Catena 232 (2023) 107460

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Modelling opportunities of potential European abandoned farmland to contribute to environmental policy targets

Catherine M.J. Fayet[a,b], Peter H. Verburg[b,c,*]

[a] International Union for Conservation of Nature (IUCN), European Regional Office, Boulevard Louis Schmidt 64, 1040 Brussels, Belgium
[b] Institute for Environmental Studies (IVM), VU University Amsterdam, De Boelelaan 1111, 1081 HV Amsterdam, The Netherlands
[c] Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland

ARTICLE INFO

Keywords:
Agricultural abandonment
Biodiversity
Abandonment trajectories
Trade-offs
Rewilding
European Green Deal

ABSTRACT

Farmland abandonment is a major proximate driver of landscape change in European rural areas and is often followed by natural revegetation. In certain conditions, it might be preferable to prevent or reverse farmland abandonment or manage these areas towards active restoration (i.e., guided rewilding with wild or domesticated animals). These alternative responses to farmland abandonment lead to context-dependent impacts, which can potentially contribute to European Green Deal objectives for environment and rural areas. While previous studies analysed direct impacts of abandonment, there is little insight into how alternative ways of managing abandoned farmland can best contribute to environmental policy goals, and what type of management is preferred where. To assess opportunities in these areas, we compared three abandonment trajectories: natural revegetation, active restoration with rewilding, and extensive re-farming. We analysed the potential positive and negative environmental and cultural impacts of developing these management strategies in all farmland locations that could potentially be abandoned across Europe. Mapping and quantification of the benefits and risks associated with different management responses to abandonment indicate a large spatial variation across regions. While natural revegetation can support high benefits for carbon sequestration and erosion reduction, it is also linked to more frequent trade-offs than re-farming and rewilding. However, there is a very strong spatial variation in these trade-offs. It is worthwhile to focus on areas with the largest gains and fewest trade-offs when targeting investments for prevention of abandonment or rewilding. Our maps can help inform interventions in abandoned farmland to maximise the potential contributions of these lands to the European Green Deal environmental and rural policy targets.

1. Introduction

Changes in how the land is used are one of the key approaches for meeting the European Union (EU)’s targets for biodiversity and climate change (Kopsieker et al., 2021). This requires restoring degraded areas and reducing land use intensity, particularly in the agriculture sector (Yang et al., 2020). To maximise benefits, these actions need to be implemented at scale (Brown, 2020; IUCN, 2020). In a context of limited land area available and competition for resources, finding sufficient space available with few conflicts between land uses is challenging (Cortina-Segarra et al., 2021; Ockendon et al., 2018). The EU acknowledged the importance of integrating natural solutions in policies and land management to respond to current environmental challenges (European Environment Agency, 2021). The European Green Deal specifically defines objectives for biodiversity protection, climate change mitigation and reviving rural areas (European Commission, 2020a). Farmland abandonment, characterised by the cessation of agricultural activities and return of natural vegetation (under favorable climatic conditions) provides opportunities for ecological restoration and climate change mitigation (Ceausu et al., 2015; Navarro and Pereira, 2012; Yang et al., 2020), especially given the low competition for other uses on these lands.

Despite the various definitions that exist for farmland abandonment (Grădinaru et al., 2015; Pointereau et al., 2008; Terres et al., 2015), there is a general consensus that it includes the cessation of farming activities and gradual return of natural vegetation. Farmland abandonment is complex to map, quantify and predict, hence estimates vary (Estel et al., 2015; Levers et al., 2018; van der Zanden et al., 2017). A

* Corresponding author at: Institute for Environmental Studies (IVM), VU University Amsterdam, De Boelelaan 1111 HV Amsterdam, The Netherlands
E-mail address: p.h.verburg@vu.nl (P.H. Verburg).

https://doi.org/10.1016/j.catena.2023.107460
Received 28 March 2023; Received in revised form 3 August 2023; Accepted 11 August 2023
Available online 19 August 2023

recent study indicated that nearly 56 million hectares (30% of total agricultural lands) in the EU are under at least a moderate risk of farmland abandonment by 2030, with 5 million hectares (3% of agricultural areas) at high likelihood of abandonment (Perpiña Castillo et al., 2018). Agricultural abandonment is therefore an important consideration for rural development policies (Schuh et al., 2020). The main drivers of abandonment include social, economic, and environmental factors (Dax et al., 2021; Rey Benayas et al., 2007; Schuh et al., 2020; Ustaoglu and Collier, 2018). Causes of abandonment can also be categorised into proximate (e.g., poor infrastructure) and underlying drivers (demographic, economic, technological, policy, and cultural factors) (Geist and Lambin, 2002).

The consequences of farmland abandonment depend on local conditions. The socio-economic and cultural impacts are generally negative given the loss of rural economies, traditional knowledge, and cultural landscapes (Dax et al., 2021; Schuh et al., 2020; van der Zanden et al., 2018). Revegetation processes on farmland can increase wildfire risk, landslides, and cause agrobiodiversity to decline (Jones et al., 2016; Lasanta et al., 2015; Regos et al., 2016; van der Zanden et al., 2017). However, abandonment also brings opportunities for ecological restoration (Navarro and Pereira, 2012; Wolff et al., 2018), rewilding (Pereira and Navarro, 2015) with wild or domesticated species (Hall and Bunce, 2019; Perino et al., 2019), and carbon sequestration (Chazdon et al., 2020; Rytter et al., 2016; Schulp et al., 2008).

Various trajectories can develop after an initial state of abandonment, ranging from active to no management (Crawford et al., 2022; Fayet et al., 2022; Munroe et al., 2013). A common approach to studying abandonment trajectories has been to look at them separately, for instance focusing on recultivation (Estel et al., 2015; Meyfroidt et al., 2016), rewilding (Ceausu et al., 2015), afforestation (Chazdon et al., 2020; Freer-Smith et al., 2019), or no management (Broughton et al., 2021; Morel et al., 2020). However, this approach does not allow for comparison of the potential impacts of a more active decision to implement a specific trajectory in a given location.

This paper aims to quantify the benefits and risks of different management responses to potential farmland abandonment across the EU. We hypothesise that the impacts of *post-abandonment* trajectories are context-dependent, leading to different preferential management strategies in different areas. We therefore evaluate the benefits, risks, and trade-offs of different management responses to abandonment, using selected impact indicators that help guide future responses to potential abandonment. We selected different management responses that represent nature-based solutions and contribute to the European Green Deal targets for climate, biodiversity, and rural areas.

2. Material and methods

We modelled the impacts of different management responses and associated trajectories in agricultural lands likely to be abandoned across Europe. Fig. 1 provides an overview of the methods.

2.1. Study area

We identified locations of potential future agricultural abandonment within the EU-27 *plus* the United Kingdom (UK) based on a series of projections of agricultural land abandonment for the period 2000–2040 (van der Zanden et al., 2017). The locations of potential abandonment were determined based on modelling land use change for four alternative scenarios using the Dyna-CLUE land use model. Given the somewhat dated nature of this dataset, we compared it with a more recent land system map (Dou et al., 2021) to ensure that we included only locations currently under agricultural use. The selected area identified by land use modelling as farmland likely to be abandoned covers approximately 160,000 km^2, including locations (pixels at 1 km^2 resolution) of arable lands, grasslands, and farmland mosaics (Appendix A for details).

2.2. Definition of post-abandonment trajectories

We defined three post-abandonment trajectories that could develop as potential management responses to farmland abandonment: Natural Revegetation, active restoration with rewilding and natural grazing (hereafter Rewilding), and reversal (or prevention) of abandonment with extensive re-farming (hereafter Re-Farming). Appendix A provides more details on how we defined these trajectories and their policy

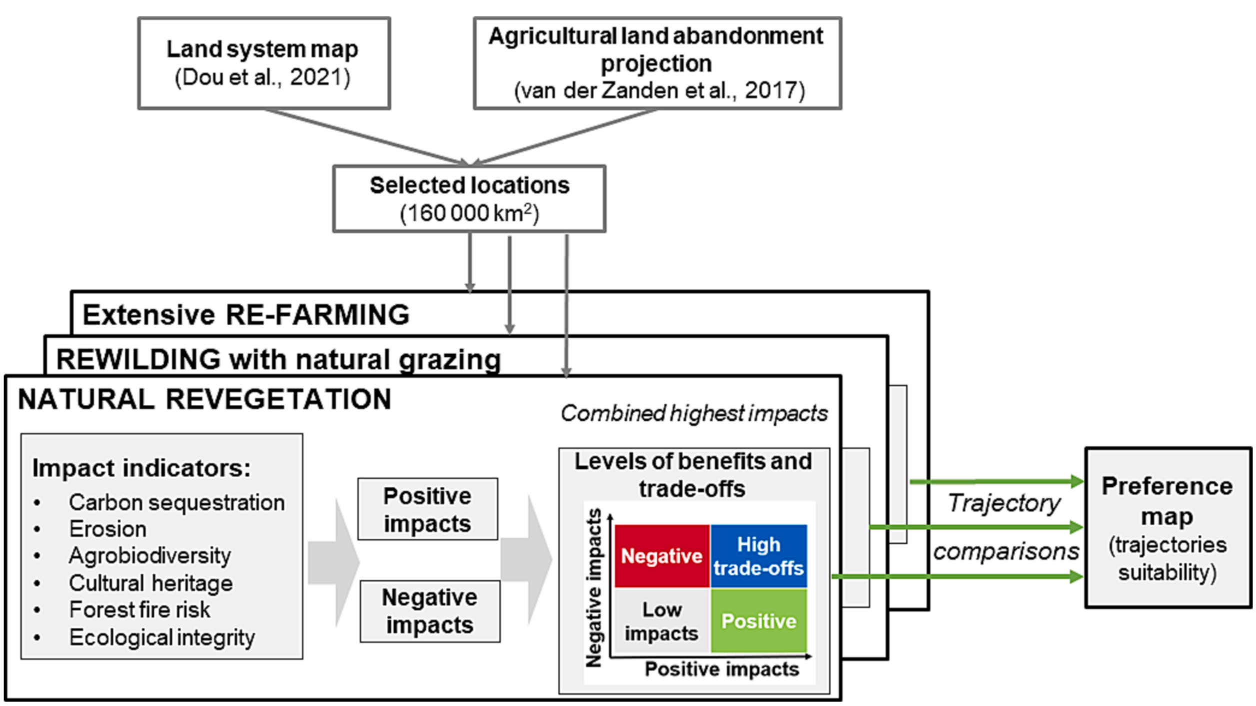

Fig. 1. Overview of the methodological steps for this study to quantify the levels of benefits and risks of the three management responses (trajectories) to agricultural abandonment.

relevance.

In the Natural Revegetation trajectory, we assumed that the development of new land cover on abandoned cells was either forest or shrubland, depending on the time required for re-growth of vegetation. This was based on estimates documented by Verburg and Overmars (2009) who assessed vegetation regrowth based on climatic, terrain and land use indicators calibrated with evidence from case-studies and expert-based contributions. Based on these estimates, we considered a location to become shrubland if a forest would not have regenerated within 30 years in that location. Otherwise, we considered it to be forest. Grassland could also be an outcome of revegetation. However, it is less common than forest and shrubland after several decades without land management (Arnaez et al., 2011; Peña-Angulo et al., 2019; Zakkak et al., 2018). Moreover, herbivore impacts on vegetation re-growth are often an important factor to maintain open landscapes, such as grassland (Malhi et al., 2022; Svenning, 2002). Since the grazing dimension is captured by the Rewilding trajectory, landscape outcomes where grassland dominates were not included in the Natural Revegetation trajectory.

Based on temperate woodland ecosystem models by Malhi et al. (2022), we defined three landscape outcomes for the Rewilding trajectory: closed vegetation (forest or shrubland), mosaic landscape of grassland and forest, and open landscape (grassland or bare land/shrubs depending on the bioclimatic region). We predicted these land classes based on the estimated impact that herbivore grazing, an important component of many rewilding projects, would have on natural vegetation re-growth. Previous studies reported preference of grazers for flat topography and proximity to water, while forest vegetation prevails on slopes (Malhi et al., 2022; Svenning, 2002). We used datasets on topography (Airbus et al., n.d.) and water courses (Dottori et al., 2021) to predict potential interactions between grazing and vegetation re-growth (Verburg and Overmars, 2009) in abandonment locations. We did not account for the difference between domesticated or wild herbivores in the modelling of the feasibility and impacts of the rewilding scenario. In practice, this would require assessing differential suitability conditions for costs, local acceptance, effects on vegetation, as well as and management opportunities and constraints (DeSilvey and Bartolini, 2018; Hall, 2018; Rouet-Leduc et al., 2021). Appendix A provides more information on the modelling of potential herbivore impacts following the Rewilding trajectory.

Dou et al. (2021) identified three intensity classes for arable lands and grasslands, and two intensity classes for permanent crops based on management practices and nitrogen (N) inputs which are used as primary indicators. For the Extensive Re-Farming trajectory, we assumed that the lowest intensity class is applied, corresponding to extensive farming with <50 kg N/ha for cropland, as well as lower livestock densities and reduced mowing frequency on grassland, as defined by Dou et al. (2021). In addition, we also assume that farming in this trajectory includes environmentally friendly practices such as cover cropping, reduction in use of synthetic pesticides and mineral fertilisers, no or minimal tillage, as well as landscape elements such as hedgerows and flower strips. Taken together these practices can be referred to as sustainable agricultural activities that bring biodiversity and environmental benefits (Oberč and Schnell, 2020).

2.3. Assessing impacts of abandonment trajectories

We selected six indicators to quantify changes (impacts) between current conditions and the potential conditions in 30 years' time that would result from management leading to one of the post-abandonment trajectories. In our selection of impacts, we considered policy relevance in terms of contributions to achieving European Green Deal objectives and societal debate on the trade-offs of agricultural abandonment (Merckx and Pereira, 2015; Perino et al., 2019; van der Zanden et al., 2017), as well as data accessibility and feasibility for mapping at European scale (Appendix B). For example, assessing carbon sequestration potential is relevant for climate change mitigation (Griscom et al., 2017) while agrobiodiversity and potential for ecological integrity are useful indicators for the biodiversity targets of the European Green Deal (European Commission, 2019).

The indicators are based on existing models (Table 1) that we modified to the land classification system used in this study. Appendix B provides additional details on the model descriptions and adaptations. Focussing on the change in impact, rather than the absolute impact, does not account for differences in initial conditions, but allows us to assess the potential effects of alternative management responses to abandonment. For Extensive Re-Farming, we assumed no change in carbon sequestration and forest fire risk since the land cover remains stable, and therefore with comparable levels to initial conditions (under farming management). In addition, benefits of extensive agricultural practices for these impacts strongly depend on local conditions and cannot be generalized easily. Since the ecological integrity indicator (Fernández et al., 2020) measures the potential to successfully rewild, it was only relevant for the Natural Revegetation and Rewilding trajectories, but not for Re-Farming as these lands remain under management.

2.4. Analysis

We modelled the potential impacts in the future situation based on the projected outcomes of the post-abandonment trajectories, while assuming stable land use in the surrounding cells. To allow

Table 1
Environmental and cultural impact indicators included to evaluate different post-abandonment trajectories. For each trajectory (NR: Natural Revegetation; REW: Rewilding; EXT: extensive Re-Farming), we indicate the expected direction of change compared to initial conditions (+increase; − decrease; +/− increase or decrease; / stable) and the (normative) judgment of the effect of the impact as positive (pos), negative (neg), stable (stb) based on its contributions to European Green Deal policy ambitions (detailed in Appendix B).

Impact indicator	Description [units]	Reference	Expected direction and effect by trajectory		
			NR	REW	EXT
Carbon sequestration	Change in potential carbon sequestration in aboveground biomass within the next 30 years [Mg C / km^2 / 30 yr]	Based on Cook-Patton et al. (2020)	+ (pos)	+ (pos)	/ (stb)
Soil erosion	Change in mean annual soil loss rate by water erosion [ton/ha/year]	Based on Panagos et al. (2015)	− (pos)	−/+ (pos/neg)	− (pos)
Agro−biodiversity	Change in relative vertebrates and plant species richness on farmland [index]	Based on Overmars et al. (2014)	− (neg)	−/+ (neg/pos)	+ (pos)
Ecological integrity	Ecological potential of agricultural lands to successfully re-wild upon abandonment [index]	Based on Fernández et al. (2020)	+ (pos)	+ (pos)	n.a.
Heritage	Change in cultural value/meaning [index]	Based on Tieskens et al. (2017)	− (neg)	− (neg)	+ (pos)
Forest fire risk	Change in forest wildfire risk [index]	Based on Sueur-Ochoa and Chuvieco (in prep.)	+ (neg)	+ (neg)	/ (stb)

comparability among the impacts of the different trajectories, we applied a min–max *normalisation* method on the raw differences between the start (initial land use values) and end conditions (outcomes of the trajectories). Since some indicators in the Rewilding trajectory had bi-directional impacts, we normalised based on the highest absolute value. Individual impact maps for each trajectory are provided in Appendix C, Section 2.2, showing absolute and normalised differences between initial and outcome conditions for the different trajectories.

From the impact maps, we quantified the highest impacts for each indicator in two different ways: (1) by (arbitrarily) selecting the 25% highest impacts within one trajectory and, (2) by selecting the 25% highest impacts of the specific indicator across the different trajectories. While the first approach highlights which areas face the largest impacts for a specific trajectory, the second one indicates where and under which trajectories the highest impacts occur for a given indicator. Tables C1 and C3 in Appendix C present the thresholds used for each approach. As the threshold is based on 25% of all pixels changing the threshold will linearly increase the area that is meeting this classification. Therefore, no separate sensitivity analysis was conducted.

To characterize the relation between positively and negatively perceived impacts (Table 1), we defined four categories that group the high impacts by their level of benefits, risks, and trade-offs. Each location (pixel) was classified in one of the four categories (Fig. 2). Positive impacts (benefits) refer to locations that score in the top 25% for gains in carbon sequestration, agrobiodiversity, heritage, erosion reduction, and ecological integrity. Negative impacts (risks) refer to locations that score in the top 25% for losses in agrobiodiversity, cultural heritage, and increase in erosion or forest fire risk. Trade-offs refer to the co-occurrence of high positive and high negative impacts in the location. The remaining areas are those with relatively little impact overall. We treated impacts equally and did not give a different weight to specific impacts. Applications in policy context might consider different weights to align with local realities and different national priorities. The resulting maps intend to identify the most suitable locations for each trajectory.

Finally, we aimed to identify which trajectory led to high positive impacts in which locations. To do that, we identified locations that are in the category "high positive impacts' for the individual trajectories (Fig. 2). We applied the same procedure for both threshold approaches (detailed in Appendix C), but only present results of the second one in the main text as it presents the comparison of trajectories in terms of their absolute impacts. In a land management and policy perspective, these maps show the preferred locations for implementation or encouragement of each trajectory (where preference is being understood as indicating high benefits, with no or few negative impacts and trade-offs associated).

3. Results

3.1. Overall impacts

Fig. 3 shows the distribution and direction of change for the indicators in the three post-abandonment trajectories. Impacts of Natural Revegetation and Rewilding are overall larger than those for Re-Farming due to larger changes in land cover that affect ecosystem structure and function. For the maps presented in the main paper (Fig. 4 and Fig. 5), we used a focal statistics method (3 by 3 aggregation) for an improved visualization only. However, all calculations were based on the original data.

Carbon: carbon sequestration gains are overall higher upon Natural Revegetation than Rewilding ($M = 1.23$ and $M = 0.61$ Mg C / km^2 / 30 yr respectively), with generally lower gains around the Mediterranean, South-Eastern Europe, and Scandinavia due to slower tree growth and climate limitations, while the largest benefits are observed in the East-Northern part of Europe (Appendix C – Fig. C.4). However, given differences in vegetation cover, the overall largest benefits are found with Natural Revegetation in the North of Portugal and Spain, Ireland, the UK, Northern France, Germany, Denmark, and Western Austria. The highest gains following Rewilding are limited to Ireland, Wales, Austria, and some locations in the Alps, where grazing impacts are lower.

Erosion: erosion reduction is overall greater with Natural Revegetation than Rewilding and Re-Farming ($M = -6.94$; $M = -5.18$ and $M = -0.36$ ton/ha/year respectively). An increase in erosion with Rewilding occurs in 4% of locations, mostly where grazing reduces permanent crop cover and mosaic forest cover. Natural Revegetation and Rewilding support the strongest erosion reduction in Southern and Eastern Europe, as well as some locations in Northern Europe (Fig. C.5). The largest reductions in erosion with Re-Farming are concentrated in intensive farmland, notably in Central France, Germany, Poland, and the Czech Republic. Due to the difference in land use and cover between trajectories, the overall largest benefits for erosion reduction occur with Natural Revegetation, while the effects of Rewilding and Re-Farming are

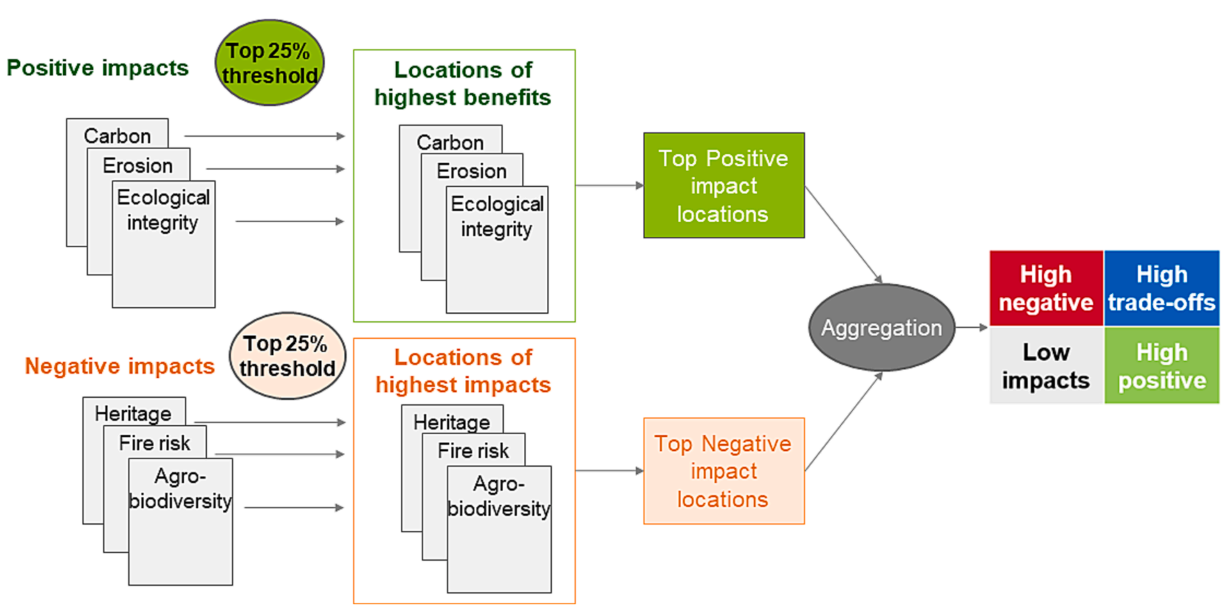

Fig. 2. Steps to identify locations with the highest benefits and risks (top 25%) to build the preference maps. The specific implementation for the different trajectories is detailed in Appendix C.

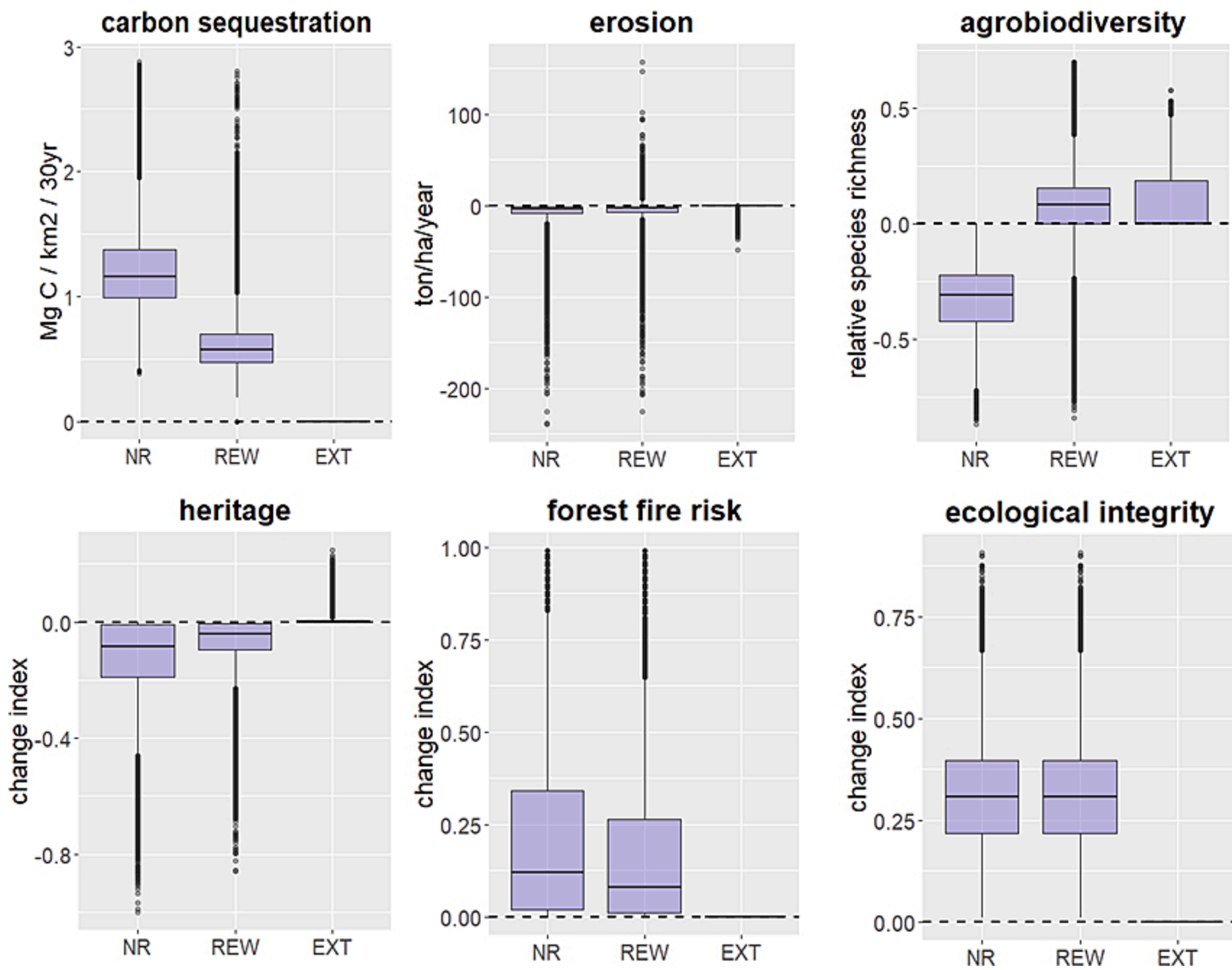

Fig. 3. Distribution of impacts of the different post-abandonment trajectories (NR = Natural Revegetation; REW = Rewilding; EXT = Extensive Re-Farming).

relatively lower.

Agrobiodiversity: the relative species richness indicator increases with Re-Farming ($M = 0.1$) but decreases on average for Rewilding ($M =$ -0.05) and decrease even more with Natural Revegetation ($M =$ -0.33). The benefits of Re-Farming for this indicator dominate in intensive farming regions (Central France, Ireland, Wales, the Netherlands, Poland, and Denmark) whereas they are more scattered across Europe with Rewilding (Fig. C.6). Increases in agrobiodiversity can be higher when Rewilding predicts a mosaic of forests and grasslands on previously intensively managed cropland compared to Re-Farming. Increases in forest cover with Natural Revegetation and Rewilding (when grazing is not sufficient) lead to a decline in agrobiodiversity, with overall higher losses following Natural Revegetation in Spain, Portugal, Italy, Sicily, Austria, Romania, and Estonia. In some places, losses are low, which can often be explained by low initial values. Specifically, if there is little agrobiodiversity before agricultural abandonment, there is relatively little to lose.

Heritage: following different degrees of revegetation, stronger losses in cultural values are expected with Natural Revegetation ($M =$ -0.12) than Rewilding ($M =$ -0.06), whereas Re-Farming is beneficial for maintaining landscapes' heritage values ($M = 0.01$). High initial heritage values combined with relatively large changes in vegetation cover lead to the highest losses of heritage function with Natural Revegetation in central France, Spain, Portugal, Italy, Germany, and Slovakia (Fig. C7). By contrast, these regions show fewer losses following Rewilding given the greater landscape openness. The highest benefits with Re-Farming dominate in intensive farmlands (i.e., France, the UK and Netherlands, North Poland) while fewer changes are observed in Eastern and Southern Europe where farming was mostly already extensive (Fig. C.7).

Forest fire risk: forest fire risk increases on average with Natural Revegetation ($M = 0.22$) and Rewilding ($M = 0.17$), with no change in the Re-Farming trajectory as the landscape structure remains the same (and changing climate conditions are not accounted for in this assessment). Natural Revegetation leads to a higher overall increase in risk, notably in Mediterranean regions, Central France, South-Eastern Europe, the UK, and Ireland (Fig. C8). The more open landscape structure in the Rewilding trajectory mitigates the increased risk for these regions by a lower frequency of high impacts. Increased risk is mostly found in locations where grazing is limited due to local conditions (topography and distance to water).

Ecological integrity: the ecological integrity indicator is not dependent on the trajectories' characteristics (Appendix B) but rather on the position of the location relative to natural areas. Therefore, we observe the same potential increase for Natural Revegetation and Rewilding ($M = 0.32$). The highest values for ecological integrity are observed in North Portugal, South-East France, the Alps, most of Eastern Europe, and Scandinavia (Fig. C.9).

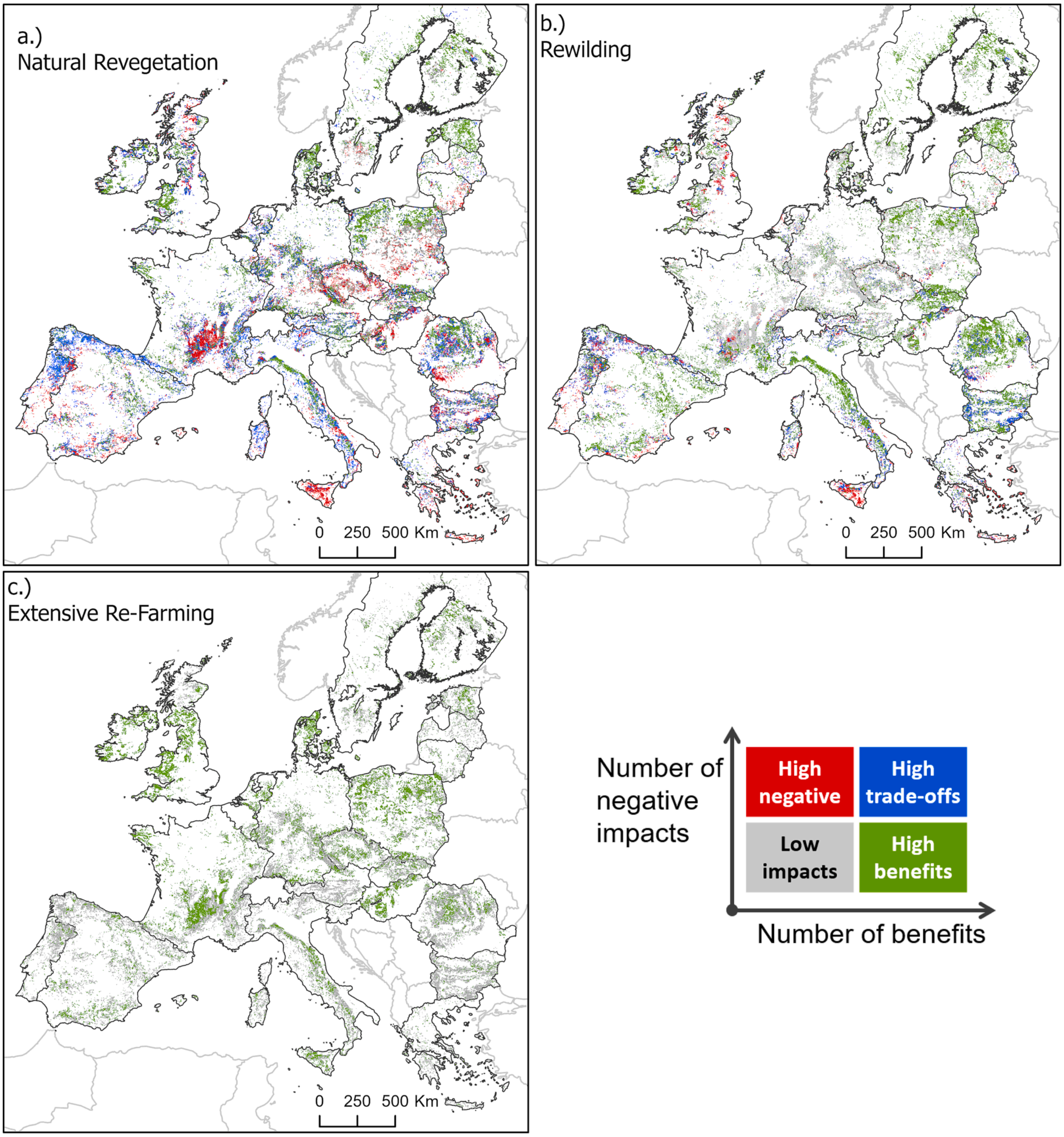

Fig. 4. Levels of benefits, risks (negative impacts), and trade-offs based on the high impact maps for Natural Revegetation (a), Rewilding (b) and Extensive Re-Farming (c).

3.2. Spatial distribution of high impacts

The distribution of high impacts varies depending on how the 25% highest impacts are defined. The results based on the 25% highest impacts within each trajectory are shown in Appendix C, Section 3. Here, we only present and discuss the results based on the 25% highest impacts per indicator across the different trajectories. These results inform, for each indictor, where and under what trajectories the highest impacts occur (see Appendix C, section 4 for detailed individual maps).

The highest impacts with Natural Revegetation (Fig. 4a and Table 2) include benefits (36% of locations), followed by trade-offs (33% of locations) and negative impacts (24% of locations). Benefits are mostly due to carbon sequestration and erosion reduction (outside fire prone and agrobiodiversity rich areas). High negative impacts dominate in France, the south of Spain, north of Portugal, Sicily, and Eastern Europe particularly due to fire risk, agrobiodiversity, and landscape heritage losses. Co-occurrence of these high positive and negative impacts leads to trade-offs.

In half of the locations, Rewilding leads to high benefits, while negative impacts and trade-offs are less frequent (in 8% and 15% of locations) (Fig. 4b and Table 2). In Eastern Europe, benefits often include agrobiodiversity gains combined with ecological integrity, while they mostly include erosion reduction and carbon sequestration in Mediterranean regions. Rewilding leads to fewer trade-offs than the other trajectories. They prevail where grazing is insufficient to mitigate the negative impacts of revegetation, like in Northern Italy and Austria where trade-offs occur between losses in agrobiodiversity and heritage and gains in carbon sequestration.

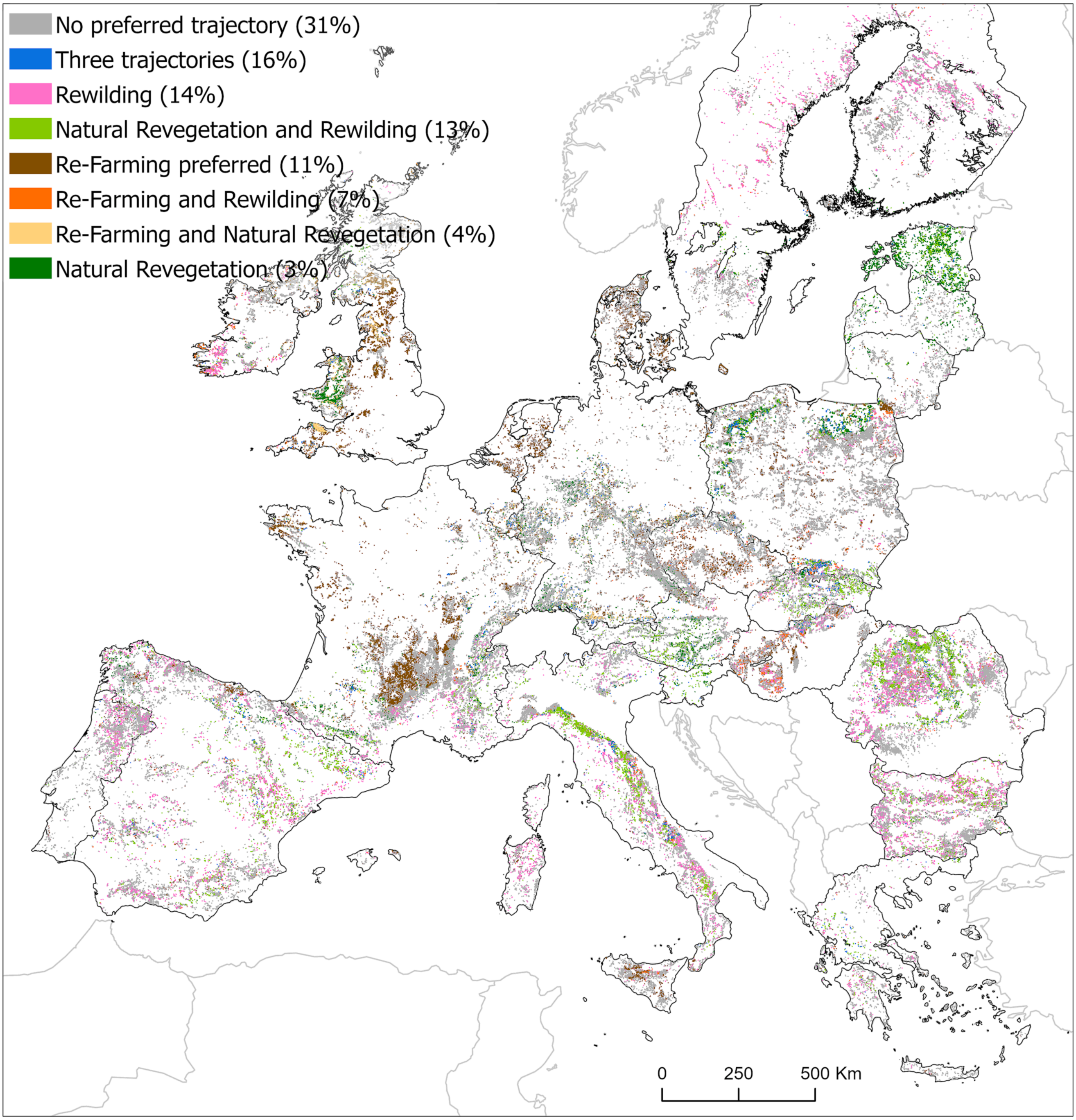

Fig. 5. Preferred management responses for potentially abandoned locations. The map shows which trajectory brings high benefits with limited trade-offs.

Regarding extensive Re-Farming, high benefits occur in one-third of locations whereas low impacts prevail overall (62% of locations) (Fig. 4c and Table 2). This is linked to the high proportion of initially extensive farmland, as well as lower changes in vegetation cover compared to the other two trajectories. Some regions (e.g., Sicily) have high trade-offs or negative impacts in the other two trajectories whereas benefits prevail upon Re-Farming, especially for heritage gains and erosion reduction.

3.3. Comparison of trajectories

We selected the locations that supported high benefits for each trajectory (Fig. 5).

For about one third of potential abandonment locations, we did not find high benefits, and therefore there was no preferred trajectory. This can be due to either small overall benefits of the trajectories at these locations, or the occurrence of strong negative impacts or trade-offs. The latter frequently occurs in Mediterranean regions and Eastern Europe upon Rewilding and Natural Revegetation, with trade-offs between benefits in carbon sequestration or erosion reduction, and increases in fire risk or losses of agrobiodiversity and cultural landscapes.

In 16% of locations, all three abandonment trajectories can lead to predominantly positive impacts. This occurs especially in lands currently under high-intensity farming. The three trajectories each bring different benefits. For instance, in Northern Poland, Re-Farming and

Table 2
Distribution of high benefits, negative impacts, trade-offs, and low impacts across trajectories. We did not include negative impact indicators for Extensive Re-Farming (Table 1).

High impacts category	Trajectory		
	Natural Revegetation	Rewilding	Extensive Re-Farming
High benefits	36%	50%	38%
High negative impacts	24%	8%	n.a.
Trade-offs	33%	15%	n.a.
Low impacts	7%	27%	62%
Total	100%	100%	100%

Rewilding benefit agrobiodiversity, while Natural Revegetation particularly benefits carbon sequestration.

For locations where a single trajectory is preferred, Rewilding is the most frequently preferred trajectory (14% of locations), notably in Southern and Eastern Europe (Italy, North of Portugal, Romania, Bulgaria, Hungary, and south of France) where open landscapes mitigate negative risks of revegetation, especially in fire-prone or highly agrobiodiverse regions. Rewilding and Natural Revegetation are preferred in 13% of locations. These locations are often in mountain regions (Italy, Pyreneans, Austria) where carbon sequestration, erosion reduction, and rewilding potential bring few trade-offs.

Maintaining agricultural management with Re-Farming is the preferred trajectory for 11% of locations, especially in Southern Europe, where vegetation re-growth would bring high risks in the other trajectories. Rewilding can be equally as positive as Re-Farming when grazing supports open landscapes that preserve cultural values and agrobiodiversity. This applied to 7% of locations, mostly in Northern Italy and intensive croplands in Poland and Finland. Re-Farming and Natural Revegetation bring the highest benefits (4% of locations, mostly in Northern Europe) for different reasons: while Natural Revegetation supports carbon sequestration and erosion reduction, Re-Farming is mostly positive for agrobiodiversity and cultural heritage.

Natural Revegetation appears as the preferred trajectory for only a minority of locations (3%). This is mostly due to an overlap in preferred locations with the Rewilding trajectory. As natural revegetation can be associated with larger benefits, it also often has trade-offs. Therefore, the locations where it is the preferred trajectory are those where initial conditions for some indicators were low (e.g., for heritage or agrobiodiversity in intensive arable lands). In this case, revegetation does not lead to such trade-offs.

4. Discussion

We analysed the environmental and cultural impacts of different management strategies in farmland that may become abandoned in the EU and UK. Levels of benefits and trade-offs vary across regions, as a function of the trajectory outcomes and local conditions. From a decision-making perspective and to support contributions to policy, our results help guide management responses to farmland abandonment.

Active management of abandoned lands towards Rewilding is a preferential trajectory in many locations. When opportunities for human management of the landscape are limited, natural grazing helps to reduce forest fire risk (Fuhlendorf et al., 2009; Lasanta et al., 2018; Rouet-Leduc et al., 2021) and preserve open areas favourable to species typical for agrobiodiversity (Putfarken et al., 2008). The favourable outcomes for Rewilding should be placed in the perspective of our approach as we only looked at optimal outcomes. In practice, additional factors should be considered such as management costs, logistics or local acceptance to avoid tensions (Lorimer et al., 2015; Loth and Newton, 2018; Regos et al., 2016; Smit et al., 2015).

Although Natural Revegetation is one of the most frequent consequences of farmland abandonment (Fayet et al., 2022; Plieninger et al., 2016; Rey Benayas et al., 2007), we found that this trajectory leads to frequent trade-offs, especially on extensive farmland and in fire prone regions. Extensive Re-Farming was particularly beneficial in locations farmed at higher intensity in initial conditions and where revegetation and rewilding would bring trade-offs.

4.1. Policy perspectives

Smaller, extensive, and family farms are more likely to be abandoned (Dax et al., 2021; Perpiña Castillo et al., 2018; Rey Benayas et al., 2007; Schuh et al., 2020). While Re-Farming indicates priority areas for farming preservation, we also identify where more "natural" options can be implemented, as observed following Natural Revegetation and Rewilding. These two trajectories should be prioritised where environmental risks and trade-offs are low, as they can contribute to the growing interest for nature-based solutions in European environmental policies (Chausson et al., 2020; Seddon et al., 2021, 2019), including for instance the EU Climate Adaptation Strategy (European Commission, 2021) and the Biodiversity Strategy for 2030 (European Commission, 2020b). When negative impacts are more likely, we recommend maintaining or restoring management at extensive levels with biodiversity-friendly farming, which can also support broader environmental and societal benefits (Lomba et al., 2019; Oberč and Schnell, 2020; Špulerová et al., 2017). In this case, avoiding farmland abandonment will require alignment with policies beyond agriculture to address the broader socio-economic challenges in rural areas (Dwyer et al., 2019; Schuh et al., 2020) with improved services and connectivity to revive local economies, as outlined in the European Commission's vision for rural areas (European Commission, 2022). Moreover, the suitability and likelihood to adopt different management responses to potential abandonment is also influenced by landowners and farmers' perceptions of these options. This may include economic, social, and individual preferences that can influence individual preferences and willingness to engage in various land management responses to abandonment (Kristensen et al., 2016; Malek et al., 2019; Malek and Verburg, 2020).

Informed decision-making about the benefits and trade-offs of different abandonment options is key to foster the most suitable post-abandonment trajectory. Targeting resources and efforts to regions where benefits can be maximised for a specific trajectory is in line with the urgency of the climate and biodiversity crises. At the same time, aiming to maximise ecosystem benefits without considering stakeholders' preferences, needs, land history, and societal relevance can lead to non-optimal and non-effective decisions (Cord et al., 2017). Here, we quantified the highest benefits based on the scale of impacts and using equal weights for the different benefits, which does not necessarily reflect local stakeholders' preferences. The loss of farming and traditional landscapes can be perceived more negatively than our indicators suggest (Frei et al., 2020; Ruskule et al., 2013; van der Zanden et al., 2018). It is therefore key to find a balance between ecological and societal considerations to navigate the implications of abandonment trajectories.

4.2. Limitations and future directions

We treated impacts equally whereas in a policy context, decision-makers would work differently to ensure that the selected response to abandonment aligns with local conditions and national or regional priorities. Consultation with experts and local stakeholders may therefore be appropriate (Ockendon et al., 2018; Ruskule et al., 2013). At the same time, a focus on EU targets for biodiversity and climate change mitigation is also essential. Achieving such targets is to the benefit of stakeholders far away from the locations discussed, and is not easily accounted for in local debates on the future of abandoned lands.

Our study assesses the impacts of different abandonment trajectories in an unchanged world, without accounting for climate change and subsequent changes in precipitation and temperature patterns (IPCC, 2019; Pielke et al., 2011). Although our results help understand the potential impacts of different management responses to abandonment, they are not intended to predict future scenarios. They should be interpretated with caution and with respect to changing environmental conditions across Europe. For instance, climate change is likely to cause more abandonment or make re-farming difficult due land degradation and unsuitable conditions for cultivation (IPCC, 2019; Malek and Verburg, 2021). Other issues include global changes in land use such as coastal erosion, land subsidence, desertification, increased fire risk, and population migration (Costa et al., 2020; Ferreira et al., 2022) which can influence abandonment trajectories. Moreover, the vegetation regrowth model (Verburg and Overmars, 2009) used in this study to model landscape outcomes of the Natural Revegetation and Rewilding trajectories may be outdated and may not account for changes in vegetation patterns, species distributions, tree line shifts as well as carbon sequestration (e.g., Cudlín et al., 2017; Verkerk et al., 2022).

Difficult conditions for farming (i.e., biophysical or climatic limitations, remoteness, low population densities) are often associated with a higher likelihood of abandonment (Dax et al., 2021; Perpiña Castillo et al., 2021; Schuh et al., 2020). In addition, most lands predicted to be abandoned in our study area were initially farmed at low to medium intensity (Appendix A, Table A1). Therefore, we did not include intensive re-farming as an option among our selected trajectories. We acknowledge that intensification could nonetheless apply, notably under suitable biophysical, socio-economic conditions, as well as policy incentives and landowners' preferences (Malek and Verburg, 2020; Nainggolan et al., 2012; Schuh et al., 2020). In this case, benefits, risks, and trade-offs for biodiversity, carbon, and other ecological indicators would differ from our trajectories. An assessment of trade-offs of intensification in current agricultural areas was notably explored by Felix et al. (2022). Future research could consider different impact indicators. We did not measure below ground carbon sequestration despite opportunities that abandoned lands can provide as carbon sinks (Bell et al., 2020; Yang et al., 2019). We also assumed a continuous vegetation re-growth, although vegetation structure is more complex, open-canopy is frequent in Mediterranean climates (Stritih et al., 2023), and carbon sequestration in forests can vary over time and by ecosystems (Kilpeläinen and Peltola, 2022). In addition, the different stages of revegetation can also provide habitat to important species and can be beneficial for conservation objectives (Broughton et al., 2022; Regos et al., 2016). We did not have a negative impact indicator for Re-Farming, although some critics expressed potential detrimental effects for biodiversity and the environment even from farming at low intensity (Merckx and Pereira, 2015). Furthermore, from a biodiversity perspective, the ecological integrity indicator only captures a small part of the multiple facets of biodiversity (Díaz et al., 2020). Finally, individual member states may have set specific targets for future land use planning. For instance, while Re-Farming is identified as a beneficial trajectory in countries like the Netherlands, the urgent need to expand the few areas of nature left in intensively farmed countryside may outweigh the trade-offs observed under the Natural Revegetation and Rewilding trajectories.

5. Conclusions

The approach of targeting interventions based on an assessment of benefits and trade-offs brings new insights to support decision-making for management in current and future farmland abandonment regions. It helps to use resources in ways that maximise contributions to EU Green Deal policy targets while providing services to nature and society. Our results indicate that the benefits and trade-offs of alternative futures for abandoned farmland are highly context-dependent. Therefore, navigating trade-offs requires targeting interventions to specific locations, providing enabling conditions to maintain agricultural management or addressing abandonment drivers where natural revegetation is unlikely to bring positive outcomes. When scientific data are combined with local knowledge, decision-making can be better informed on the risks, benefits, and costs of action (and inaction), hence ensuring that management responses to farmland abandonment align with local conditions and contribute to EU level targets.

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.

Data availability

Data of the figures presented in this paper are available at https://dx.doi.org/10.34894/E5BQK0.

Acknowledgements

This work was supported by the project TERRANOVA the European Landscape Learning Initiative, which has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813904. The output reflects the views only of the authors, and the European Union cannot be held responsible for any use, which may be made of the information contained therein. The authors expressed their gratitude for the data kindly shared for this research by Emma van der Zanden, Leen Felix, Clara Sueur-Ochoa and Emilo Chuvieco. The authors thank Elena Pearce and Jens-Christian Svenning for their help in designing the Rewilding trajectory. The authors are also highly grateful for the constructive discussions and feedback provided on the manuscript by Chantal Van Ham, Alberto Arroyo Schnell, and Antonia Matthies.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2023.107460.

References

Arnaez, J., Lasanta, T., Errea, M.P., Ortigosa, L., 2011. Land abandonment, landscape evolution, and soil erosion in a Spanish Mediterranean mountain region: the case of Camero Viejo. Land Degrad. Dev. 22, 537–550. https://doi.org/10.1002/ldr.1032.
Bell, S., Barriocanal, C., Terrer, C., Rosell-Melé, A., 2020. Management opportunities for soil carbon sequestration following agricultural land abandonment. Environ. Sci. Policy 108, 104–111. https://doi.org/10.1016/j.envsci.2020.03.018.
Broughton, R.K., Bullock, J.M., George, C., Hill, R.A., Hinsley, S.A., Maziarz, M., Melin, M., Mountford, J.O., Sparks, T.H., Pywell, R.F., Gomory, D., 2021. Long-term woodland restoration on lowland farmland through passive rewilding. PLoS One 16 (6), e0252466.
Broughton, R.K., Bullock, J.M., George, C., Gerard, F., Maziarz, M., Payne, W.E., Scholefield, P.A., Wade, D., Pywell, R.F., Koch, F.H., 2022. Slow development of woodland vegetation and bird communities during 33 years of passive rewilding in open farmland. PLoS One 17 (11), e0277545.
Brown, I., 2020. Challenges in delivering climate change policy through land use targets for afforestation and peatland restoration. Environ. Sci. Policy 107, 36–45. https://doi.org/10.1016/j.envsci.2020.02.013.
Ceausu, S., Hofmann, M., Navarro, L.M., Carver, S., Verburg, P.H., Pereira, H.M., 2015. Mapping opportunities and challenges for rewilding in Europe. Conserv. Biol. 29, 1017–1027. https://doi.org/10.1111/cobi.12533.
Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C.A.J., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., Seddon, N., 2020. Mapping the effectiveness of nature-based solutions for climate change adaptation. Glob. Chang. Biol. 26, 6134–6155. https://doi.org/10.1111/gcb.15310.
Chazdon, R.L., Lindenmayer, D., Guariguata, M.R., Crouzeilles, R., Rey Benayas, J.M., Lazos Chavero, E., 2020. Fostering natural forest regeneration on former agricultural land through economic and policy interventions. Environ. Res. Lett. 15 (4), 043002.
Commission, E., 2020a. EU Biodiversity Strategy for 2030 - Bringing Nature Back into Our Lives. European Commission, Brussels https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020DC0380.
Commission, E., 2020b. EU Biodiversity Strategy for 2030 [WWW Document]. accessed 9.9.20. https://ec.europa.eu/environment/nature/biodiversity/strategy/index_en.htm.
Cord, A.F., Bartkowski, B., Beckmann, M., Dittrich, A., Hermans-Neumann, K., Kaim, A., Lienhoop, N., Locher-Krause, K., Priess, J., Schröter-Schlaack, C., Schwarz, N.,

Seppelt, R., Strauch, M., Václavík, T., Volk, M., 2017. Towards systematic analyses of ecosystem service trade-offs and synergies: main concepts, methods and the road ahead. Ecosyst. Serv. 28, 264–272. https://doi.org/10.1016/j.ecoser.2017.07.012.

Cortina-Segarra, J., García-Sánchez, I., Grace, M., Andrés, P., Baker, S., Bullock, C., Decleer, K., Dicks, L.V., Fisher, J.L., Frouz, J., Klimkowska, A., Kyriazopoulos, A.P., Moreno-Mateos, D., Rodríguez-González, P.M., Sarkki, S., Ventocilla, J.L., 2021. Barriers to ecological restoration in Europe: expert perspectives. Restor. Ecol. 29 (4) https://doi.org/10.1111/rec.13346.

Costa, H., de Rigo, D., Libertà, G., Houston Durrant, T., San-Miguel-Ayanz, J., 2020. European wildfire danger and vulnerability in a changing climate: towards integrating risk dimensions. https://doi.org/10.2760/46951.

Crawford, C.L., Yin, H., Radeloff, V.C., Wilcove, D.S., 2022. Rural land abandonment is too ephemeral to provide major benefits for biodiversity and climate. Sci. Adv. 8, eabm8999. https://doi.org/10.1126/sciadv.abm8999.

Cudlín, P., Cudlín, P., Cudlín, P., Tognetti, R., Malis, F., Alados, C.L., Bebi, P., Grunewald, K., Zhiyanski, M., Andonowski, V., La Porta, N., Bratanova-Doncheva, S., Kachaunova, E., Edwards-Jonášová, M., Ninot, J.M., Rigling, A., Hofgaard, A., Hlásny, T., Skalák, P., Wielgolaski, F.E., 2017. Drivers of treeline shift in different European mountains. Clim. Res. 73 (1-2), 135–150.

Dax, T., Schroll, K., Machold, I., Derszniak-Noirjean, M., Schuh, B., Gaupp-Berghausen, M., 2021. Land abandonment in mountain areas of the EU: an inevitable side effect of farming modernization and neglected threat to sustainable land use. Land 10 (6), 591.

DeSilvey, C., Bartolini, N., 2018. Where horses run free? Autonomy, temporality and rewilding in the Côa Valley, Portugal. Trans. Inst. Br. Geogr. 44, 94–109. https://doi.org/10.1111/tran.12251.

Díaz, S., Zafra-Calvo, N., Purvis, A., Verburg, P.H., Obura, D., Leadley, P., Chaplin-Kramer, R., De Meester, L., Dulloo, E., Martín-López, B., Shaw, M.R., Visconti, P., Broadgate, W., Bruford, M.W., Burgess, N.D., Cavender-Bares, J., DeClerck, F., Fernández-Palacios, J.M., Garibaldi, L.A., Hill, S.L.L., Isbell, F., Khoury, C.K., Krug, C.B., Liu, J., Maron, M., McGowan, P.J.K., Pereira, H.M., Reyes-García, V., Rocha, J., Rondinini, C., Shannon, L., Shin, Y.-J., Snelgrove, P.V.R., Spehn, E.M., Strassburg, B., Subramanian, S.M., Tewksbury, J.J., Watson, J.E.M., Zanne, A.E., 2020. Set ambitious goals for biodiversity and sustainability. Science 370, 411–413. https://doi.org/10.1126/science.abe1530.

Dottori, F., Alfieri, L., Bianchi, A., Skoien, J., Salamon, P., 2021. River flood hazard maps for Europe and the Mediterranean Basin region. European Commission. https://doi.org/10.2905/1D128B6C-A4EE-4858-9E34-6210707F3C81. Joint Research Centre (JRC) [River network map].

Dou, Y., Cosentino, F., Malek, Z., Maiorano, L., Thuiller, W., Verburg, P.H., 2021. A new European land systems representation accounting for landscape characteristics. Landsc. Ecol. 36, 2215–2234. https://doi.org/10.1007/s10980-021-01227-5.

Airbus, USGS, NGA, NASA, CGIAR, NLS, OS, NMA, Geodatastyrelsen, GSA, GSI, the GIS User Community, n.d. Terrain: Slope Map. Esri Image Service Data Type Elevation. https://www.arcgis.com/home/item.html?id=a1ba14d09df14f42ad6ca3c4bcebf3b4 (accessed on 10/05/2022).

Dwyer, J., Micha, E., Kubikanova, K., van Bunnen, P., Schuh, B., Maucorps, A., Mantino, F., 2019. Evaluation of the impact of the CAP on generational renewal, local development and jobs in rural areas, Directorate-General for Agriculture and Rural Development. Publications Office of the European Union, Luxembourg. 10.2762/364362.

Estel, S., Kuemmerle, T., Alcántara, C., Levers, C., Prishchepov, A., Hostert, P., 2015. Mapping farmland abandonment and recultivation across Europe using MODIS NDVI time series. Remote Sens. Environ. 163, 312–325. https://doi.org/10.1016/j.rse.2015.03.028.

European Commission, 2019. Communication From the Commission to the European Parliament. the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal.

European Commission, 2022. A Long-term vision for the EU's rural areas [WWW Document]. accessed 10.31.22. https://ec.europa.eu/info/strategy/priorities-2019-2024/new-push-european-democracy/long-term-vision-rural-areas_en#documents.

European Commission, 2021. Forging a climate-resilient Europe -the new EU Strategy on Adaptation to Climate Change, Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of The Regions. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN.

European Environment Agency, 2021. Nature-based solutions in Europe: policy, knowledge and practice for climate change adaptation and disaster risk reduction. 10.1163/9789004322714_cclc_2021-0190-608.

Fayet, C.M.J., Reilly, K.H., Van Ham, C., Verburg, P.H., 2022. What is the future of abandoned agricultural lands? A systematic review of alternative trajectories in Europe. Land Use Policy 112, 105833.

Felix, L., Houet, T., Verburg, P.H., 2022. Mapping biodiversity and ecosystem service trade-offs and synergies of agricultural change trajectories in Europe. Environ. Sci. Policy 136, 387–399. https://doi.org/10.1016/j.envsci.2022.07.004.

Ferreira, C.S.S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., Kalantari, Z., 2022. Soil degradation in the European Mediterranean region: processes, status and consequences. Sci. Total Environ. 805, 150106 https://doi.org/10.1016/j.scitotenv.2021.150106.

Freer-Smith, P., Muys, B., Bozzano, M., Drössler, L., Farrelly, N., Jactel, H., Korhonen, J., Minotta, G., Nijnik, M., Orazio, C., 2019. Plantation forests in Europe: challenges and opportunities. From Science to Policy 9.

Frei, T., Derks, J., Rodríguez Fernández-Blanco, C., Winkel, G., 2020. Narrating abandoned land: perceptions of natural forest regrowth in Southwestern Europe. Land Use Policy 99, 105034. https://doi.org/10.1016/j.landusepol.2020.105034.

Fuhlendorf, S.D., Engle, D.M., Kerby, J., Hamilton, R., 2009. Pyric herbivory: rewilding landscapes through the recoupling of fire and grazing. Conserv. Biol. 23, 588–598. https://doi.org/10.1111/j.1523-1739.2008.01139.x.

Geist, H.J., Lambin, E.F., 2002. Proximate causes and underlying driving forces of tropical deforestation. Bioscience 52, 143–150. https://doi.org/10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2.

Grădinaru, S.R., Iojă, C.I., Onose, D.A., Gavrilidis, A.A., Pətru-Stupariu, I., Kienast, F., Hersperger, A.M., 2015. Land abandonment as a precursor of built-up development at the sprawling periphery of former socialist cities. Ecol. Ind. 57, 305–313. https://doi.org/10.1016/j.ecolind.2015.05.009.

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E., Fargione, J., 2017. Global Reforestation Potential Map [WWW Document]. https://zenodo.org/record/883444.

Hall, S.J.G., 2018. A novel agroecosystem: beef production in abandoned farmland as a multifunctional alternative to rewilding. Agr. Syst. 167, 10–16. https://doi.org/10.1016/j.agsy.2018.08.009.

Hall, S.J.G., Bunce, R.G.H., 2019. The use of cattle Bos taurus for restoring and maintaining holarctic landscapes: conclusions from a long-term study (1946–2017) in northern England. Ecol. Evol. 9, 5859–5869. https://doi.org/10.1002/ece3.5169.

IPCC, 2019. Summary for Policymakers, in: P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P., Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malle (Eds.), Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Cambridge University Press. 10.1017/9781009157988.

IUCN, 2020. IUCN Global Standard for Nature-based Solutions. Guidance for using the IUCN Global Standard for Nature-based Solutions: first editions.

Jones, N., Duarte, F., Rodrigo, I., van Doorn, A., de Graaff, J., 2016. The role of EU agri-environmental measures preserving extensive grazing in two less-favoured areas in Portugal. Land Use Policy 54, 177–187. https://doi.org/10.1016/j.landusepol.2016.01.014.

Kilpeläinen, A., Peltola, H., 2022. Carbon sequestration and storage in European forests. Forest Bioecon. Clim. Change Spinger 113–128.

Kopsieker, L., Gerritsen, E., Stainforth, T., Lucic, A., Costa Domingo, G., Naumann, S., Röschel, L., Davis, M.c., 2021. Nature-based solutions and their socio-economic benefits for Europe's recovery: Enhancing the uptake of nature-based solutions across EU policies. Policy Briefing by the Institute for European Environmental Policy (IEEP) and the Ecologic Institute.

Kristensen, S.B.P., Busck, A.G., van der Sluis, T., Gaube, V., 2016. Patterns and drivers of farm-level land use change in selected European rural landscapes. Land Use Policy 57, 786–799. https://doi.org/10.1016/j.landusepol.2015.07.014.

Lasanta, T., Nadal-Romero, E., Arnáez, J., 2015. Managing abandoned farmland to control the impact of re-vegetation on the environment. The state of the art in Europe. Environ. Sci. Policy 52, 99–109. https://doi.org/10.1016/j.envsci.2015.05.012.

Lasanta, T., Khorchani, M., Pérez-Cabello, F., Errea, P., Sáenz-Blanco, R., Nadal-Romero, E., 2018. Clearing shrubland and extensive livestock farming: active prevention to control wildfires in the Mediterranean mountains. J. Environ. Manage. 227, 256–266. https://doi.org/10.1016/j.jenvman.2018.08.104.

Levers, C., Schneider, M., Prishchepov, A.V., Estel, S., Kuemmerle, T., 2018. Spatial variation in determinants of agricultural land abandonment in Europe. Sci. Total Environ. 644, 95–111. https://doi.org/10.1016/j.scitotenv.2018.06.326.

Lomba, A., Moreira, F., Klimek, S., Jongman, R.H.G., Sullivan, C., Moran, J., Poux, X., Honrado, J.P., Pinto-correia, T., Plieninger, T., Mccracken, D.I., 2019. Back to the future: rethinking socioecological systems underlying high nature value farmlands. Front. Ecol. Environ. 18, 1–7. https://doi.org/10.1002/fee.2116.

Lorimer, J., Sandom, C., Jepson, P., Doughty, C., Barua, M., Kirby, K.J., 2015. Rewilding: science, practice, and politics. Annu. Rev. Env. Resour. 40, 39–62. https://doi.org/10.1146/annurev-environ-102014-021406.

Loth, A.F., Newton, A.C., 2018. Rewilding as a restoration strategy for lowland agricultural landscapes: stakeholder-assisted multi-criteria analysis in Dorset, UK. J. Nat. Conserv. 46, 110–120. https://doi.org/10.1016/j.jnc.2018.10.003.

Malek, Ž., Verburg, P.H., 2020. Mapping global patterns of land use decision-making. Glob. Environ. Chang. 65, 102170 https://doi.org/10.1016/j.gloenvcha.2020.102170.

Malek, Ž., Verburg, P.H., 2021. Representing responses to climate change in spatial land system models. Land Degrad. Dev. 32 (17), 4954–4973.

Malek, Ž., Douw, B., Van Vliet, J., Van Der Zanden, E.H., Verburg, P.H., 2019. Local land-use decision-making in a global context. Environ. Res. Lett. 14 (8), 083006.

Malhi, Y., Lander, T., le Roux, E., Stevens, N., Macias-Fauria, M., Wedding, L., Girardin, C., Kristensen, J.Å., Sandom, C.J., Evans, T.D., Svenning, J.C., Canney, S., 2022. The role of large wild animals in climate change mitigation and adaptation. Curr. Biol. 32, R181–R196. https://doi.org/10.1016/j.cub.2022.01.041.

Merckx, T., Pereira, H.M., 2015. Reshaping agri-environmental subsidies: from marginal farming to large-scale rewilding. Basic Appl. Ecol. 16, 95–103. https://doi.org/10.1016/j.baae.2014.12.003.

Meyfroidt, P., Schierhorn, F., Prishchepov, A.V., Müller, D., Kuemmerle, T., 2016. Drivers, constraints and trade-offs associated with recultivating abandoned cropland in Russia, Ukraine and Kazakhstan. Glob. Environ. Chang. 37, 1–15. https://doi.org/10.1016/j.gloenvcha.2016.01.003.

Morel, L., Barbe, L., Jung, V., Clément, B., Schnitzler, A., Ysnel, F., 2020. Passive rewilding may (also) restore phylogenetically rich and functionally resilient forest plant communities. Ecol. Appl. 30, 1–12. https://doi.org/10.1002/eap.2007.
Munroe, D.K., van Berkel, D.B., Verburg, P.H., Olson, J.L., 2013. Alternative trajectories of land abandonment: causes, consequences and research challenges. Curr. Opin. Environ. Sustain. 5, 471–476. https://doi.org/10.1016/j.cosust.2013.06.010.
Nainggolan, D., de Vente, J., Boix-Fayos, C., Termansen, M., Hubacek, K., Reed, M.S., 2012. Afforestation, agricultural abandonment and intensification: competing trajectories in semi-arid Mediterranean agro-ecosystems. Agr. Ecosyst. Environ. 159, 90–104. https://doi.org/10.1016/j.agee.2012.06.023.
Navarro, L.M., Pereira, H.M., 2012. Rewilding abandoned landscapes in Europe. Ecosystems 15, 900–912. https://doi.org/10.1007/s10021-012-9558-7.
Oberč, B.P., Schnell, A.A., 2020. Approaches to sustainable agriculture. Exploring the Pathways towards the Future of Farming. IUCN EURO, Brussels, Belgium. 10.2305/IUCN.CH.2020.07.en.
Ockendon, N., Thomas, D.H.L., Cortina, J., Adams, W.M., Aykroyd, T., Barov, B., Boitani, L., Bonn, A., Branquinho, C., Brombacher, M., Burrell, C., Carver, S., Crick, H.Q.P., Duguy, B., Everett, S., Fokkens, B., Fuller, R.J., Gibbons, D.W., Gokhelashvili, R., Griffin, C., Halley, D.J., Hotham, P., Hughes, F.M.R., Karamanlidis, A.A., McOwen, C.J., Miles, L., Mitchell, R., Rands, M.R.W., Roberts, J., Sandom, C.J., Spencer, J.W., ten Broeke, E., Tew, E.R., Thomas, C.D., Timoshyna, A., Unsworth, R.K.F., Warrington, S., Sutherland, W.J., 2018. One hundred priority questions for landscape restoration in Europe. Biol. Conserv. 221, 198–208. https://doi.org/10.1016/j.biocon.2018.03.002.
Peña-Angulo, D., Khorchani, M., Errea, P., Lasanta, T., Martínez-Arnáiz, M., Nadal-Romero, E., 2019. Factors explaining the diversity of land cover in abandoned fields in a Mediterranean mountain area. Catena 181, 104064. https://doi.org/10.1016/j.catena.2019.05.010.
Pereira, H.M., Navarro, L.M., 2015. Rewilding European landscapes. Rewild. Eur. Landscapes 1–227. https://doi.org/10.1007/978-3-319-12039-3.
Perino, A., Pereira, H.M., Navarro, L.M., Fernández, N., Bullock, J.M., Ceaușu, S., Cortés-Avizanda, A., van Klink, R., Kuemmerle, T., Lomba, A., Pe'er, G., Plieninger, T., Rey Benayas, J.M., Sandom, C.J., Svenning, J.-C., Wheeler, H.C., 2019. Rewilding complex ecosystems. Science 364 (6438).
Perpiña Castillo, C., Kavalov, B., Diogo, V., Jacobs, C., Batista E Silva, F., Lavalle, C., 2018. Agricultural Land Abandonment in the EU within 2015-2030 | EU Science Hub [WWW Document]. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/agricultural-land-abandonment-eu-within-2015-2030 (accessed 11.19.19).
Perpiña Castillo, C., Jacobs-Crisioni, C., Diogo, V., Lavalle, C., 2021. Modelling agricultural land abandonment in a fine spatial resolution multi-level land-use model: an application for the EU. Environ. Model. Softw. 136, 104946 https://doi.org/10.1016/j.envsoft.2020.104946.
Pielke, R.A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K.K., Nair, U., Betts, R., Fall, S., Reichstein, M., Kabat, P., de Noblet, N., 2011. Land use/land cover changes and climate: modeling analysis and observational evidence. WIREs Clim. Change 2 (6), 828–850.
Plieninger, T., Draux, H., Fagerholm, N., Bieling, C., Bürgi, M., Kizos, T., Kuemmerle, T., Primdahl, J., Verburg, P.H., 2016. The driving forces of landscape change in Europe: a systematic review of the evidence. Land Use Policy 57, 204–214. https://doi.org/10.1016/j.landusepol.2016.04.040.
Pointereau, P., Coulon, F., Girard, P., Lambotte, M., Stuczynski, T., Sánchez Ortega, V., Del Rio, A., 2008. Analysis of the Driving Forces behind Farmland Abandonment and the Extent and Location of Agricultural Areas that are Actually Abandoned or are in Risk to be Abandoned, JRC Scientific and Technical Reports. Institute for Environment and Sustainability, Luxembourg: Office for Official Publications of the European Communities ©.
Putfarken, D., Dengler, J., Lehmann, S., Härdtle, W., 2008. Site use of grazing cattle and sheep in a large-scale pasture landscape: a GPS/GIS assessment. Appl. Anim. Behav. Sci. 111, 54–67. https://doi.org/10.1016/j.applanim.2007.05.012.
Regos, A., Domínguez, J., Gil-Tena, A., Brotons, L., Ninyerola, M., Pons, X., 2016. Rural abandoned landscapes and bird assemblages: winners and losers in the rewilding of a marginal mountain area (NW Spain). Reg. Environ. Chang. 16, 199–211. https://doi.org/10.1007/s10113- 014-0740-77.
Rey Benayas, J.M., Martins, A., Nicolau, J.M., Schulz, J.J., 2007. Abandonment of agricultural land: an overview of drivers and consequences. CAB Rev.: Perspect. Agric., Vet. Sci. Nutr. Nat. Resour. 2 https://doi.org/10.1079/PAVSNNR20072057.
Rouet-Leduc, J., Pe'er, G., Moreira, F., Bonn, A., Helmer, W., Shahsavan Zadeh, S.A.A., Zizka, A., van der Plas, F., 2021. Effects of large herbivores on fire regimes and wildfire mitigation. J. Appl. Ecol. 58 (12), 2690–2702.
Ruskule, A., Nikodemus, O., Kasparinskis, R., Bell, S., Urtane, I., 2013. The perception of abandoned farmland by local people and experts: landscape value and perspectives on future land use. Landsc. Urban Plan. 115, 49–61. https://doi.org/10.1016/j.landurbplan.2013.03.012.
Rytter, L., Ingerslev, M., Kilpeläinen, A., Torssonen, P., Lazdina, D., Löf, M., Madsen, P., Muiste, P., Stener, L.G., 2016. Increased forest biomass production in the Nordic and Baltic countries - A review on current and future opportunities. Silva Fennica 50, 1–33. 10.14214/sf.1660.
Schuh, B., Derszniak-Noirjean, M., Gaupp-Berghausen, M., Hsiung, C.-H., Münch, A., Dax, T., Machold, I., Schroll, K., Brkanovic, S., 2020. Research for AGRI Committee – The challenge of land abandonment after 2020 and options for mitigating measures. European Parliament, Policy Department for Structural and Cohesion Policies, Brussels, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels.
Schulp, C.J.E., Nabuurs, G.-J., Verburg, P.H., 2008. Future carbon sequestration in Europe-Effects of land use change. Agr. Ecosyst. Environ. 127, 251–264. https://doi.org/10.1016/j.agee.2008.04.010.
Seddon, N., Sengupta, S., Hauler, I., Rizvi, A.R., 2019. Nature-based Solutions in Nationally Determined Contributions: Synthesis and Recommendations for Enhancing Climate Ambition and Action by 2020. IUCN and University of Oxford, Gland, Switzerland and Oxford, UK.
Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., Turner, B., 2021. Getting the message right on nature-based solutions to climate change. Glob. Chang. Biol. 27, 1518–1546. https://doi.org/10.1111/gcb.15513.
Smit, C., Ruifrok, J.L., van Klink, R., Olff, H., 2015. Rewilding with large herbivores: the importance of grazing refuges for sapling establishment and wood-pasture formation. Biol. Conserv. 182, 134–142. https://doi.org/10.1016/j.biocon.2014.11.047.
Špulerová, J., Bezák, P., Dobrovodská, M., Lieskovský, J., Štefunková, D., 2017. Traditional agricultural landscapes in Slovakia: why should we preserve them? Landsc. Res. 42, 891–903. https://doi.org/10.1080/01426397.2017.1385749.
Stritih, A., Seidl, R., Senf, C., 2023. Alternative states in the structure of mountain forests across the Alps and the role of disturbance and recovery. Landsc. Ecol. 38 (4), 933–947.
Svenning, J.-C., 2002. A review of natural vegetation openness in north-western Europe. Biol. Conserv. 104, 133–148. https://doi.org/10.1016/S0006-3207(01)00162-8.
Terres, J.-M., Scacchiafichi, L.N., Wania, A., Ambar, M., Anguiano, E., Buckwell, A., Coppola, A., Gocht, A., Källström, H.N., Pointereau, P., Strijker, D., Visek, L., Vranken, L., Zobena, A., 2015. Farmland abandonment in Europe: identification of drivers and indicators, and development of a composite indicator of risk. Land Use Policy 49, 20–34. https://doi.org/10.1016/j.landusepol.2015.06.009.
Ustaoglu, E., Collier, M.J., 2018. Farmland abandonment in Europe: an overview of drivers, consequences, and assessment of the sustainability implications. Environ. Rev. 26 https://doi.org/10.1139/er-2018-0001.
van der Zanden, E.H., Verburg, P.H., Schulp, C.J.E., Verkerk, P.J., 2017. Trade-offs of European agricultural abandonment. Land Use Policy 62, 290–301. https://doi.org/10.1016/j.landusepol.2017.01.003.
van der Zanden, E.H., Carvalho-Ribeiro, S.M., Verburg, P.H., 2018. Abandonment landscapes: user attitudes, alternative futures and land management in Castro Laboreiro, Portugal. Reg. Environ. Chang. 18 (5), 1509–1520.
Verburg, P.H., Overmars, K., 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landsc. Ecol. 24, 1167–1181. https://doi.org/10.1007/s10980-009-9355-7.
Verkerk, P.J., Delacote, P., Hurmekoski, E., Kunttu, J., Matthews, R., Mäkipää, R., Mosley, F., Perugini, L., Reyer, C.P.O., Roe, S., Trømborg, E., 2022. Forest-based climate change mitigation and adaptation in Europe. 10.36333/fs14.
Wolff, S., Schrammeijer, E.A., Schulp, C.J.E., Verburg, P.H., 2018. Meeting global land restoration and protection targets: what would the world look like in 2050? Glob. Environ. Chang. 52, 259–272. https://doi.org/10.1016/j.gloenvcha.2018.08.002.
Yang, Y., Tilman, D., Furey, G., Lehman, C., 2019. Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nat. Commun. 10, 1–7. https://doi.org/10.1038/s41467-019-08636-w.
Yang, Y., Hobbie, S.E., Hernandez, R.R., Fargione, J., Grodsky, S.M., Tilman, D., Zhu, Y.-G., Luo, Y., Smith, T.M., Jungers, J.M., Yang, M., Chen, W.-Q., 2020. Restoring abandoned farmland to mitigate climate change on a full earth. One Earth 3, 176–186. https://doi.org/10.1016/j.oneear.2020.07.019.
Zakkak, S., Radovic, A., Panitsa, M., Vassilev, K., Shuka, L., Kuttner, M., Schindler, S., Kati, V., Woods, K., 2018. Vegetation patterns along agricultural land abandonment in the Balkans. J. Veg. Sci. 29 (5), 877–886.