acuña V 2016a Integrating ecosystem services in river basin management plans *J. Appl. Ecol.* **53** 865–75

Terrado M, Sabater S, Chaplin-Kramer B, Mandle L, Ziv G and Acuña V 2016b Model development for the assessment of terrestrial and aquatic habitat quality in conservation planning *Sci. Total Environ.* **540** 63–70

Thomas A 2008 Agricultural irrigation demand under present and future climate scenarios in China *Glob. Planet. Change* **60** 306–26

Tulloch V J D *et al* 2015 Why do we map threats? Linking threat mapping with actions to make better conservation decisions *Frontiers Ecol. Environ.* **13** 91–9

UNESCO 2009 World water assessment programme *The United Nations World Water Development Report 3: Water in a Changing world* UNESCO and Earthscan, Paris and London

Verboom J, Alkemade R, Klijn J, Metzger M J and Reijnen R 2007 Combining biodiversity modeling with political and economic development scenarios for 25 EU countries *Ecol. Econ.* **62** 267–76

Verones F, Bartl K, Pfister S, Vílchez R J and Hellweg S 2012 Modeling the local biodiversity impacts of agricultural water use: case study of a wetland in the coastal arid area of Peru *Environ. Sci. Technol.* **46** 4966–74

Verones F, Huijbregts M A J, Chaudhary A, de Baan L, Koellner T and Hellweg S 2015 Harmonizing the assessment of biodiversity effects from land and water use within LCA *Environ. Sci. Technol.* **49** 3584–92

van Vuuren D P, Sala O E and Pereira H M 2006 The future of vascular plant diversity under four global scenarios *Ecol. Soc.* **11** 25

Vörösmarty C J *et al* 2010 Global threats to human water security and river biodiversity *Nature* **467** 555–61

Woolmer G, Trombulak S C, Ray J C, Doran P J, Anderson M G, Baldwin R F, Morgan A and Sanderson E W 2008 Rescaling the human footprint: a tool for conservation planning at an ecoregional scale *Landscape Urban Plan.* **87** 42–53

WWF 2014 *Living Planet Report 2014: Summary* ed R McLellan *et al* (Gland, Switzerland: WWF)