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Spatial opportunities and constraints for green infrastructure network design

Douglas Spencer, Alexandra Marques, Clara Veerkamp, Martijn van der Marel, Peter Verburg, Anandi Sarita Namasivayam, Moreno Di Marco, Martin Jung, Heini Kujala, Louise O'Connor, Piero Visconti, Aafke Schipper

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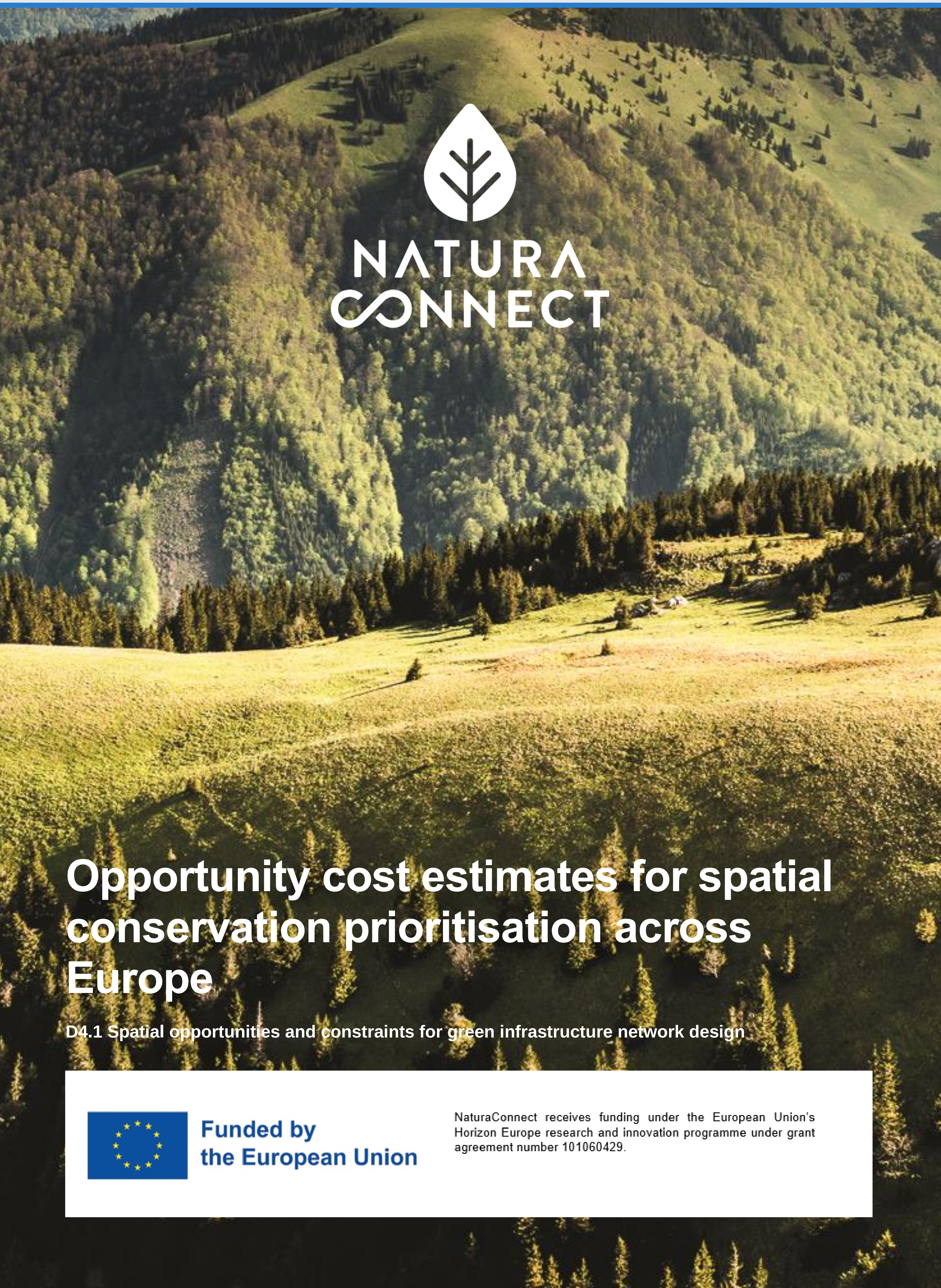

NATURA CONNECT

Opportunity cost estimates for spatial conservation prioritisation across Europe

D4.1 Spatial opportunities and constraints for green infrastructure network design

Funded by the European Union

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Project reference number	101060429
Project title	NATURACONNECT - DESIGNING A RESILIENT AND COHERENT TRANS- EUROPEAN NETWORK FOR NATURE AND PEOPLE

Deliverable title	Spatial opportunities and constraints for green infrastructure network design
Deliverable number	D4.1
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Institution leading task	PBL
Author(s)	Douglas Spencer, Martijn van der Marel, Alexandra Marques, Clara Veerkamp, Aafke Schipper, Peter Verburg, Anandi Sarita Namasivayam, Martin Jung, Piero Visconti, Louise O'Connor, Heini Kujala and Moreno Di Marco.
EC project officer	Christophe Coudun

Deliverable description	The datasets will include spatially explicit data representative of socio-economic and land-use opportunities and constraints for creating or modifying GI. This includes all protected areas, relevant remotely sensed variables (from Copernicus) and proxies of farmland management intensity, which allows to delineate potential high nature value as well as high-intensity farmlands (which are unlikely to be taken out of production). We will also map direct and indirect threats to biodiversity (e.g., hunting pressure) and proxies for opportunity costs, such as land value, and human population density.
Keywords	Systematic conservation planning, nature conservation costs, opportunity costs

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Abbreviations

EC	European Commission
ELS	European Land System
ES	Ecosystem Services
EUROSTAT	European Statistical Office
FAOSTAT	The Food and Agriculture Organization Corporate Statistical Database
GLW4	Gridded Livestock of the World
IMAGE	Integrated Model to Assess the Global Environment
MAGNET	Modular Applied General Equilibrium Tool
MapSPAM	Spatial Production Allocation Model
NUTS	Nomenclature of Territorial Units for Statistics
SCP	Systematic Conservation Planning
TEN-N	Trans-European Nature Network

COUNTRY CODES

AL	Albania
AT	Austria
BE	Belgium
BG	Bulgaria
BH	Bosnia and Herzegovina
CH	Switzerland
CY	Cyprus
CZ	Czechia
DE	Germany
DK	Denmark
EE	Estonia
EL	Greece
ES	Spain
FI	Finland
FR	France
HR	Croatia
HU	Hungary
IE	Ireland

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IT	Italy
KO	Kosovo
LT	Lithuania
LU	Luxembourg
LV	Latvia
ME	Montenegro
MK	North Macedonia
MT	Malta
NL	Netherlands
NO	Norway
PL	Poland
PT	Portugal
RO	Romania
RS	Serbia
SE	Sweden
SI	Slovenia
SK	Slovakia
UK	United Kingdom

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Executive summary

The EU Biodiversity Strategy for 2030 aims to put biodiversity on the path to recovery by 2030. A key component of the EU Biodiversity Strategy is the development of a coherent Trans-European Nature Network (TEN-N), which should increase the coherence of the existing network of Natura 2000 sites and other nationally designated protected areas and address gaps in the coverage of priority habitats and species. The NaturaConnect project aims to design and develop a blueprint for a truly coherent TEN-N of conserved areas, covering at least 30% of land in the European Union, with at least one third of it under strict protection. Possible configurations of the Network, accounting for multiple objectives regarding both biodiversity and ecosystem services (ES), will be identified through spatial conservation prioritisation. In addition, the spatial conservation prioritisation efforts will consider the costs of implementing the TEN-N, in order to inform about the (economic) constraints and feasibility. This report describes the methodology that we developed and implemented in order to establish a coherent set of cost layers for use in NaturaConnect's spatial conservation prioritisation efforts.

We first performed an exploratory review of the literature in order to identify existing approaches and variables commonly used to account for conservation costs. Next, we established a list of desirable properties of cost layers in the context of the NaturaConnect project, including that the cost estimates should be representative of the implementation phase of the TEN-N and that costs should be comparable both across countries and across the 1 km^2 planning units that are used as a basis for the prioritisation. Following this, we decided to approximate the cost of conservation based on opportunity costs, i.e., the foregone economic benefits of exploitation when setting aside land for nature conservation or restoration, which in turn can be approximated by land rent, i.e., the total net revenue or benefits from a parcel of land. For production land (arable, pastoral and forestry land), we used regional and national land rent data and allocated these to the planning units based on the yields of crops, livestock products and wood combined with country-specific commodity prices. For urban land, we used empirical data on property rents as available for a sample of cities and extrapolated these values across countries based on settlement density, assuming a linear relationship between property rents and density of housing.

We found that opportunity costs for urban land were the highest overall and ranged from 6,000 to 500,000 euros per hectare per year (€/ha/yr) across Europe (for Bosnia and Herzegovina and France, respectively). Opportunity costs for agricultural land were mostly in the range of

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5 to 400 €/ha/yr, with considerably higher values in some countries or regions (notably Italy and the Netherlands), reflecting the higher land rents in these regions. Opportunity costs for forestry land were the lowest overall (in the range of 0 to 800 €/ha/yr), which may reflect the longer rotation times of forestry as compared to agricultural land. We combined our set of maps into one by averaging them across the cells (such that mosaic land types get the mean value of the constituent types) and provide an additional combined layer with the costs standardised within countries (zero mean and unit standard deviation), in order to avoid that the outcomes of the spatial conservation prioritisation are biased to countries with lower land rents overall. Our maps can be used to include a proxy of opportunity costs into pan-European spatial conservation prioritisation efforts.

Future improvements to the opportunity cost layers can be implemented by adding more empirical rent data (in particular for cities) and by using more refined yield data. In addition, the combination of the individual opportunity cost layers could be further enhanced by proportional allocation using high resolution land cover data. Standardisation of the combined layer using the purchasing power parity may offer a useful alternative to z-score standardization, depending on the aim of the user.

Finally, we acknowledge the need to consider additional costs of conservation, next to opportunity costs, such as management and restoration costs. Nevertheless, the added value of such management and restoration cost layers would rely heavily on the amount and quality of empirical data, which were deemed insufficient for inclusion in the current set of layers.

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1. Introduction

1.1. Background

Spatial conservation prioritisation has long supported conservation decisions by identifying the 'best' areas for the conservation of biodiversity and ecosystems (Moilanen, Anderson, et al., 2011; Smith et al., 2010). Spatial conservation prioritisation corresponds to the technical phase of systematic conservation planning (SCP) and is typically implemented using site selection software based on optimisation algorithms, such as Zonation, Marxan, and C-Plan (Honeck et al., 2020). Spatial conservation prioritisation can be based solely on the distribution of biodiversity features (e.g., species, habitats, ecosystem services (ES)), or on a combination of biodiversity features and variables representing the assumed costs of the intended action (Moilanen et al., 2022). Naidoo et al. (2006) suggest to distinguish between five types of conservation costs: opportunity costs; acquisition costs; management costs; damage costs; and transaction costs (Figure 1; Table A1). Estimates or proxies of costs can be monetary, such as net present value of farmland (€/ha), or non-monetary, such as slope (Chomitz et al., 2005; Moilanen, Anderson, et al., 2011).

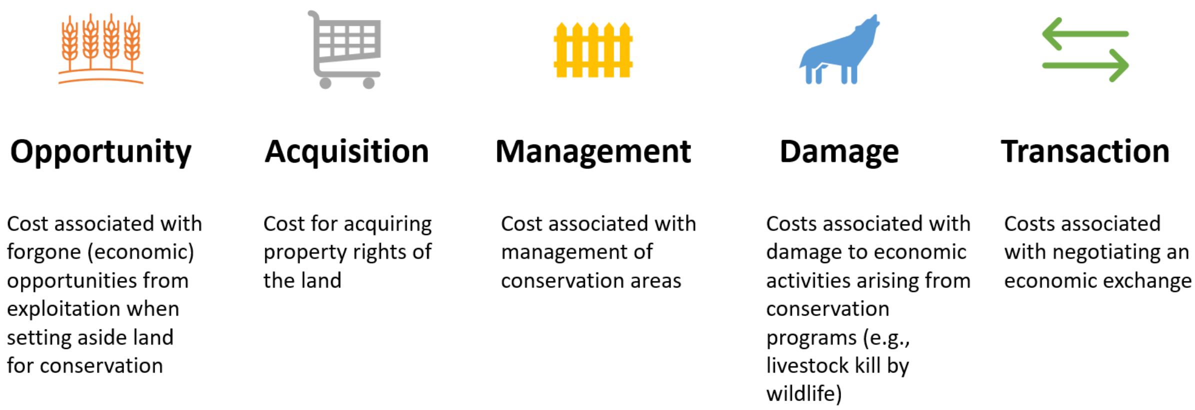

Figure 1: Typology of the (economic) costs of nature conservation. Building on Naidoo et al. (2006).

So far, many spatial conservation prioritisation attempts have ignored costs and identified conservation priorities only based on biodiversity and ES features (Jalkanen et al., 2020; O'Connor et al., 2021). This omission of costs may reflect, among others, the goal and scope of the analysis (e.g., if the goal is to identify priority sites for conservation just from a biodiversity perspective, costs are deliberately omitted; Smith et al., 2018), barriers in cost data acquisition, a reluctance to make existing models more complex, or a lack of trust in the reliability of the cost estimates (McCreless et al., 2013; Rodewald et al., 2019). In addition,

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and particularly across larger areas (e.g., continental or global extent), available cost data may insufficiently capture the spatial heterogeneity of these costs or the type of action that is required for any conservation or restoration intervention (Jung et al., 2021).

Including conservation costs in spatial conservation prioritisation efforts may affect the outcomes significantly (Ferraro 2003; Naidoo et al. 2006; Kujala et al. 2018). Ferraro (2003), for example, showed that costs considerations might be even more decisive for spatial conservation prioritisation outcomes than biodiversity information. This finding may reflect that spatial heterogeneity in conservation costs tend to fluctuate over 2-4 orders of magnitude, whereas species richness or endemism values mainly vary by one order of magnitude (Naidoo et al., 2006; Green et al., 2018). In addition, the number of biodiversity layers is generally greater than the number of cost layers, which can diminish the influence of singular biodiversity layers in comparison with singular cost layers on the spatial conservation prioritisation outcome (Kujala et al. 2018). This implies that including costs does not necessarily improve the outcomes of a spatial conservation prioritisation effort: with poor quality cost data, the outcome may actually be impaired. Nevertheless, accounting for conservation costs in spatial conservation prioritisation, if done properly, is helpful if the analysis is to inform not just about biodiversity or ES hotpots, but also about the feasibility of conservation implementation.

1.2. Aim

We aimed to establish a set of pan-European layers indicative of the costs associated with the implementation of a Trans-European Nature Network (TEN-N), to be used in the spatial conservation prioritisation to be carried out in the NaturaConnect project.

1.3. Outline

This report starts with a summary of the results of an exploratory literature review that we performed in order to identify existing approaches to include costs (or proxies thereof) in spatial conservation prioritisation (Chapter 2). We used this information, alongside a list of desirable properties of a cost layer (Chapter 3), as a basis to develop and implement an approach for establishing a set of Pan-European cost layers (Chapter 4). In Chapter 5, we describe and explain the resulting layers.

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2. Review of conservation cost estimation approaches

We conducted an exploratory and non-exhaustive review of studies that estimate conservation costs in the context of spatial conservation prioritisation, with the aim of understanding (i) the types of costs covered, following the typology proposed by Naidoo et al. (2006) (Figure 1), (ii) the type of variables used to represent or determine costs, and (iii) the methods used to translate the cost variables or proxies into a cost layer. While we acknowledge that our sample of reviewed literature (n = 20) is small compared to the number of SCP studies available (Armsworth, 2014), we identified a few patterns.

We observed that opportunity costs were used by the majority of studies, with management, acquisition and transaction costs occurring far less frequently and damage costs not being observed at all (Table A2). Variables used to represent opportunity costs were diverse and included land price, land rent, land use, productive land suitability, agricultural production, and forest conversion probability (Chomitz et al., 2005; Doelman et al., 2020; Fastré et al., 2021; Karimi et al., 2023; Moilanen, Anderson, et al., 2011; Naidoo & Adamowicz, 2006). Acquisition costs were solely represented by land price (Carwardine et al., 2008). Transaction costs have been represented by administrative costs and naturalness of planning units (Fastré et al., 2021).

Of the opportunity cost variables used, the most frequent were agricultural production or yields, agricultural land rents, land prices and land use. However, some of these variables were used as proxies for multiple types of costs (Table A2). Taking land use as an example, Karimi et al. (2023) considered land use (specifically the level of urbanisation) as an opportunity cost, whereas Moilanen, Leathwick, et al. (2011) use land use information to estimate the management cost per planning unit. Similarly, Carwardine et al. (2008) used land price to represent acquisition cost while Chomitz et al. (2005) associated it with opportunity cost. These observations demonstrate that in the reviewed literature there are no clear one-to-one relationships between cost types and cost variables, which may reflect the lack of available cost data as well as limited economic expertise in the field of ecology. This in turn may also explain why many of the studies did not specify the type of conservation cost. This sentiment of loosely relevant proxies for costs was also expressed by Armsworth (2014).

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The sample of reviewed literature further shows that multiple methods have been used to aggregate cost variables or proxies (Table A 2). When there are multiple cost variables each expressed in monetary terms, they can be simply summed (Carwardine et al., 2008; Doelman et al., 2020; Strassburg et al., 2020). However, if there are multiple cost variables or proxies with different units (e.g., multiple biophysical variables), the aggregation is more challenging. This challenge has been tackled by assigning weights to the different variables (e.g., based on perceived importance) and then aggregating them into a single layer (Di Minin et al., 2017).

If empirical cost data are available yet the coverage is incomplete, regression-based approaches have been used to estimate the conservation costs of a given planning unit as a function of multiple predictor variables. For example, Chomitz et al. (2005) used this approach to estimate land value in the Atlantic Forest of Bahia, Brazil. They used land cover and other biophysical data such as soil quality and slope together with distance to road as predictor variables and then trained a regression model with the market value of land derived from surveyed properties as the response variable. Next, they used the trained regression model to obtain a cost layer based on predictor variable layers. A more recent study by Nolte (2020) demonstrated this approach on a larger scale, across the whole of the contiguous United States. In this study, Nolte (2020) used predictor variables at the parcel-level such as ownership, buildings footprints, terrain, accessibility, land cover, hydrography, flood risk, demographics, and protection status. The model was then trained on property sales data and validated using data on cost of land acquisitions for conservation purposes.

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3. Desirable properties of a Pan-European cost layer

To be useful in the context of the NaturaConnect project, we identified the following criteria or desirable properties for the cost layer(s):

- Cost estimates should be representative of the implementation phase of conservation and restoration, in line with the focus of NaturaConnect and the spatial planning and corresponding problem formulation.
- The cost layers should extend across Europe, covering the European Union Member States and key neighbouring countries, in order to facilitate a Pan-European spatial conservation prioritization:
  - Norway
  - Switzerland
  - The Balkans (Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia and Serbia)
  - United Kingdom (UK)
- The cost estimates should be tailored to the projection, resolution and extent of the map with planning units and their specific land use classes as used in NaturaConnect.
- The layers should be applicable to different conservation actions:
  - Conservation;
  - Restoration; and
  - Creation of Green (and Blue) Infrastructure.
- The costs must be comparable between planning units (and associated land use) and countries.
- Data to estimate the costs should be available.

In view of these criteria, we propose to approximate the costs of conservation by opportunity costs (i.e., the foregone (economic) opportunities from exploiting when setting aside land for conservation) as approximated by property rent (i.e., the total net revenue or benefits from a parcel of land). These costs are representative of the implementation phase of conservation (in contrast to for example damage costs, which arise after implementation) and can be estimated across Europe based on publicly available data (in contrast to for example transaction costs, which are not feasible to obtain in a comparative manner across Europe). Despite their importance in the conservation cost analysis of a planning unit, restoration and

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management costs, such as those gathered by the European Commission (2023), have been excluded from the analysis due to inconsistencies in the empirical data across Member States, uncertainties in restoration land transitions and the lack of disaggregation of the costs into management-specific or restoration-specific actions.

In absence of land price data, land rent is a common proxy to estimate opportunity costs (see Section 2; Doelman et al., 2020; Müller et al., 2020; Schleupner & Schneider, 2013). Further, land rent data are differentiated between land types and countries, can be expressed per unit of area, and can be standardised to the same reference year, which enhances comparability across planning units and countries. Finally, using rent-based opportunity cost estimates allows to differentiate between conservation actions, as the conservation of existing natural land will be associated with different foregone economic benefits than establishing 'new' nature or Green Infrastructure.

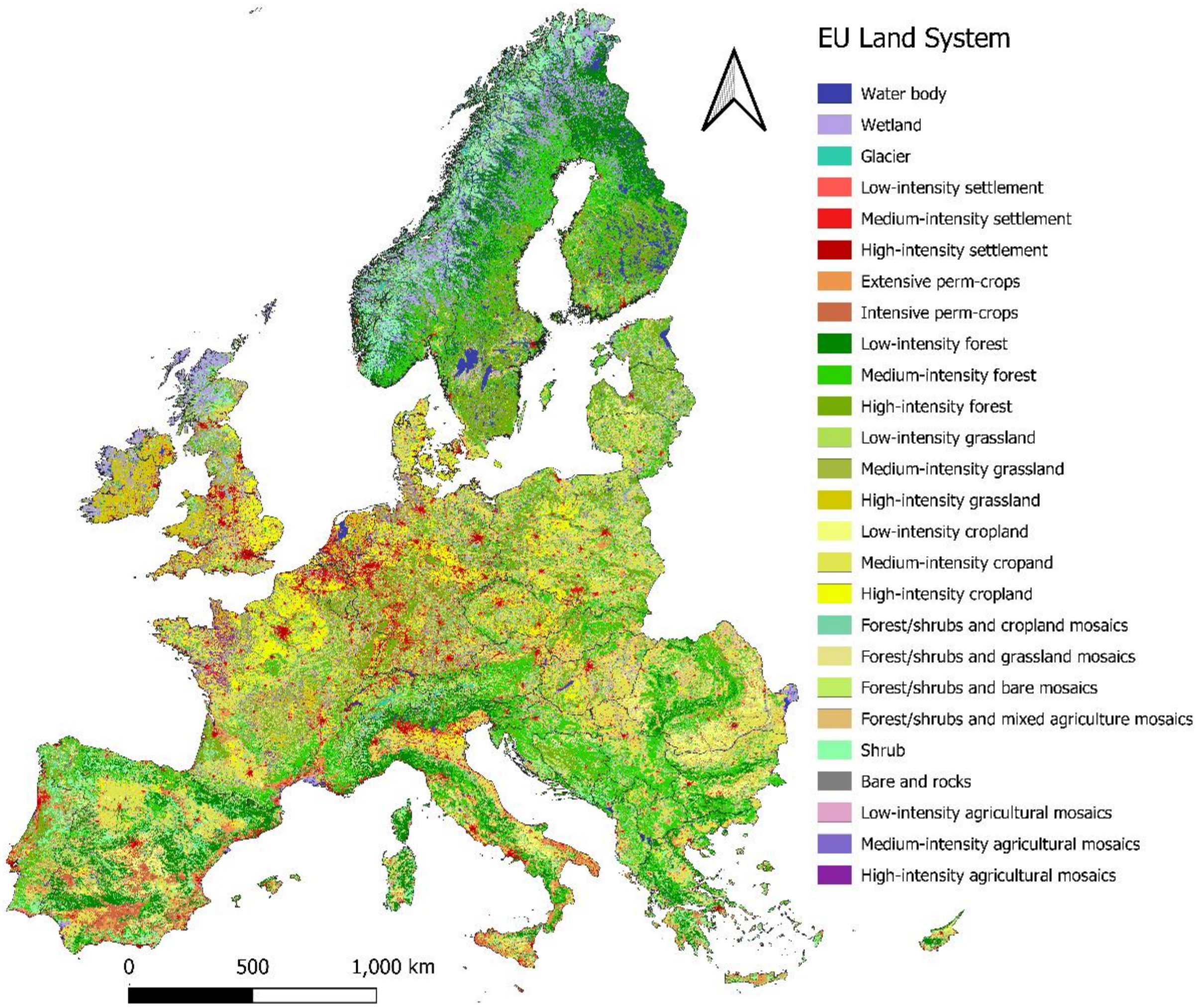

Figure 2: European Land Systems (ELS) map. Dou et al. (2021).

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4. Methodology

4.1. General approach

We use the European Land System (ELS) map by Dou (2021) as a basis to define planning units and their land use. This layer is in EPSG:3035 - ETRS89-extended / LAEA Europe projection and has a resolution of 1-km^2. It distinguishes between seven land system classes, which are further classified into 26 subdivisions (Figure 3). We reclassified the land systems into five categories and used these five categories to base the different opportunity cost estimations on: arable land, pastoral land, forestry land, urban land, and unproductive land (Table A3). We estimate the opportunity costs of productive lands (arable land, pastoral land and forestry) based on (sub)national land rent data, which we downscale based on yield, thus accounting for differences in productivity (see Section 4.2). For urban land, we use empirical data on property rent (as explained in Section 4.3). We assume that the opportunity costs of conserving economically unproductive natural lands (land covered by snow, ice and rocks) are negligible and set these to zero.

4.2. Opportunity costs of productive land

4.2.1. Land rent allocation procedure

For productive lands, land rent data is only available at a relatively coarse spatial resolution, i.e., at NUTS level 3 (sub-national administrative regions, like provinces) to NUTS level 0 (nations). To capture a greater spatial heterogeneity in opportunity costs, we proportionally allocated the coarse-grain land rent data to the planning unit level of the land systems map (1 km^2), following the approach as described by Doelman et al. (2020) and Jantke et al. (2013). Essentially, each planning unit (grid cell) is assigned a rent value that is proportional to yield obtained in that cell, as (Eq. 1):

$$mc_{i,j} = y_{i,j} \cdot \frac{mc_j}{\sum_i^n (s_{i,j} \cdot y_{i,j})} \qquad \text{Equation (1)}$$

Where j denotes the set of coarse-grain regions $j = \{1, \dots, J\}$ with land rent data available, i denotes the set of planning units within j, with $i = \{1, \dots, I\}$, $mc_{i,j}$ refers to the land rent allocated to a given planning unit in a given region (€/ha/yr), $y_{i,j}$ refers to the yield value of a planning unit within the region (€/ha/yr), mc_j denotes the regional land rent (€/ha/yr), and $s_{i,j}$ refers to the share of each planning unit in the total area of the same land type within region j (dimensionless). Since all planning units have the same area (1 km^2), $s_{i,j}$ is constant within a

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region *j* and we can equate $\sum_i^I (s_{i,j} \cdot y_{i,j})$ with the regional average of the gridded yield values $\bar{y}_{i,j}$ as (Eq. 2):

$$\sum_i^n (s_{i,j} \cdot y_{i,j}) = \bar{y}_{i,j} \qquad \text{Equation (2)}$$

which then simplifies Eq. 1 to:

$$mc_{i,j} = y_{i,j} \cdot \frac{mc_j}{\bar{y}_{i,j}} \qquad \text{Equation (3)}$$

The input data required for the opportunity cost estimation for productive lands thus include land rent data for arable land, pastoral land and forestry land (i.e., variable mc_j in Eq. 3) and spatially explicit monetary-based yield data for these land categories (i.e., variable $y_{i,j}$ in Eq. 3). The latter is typically obtained by multiplying yield data in biophysical units (kg/ha) by the unit price of the commodity (€/kg). Below we further explain how we obtained and processed the land rent data (Section 4.2.2) and the yield data (Section 4.2.3).

4.2.2. Land rent data

4.2.2.1. Arable and pastoral lands

For arable and pastoral lands, we obtained land rent data from Eurostat (Eurostat, 2023a) where available, and where not, we took values from the offices for national statistics: Federal Statistical Office of Germany (Destatis) (2021); DAERA (2022); Statistics for Wales (2013); The Scottish Government (2017); and the Federal Statistical Office of Switzerland (2022). Where we could not obtain agricultural land rent data from the offices for national statistics, we used the Modular Applied General Equilibrium Tool (MAGNET) agricultural land rent values from Doelman et al. (2020). The resolution of the compiled agricultural land rent values vary from the NUTS 3 level to the sub-continental level of the Integrated Model to Assess Global Environment (IMAGE) regions (Table 1). In the Eurostat (2023a) dataset, rent data are available for three categories: arable land rents, permanent grassland rents, and arable/permanent grassland rents, where the latter are an average of the arable and permanent grassland rents (Eurostat, 2023a). Where available, we used land rent data specific to arable land or pastoral land (using the permanent grassland rents), and where not, we used the combined arable/permanent grassland rent values. The latter applied to 16 countries (AT, CZ, DK, EE, EL, ES, FI, FR, LU, LV, MT, NL, PL, SE, SI, and UK).

Statistics Portugal (2022) provides total payable agricultural land rent values, instead of per unit area land rent values. We converted this value to a rent per hectare value based on the

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total area per NUTS 2 region of cropland and grassland obtained from the land systems map (in total, 5,200,000 ha) and we assumed the resulting value to be valid for both arable and pastoral lands. For Wales and Northern Ireland, land rent data are available per farm type, which did not always conform to the arable-pastoral land split. Therefore, we used the average value across farm types as a combined agricultural land rent value. From the remaining offices for national statistics (Switzerland, Scotland and Germany), only Germany had separate values for arable and permanent grassland land rents.

If land rent values were provided in a currency other than euro, we converted them to euros based on the exchange rate specific to the respective year. We then converted all land rents to 2021, which was the most recent year available in Eurostat (Eurostat, 2023a) at the time of analysis (i.e., first half of 2023), using a year-to-year Eurozone specific annual inflation rate (EUR Inflation Calculator - Euro, n.d.) of the euro. The resulting agricultural land rent maps are provided in Figures A1 and A2.

Table 1: Agricultural land rent data.

Resolution varies from the NUTS 3 to the sub-continental level (IMAGE region).

Agricultural land rent data source	Resolution	Countries	Number of countries
Eurostat (2023a)	NUTS 0	EE, LV, LT, LU, MT, FR	6
	NUTS 1	UK**	1
	NUTS 2	BG, CZ, DK, EL, ES, IE, HR, IT, HU, NL, AT, PL, SI, SK, FI, RO, SE, NO, UK	18
Federal Statistical Office of Germany (Destatis) (2021), **DAERA (2022),** **Statistics for Wales (2013),** **The Scottish Government (2017)**	NUTS 1	DE, UK***	2
Statistics Portugal (2022)	NUTS 2	PT	1
Federal Statistical Office of Switzerland (2022)	Provinces (NUTS 3)	CH	1
MAGNET land rent data (Doelman et al., 2020) ****	Central Europe	AL, MK, RS, BH*, ME, KO*, CY	7

* Since Bosnia and Herzegovina and Kosovo do not have NUTS codes, we use BH as two-letter country code for Bosnia and Herzegovina, and KO for Kosovo.
** Denotes England only.
*** Denotes all the countries in the UK except England: Wales, Northern Ireland, and Scotland.
**** An overview of IMAGE/MAGNET regions and respective countries is given in Table A 4.

4.2.2.2. Forestry lands

We obtained forestry land rent data from the World Bank (World Bank, 2022), which provides rent data at the national level (i.e., NUTS 0) as a percentage of a country's GDP for timber and non-timber forest products. We use the World Bank's GDP data (World Bank, 2023) to

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convert the relative values to absolute monetary values for the year 2021 and then convert these values into a per hectare unit using the total forestry area as defined by the ELS map by Dou, (2021). The forestry rent dataset covered all European countries except Kosovo (KO) and Malta (MT). We used the Serbian forest land rent value for Kosovo and for Malta, we took the average of the neighbouring countries (Italy and Greece). Similar to the agricultural land rent data, we first converted non-euro currencies to euros and then standardised all values to 2021 levels using year-to-year inflation rates. The resulting forestry land rent map is provided in Figure A 3.

4.2.3. Yield data

4.2.3.1. Arable land

To obtain arable land yield data, we combined gridded biomass-based crop yield data (available in kg/ha) with the country-specific unit price per crop (available in €/kg). We obtained crop biomass yields from the MapSPAM v2 dataset (Yu et al., 2020), which provides spatially explicit yield data at a 10 km resolution for 42 crop categories. We included all MapSPAM crop categories that are produced in Europe, according to FAOSTAT (2023b), and with crop price data available (see below), and we used the total crop biomass yield (kg/ha) across all farming technologies (irrigated, rainfed high inputs, rainfed low inputs, rainfed subsistence and rainfed), the combination of the four farming technologies was performed by Yu et al. (2020) via a weighted average of the four yields. The list of MapSPAM crops included in the calculations is provided in Table A 5. As the MapSPAM layers are in a different projection (EPSG:4326 - WGS 84) and spatial resolution (10-km^2) to the land systems projection (EPSG:3035 - ETRS89-extended / LAEA Europe) and spatial resolution (1-km^2), we reprojected and then up-sampled the MapSPAM maps. We used the ‘nearest neighbour’ resampling method in reprojection step since it minimises changes to pixel values and the ‘bilinear’ resampling method for the up-sampling.

We obtained crop producer prices from Eurostat (2020) and FAOSTAT (2023a), available at the country (NUTS 0) level. Primarily, we used the crop producer prices from Eurostat (2020), which are provided in euros per tonne (€/t); if not available we took the FAOSTAT (2023a) producer prices, which are provided in US dollars per tonne (USD$/t). Crop price data were missing for Cyprus, Kosovo and Montenegro. For Kosovo we assumed that the Serbian crop prices would be the same and for Montenegro and Cyprus we used an average of the price of neighbouring countries. We defined the neighbouring countries for Montenegro as Bosnia and Herzegovina, Serbia, and Albania and for Cyprus we defined the neighbour as Greece since it was the only European country sharing a (maritime) border with Cyprus. Similar to the land

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rent data, we first converted non-euro currencies to euros and then standardised all values to 2021 levels using year-to-year inflation rates. Finally, we converted prices per tonne to prices per kg for consistency with the MapSPAM data.

To combine the yield and the price data, we then matched the MapSPAM crop categories, which are based on the FAOSTAT system of crop categorisation, with the Eurostat system of crop categorisation (Table A 6). For MapSPAM crop categories that correspond to multiple crop prices, such as temperate fruit, we averaged the prices per country. Finally, we averaged the monetary yield values across the crop categories present in a grid cell in order to obtain a single monetary crop yield value per grid cell, as (Eq. 4):

$$y_{i,j} = \sum_{1}^{c} y_{c,i,j} \cdot p_{c,j} \Big/ n_{c,j} \qquad \text{Equation (4)}$$

Where $y_{i,j}$ is the yield in grid cell *i* in country *j* (€/ha/yr), $y_{c,i,j}$ is the yield of crop category *c* in grid cell *i* in region *j* (kg/ha), $p_{c,j}$ is the unit price of crop category *c* in country *j* (€/kg) and $n_{c,j}$ is the number of crop categories *c* present in country *j* according to the Eurostat (2020) and FAOSTAT (2023a) price data. The monetary crop yield layer is provided in *Figure A 4*.

4.2.3.2. Pastoral land

We quantify the yield of pastoral land based on livestock production. Because livestock production data is only available at the country level (NUTS 0), we used livestock density data from the Gridded Livestock of the World (GLW4) database (Gilbert et al., 2022a, 2022c, 2022b) to allocate the (sub)national pastoral land rent data to the grid level. We assumed that pastoral land is occupied primarily by grazing animals and therefore selected grazing ruminant livestock from the GLW4 dataset: cattle, goats, and sheep. We excluded horses assuming their contribution to livestock products (meat and milk) is negligible. While reindeer are an important source of meat and milk in Nordic countries, we could not include them because they are absent from the GLW4 data. The GLW4 dataset has a spatial resolution of approximately 10 km^2 (0.0833 decimal degrees) and includes dasymetric and areal-weighted livestock density maps (expressed in heads per 10 km^2). The areal-weighted method simply considers that all pixels of the census area are equally suitable, and assigns them an equal weight. It simply corresponds to the density of animals per km^2 in the census unit multiplied by the pixel area. The dasymetric method assigns different weights to different pixels based on high resolution environmental predictor variables and Random Forest models, and the animal census counts are distributed according to these weights (Gilbert et al., 2022a). Since we are not studying the impact on any of the spatial predictors (human population density,

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travel time to cities, elevation, slope, vegetation, and climate) used in the dasymetric method, there is no risk of circularity, hence we chose the dasymetric method, which resulted in more realistic distribution patterns (Gilbert et al., 2022a). Since the GLW4 maps are in the same projection and resolution as the MapSPAM maps, we took the same approach to resample the maps to the project projection and resolution as was done for the crop yield. We then divided the result by 1000 to convert the units from heads per 10 km^2 to heads per ha.

We converted the GLW layers (in heads/ha) to monetary values (€/ha/yr) by estimating the monetary value per head, separately for cattle, sheep and goats. To that end, we first quantified the total population (heads) of cattle, sheep and goats in each country by summing the livestock densities across the planning unit grid cells (1 km^2), as (Eq. 5):

$$n_{l,j} = \sum_1^i d_{l,i,j} \cdot 100 \qquad \text{Equation (5)}$$

Where $n_{l,j}$ is the total number of heads of livestock species *l* in country j, $d_{l,i,j}$ is the density of livestock species *l* in grid cell *i* in country *j* (heads per ha), and the factor of 100 converts head per ha to heads per km^2.

We then quantified the production per head by dividing the country-level total summed production of milk and meat, per livestock species and expressed in monetary terms, by the country-level number of heads per species, as (Eq. 6):

$$y_{l,j} = \sum_1^p y_{p,l,j} \cdot p_{p,l,j} \Big/ n_{l,j} \qquad \text{Equation (6)}$$

Where $y_{l,j}$ is the yield of livestock species *l* in country *j* (€/head), $y_{p,l,j}$ is the yield of product *p* (milk or meat) obtained from livestock species *l* in country *j* (in kg), and $p_{p,l,j}$ is the unit price of product *p* (milk or meat) obtained from livestock species *l* in country *j* (in €/kg).

We obtained the total yields of milk and meat per livestock species per country from Eurostat (2023c and 2023d), which were present in nearly all cases (except Kosovo). We obtained unit producer prices (€/kg) from Eurostat (2023b) and FAOSTAT (2023a) for the meat and milk of cattle, sheep, and goats. We note that the availability of price data was higher for cattle than for goats and sheep. We missed producer prices for all livestock species from Montenegro, Serbia, and North Macedonia, and since these countries neighbour each other, we took an average of the producer prices across the countries in the Central Europe IMAGE region. Since Kosovo was missing from all the livestock datasets (besides the GLW4) we used the Serbian livestock specific €/head values as an approximation of the Kosovan values.

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Next, we multiplied the monetary yield per head values with the GLW4 gridded population maps to obtain gridded livestock monetary yield maps (€/ha/yr), as (Eq. 7):

$$y_{l,i,j} = y_{l,j} \cdot d_{l,i,j}/1000 \qquad \text{Equation (7)}$$

where $y_{l,i,j}$ is the yield of livestock species *l* in grid cell *i* in country *j* (€/ha/yr), $y_{l,j}$ is the yield of livestock species *l* in country *j* (€/head) as obtained with Eq. 5, $d_{l,i,j}$ is the density of livestock species *l* in grid cell *i* in country *j* (in head per 10 km^2), and the factor of 1000 is to convert from 10 km^2 to ha.

Finally, we averaged the yield data across the livestock species in a grid cell to arrive at the total monetary pastoral yield per grid cell, as (Eq. 8):

$$y_{i,j} = {\sum_1^l y_{l,i,j}}\Big/{n_{l,j}} \qquad \text{Equation (8)}$$

Where $n_{l,j}$ represents the number of livestock species (0-3) in country *j* according to the livestock price data Eurostat (2023b FAOSTAT (2023a). The monetary pastoral land yield map is provided in Figure A 5.

4.2.3.3. Forestry land

We obtained timber yield values in monetary terms by multiplying grid-specific woody biomass yield per year values (available in 1000m^3/km^2) by the export roundwood timber prices per country (available in €/1000m^3), as (Eq. 9):

$$y_{i,j} = {y_{t,i,j} \cdot p_{t,j}}\Big/{100} \qquad \text{Equation (9)}$$

where $y_{i,j}$ is the yield in grid cell *i* in country *j* (€/ha/yr), $y_{t,i,j}$ is the timber yield in grid cell *i* in country *j* (1000m^3/km^2), $p_{t,j}$ is the unit price of timber in country *j* (€/1000m^3), and the division by 100 is to convert from km^2 to ha.

We retrieved the gridded timber yield data from the wood production dataset by Verkerk et al (2015). They used wood production statistics for 29 European countries from 2000-2010 in combination with a regression model using biophysical and socioeconomic location factors to downscale wood production to a 1 km^2 resolution for each year. We used the latest map available in the Verkerk et al. (2015) dataset, i.e., the annual wood production of 2010. The projection and extent of this map are already aligned to our land systems map. The wood production map omits Malta and the Western Balkan states (HR, RS, ME, MK, BH, AL, KO);

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we used the remaining nations in the IMAGE Central Europe region to derive an average forest production value for these countries.

We obtained roundwood export timber prices (€/1000m^3) from UNECE/FAO (2023) and converted these to 2021 levels. Timber price data were missing for Kosovo, North Macedonia, Bosnia and Herzegovina, Cyprus and Malta. For the latter two countries, we used price values for Greece, and an average of Italy and Greece, respectively. Following our assumption that Serbia has the closest values to missing Kosovo values, we used the Serbian timber price value for Kosovo. We used an average of the neighbouring country values for North Macedonia (AL, BG, RS and EL) and Bosnia and Herzegovina (RS, HR, and ME). The monetary forestry yield map is provided in Figure A 6.

4.2.4. Technical validation

After allocating the rents for arable, pastoral and forestry land, we checked whether the implementation was done correctly by calculating the average allocated land rent values across the cells in each region and comparing them to the regional input land rent values. These two averages were then again averaged to arrive at two mean values for the input and the output proportionally allocated land rents. The mean of the input rents should be equal to the mean of the output land rents. Our check showed that the allocated values were in line with the region-level values (Table A7), however we note small deviations between the means that are due to the spatial misalignment of the input datasets.

4.3. Urban land rent

To approximate urban land opportunity costs, we used residential rent values (Eurostat, 2023f). Monthly residential rent values are available for all capital cities across Europe, and some additional cities (DE: Bonn, Karlsrühe and München; IT: Varese; CH: Genève) and a village (UK: Culham). The rent values are specified for different dwelling types: non-detached house, detached house and 1-, 2-, and 3-bedroom flats. We aggregated these dwelling types into two groups, houses and flats, and averaged the rents. As for all monetary-based datasets in this study, we applied the aforementioned nominal-to-real conversion method, to get city rent monetary values into 2021 euros. We then converted the monthly values into yearly values, to get the average yearly rent per city per dwelling type.

Since the rent values were per dwelling type, we converted them into per hectare values. To achieve this, we derived the total population per dwelling per city, using the proportion of city population per dwelling type per country (Eurostat, 2023g) in combination with the total population per city in 2017 (Eurostat, 2023h; UN Statistics Division, 2023 (for MK, RS);

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INSTAT 2013; Statistical Office of Montenegro, 2011; Office for National Statistics of the UK, 2011; Agency of statistics of Bosnia and Herzegovina, 2013; Kosovo agency of Statistics, 2016) (Eq. 10):

$$P_{d,c} = \rho_{d,c} \cdot P_c \qquad \text{Equation (10)}$$

Where P_c is the total population in city c, and $\rho_{d,c}$ is the proportion of the population in dwelling type d in city c.

Data linking household size and dwelling type was not available, therefore we assumed the typical household sizes for houses and flats to be four (a family with two kids) and two (a couple), respectively. Using these assumptions on household size per dwelling group (houses and flats), and the total population per city, we derived an estimate for the number of units of each dwelling type per city (Eq. 11):

$$N_{d,c} = P_{d,c}/H_d \qquad \text{Equation (11)}$$

Where $N_{d,c}$ is the number of units per dwelling type *d,* in city c, and H_d is the assumed household size in dwelling group d .

Next, we multiplied the number of units per dwelling group per city by the yearly rent per city per dwelling type to find the yearly cumulative rent per dwelling type per city (Eq. 12):

$$R_{d,c} = r_{d,c} \cdot N_{d,c} \qquad \text{Equation (12)}$$

Where $r_{d,c}$ is the average yearly rent for dwelling type d in city c, and $R_{d,c}$ is the total yearly rent in dwelling group, d, in city, c. We then summed the yearly cumulative rents across dwelling types to get to the annual total rent per city (Eq. 13):

$$R_c = \sum_d^D R_{d,c} \qquad \text{Equation (13)}$$

Where D is the upper limit of dwelling groups and d is the lower limit, and R_c is the yearly total rent in city c. Finally, we used city area values (Eurostat 2021; Eurostat 2019 (London); City of Belgrade, 2023; Albanian Association of Municipalities, 2011 (Tirana); Republic of Kosovo, 2017 (Pristina); Wikipedia, 2023 (Skopje, Podgorica, Sarajevo); City Population, 2023 (Culham)) to derive a per-hectare yearly total rent (Eq. 14):

$$R_{a,c} = \frac{R_c}{A_c} \qquad \text{Equation (14)}$$

Where $R_{a,c}$ is the area-standardised yearly total rent (€/ha/yr) and A_c is the area (ha) of city, c.

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To approximate the expected difference in urban land opportunity costs between low and high-intensity settlements (Figure 3), we decided to use a residential rent factor of difference between villages and cities in the Eurostat (2023f) dataset. However, since there was only one village in the whole dataset (Culham), we could establish only a single conversion factor for urban-to-rural rents (London to Culham), which we used to convert opportunity cost values for high- and medium-intensity cities to low-intensity cities across Europe.

4.4. Integrating opportunity cost layers across land types

Finally, we averaged across all opportunity cost layers to arrive at an opportunity cost layer integrating all land subdivisions from the ELS map (besides water bodies). Using this layer we standardised the average opportunity cost values within each nation via standard-score (Z-score) normalisation (Eq. 15):

$$x' = \frac{x - \bar{x}_j}{\sigma_j} \quad \text{Equation (15)}$$

Where x' refers to the Z-score, x refers to the raw value of opportunity cost, $\bar{x}_j$ refers to the mean of the opportunity cost in country j, and σ_j refers to the standard deviation in country j.

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5. Results and Discussion

5.1. Arable land opportunity cost layer

The arable land opportunity cost layer showed the highest heterogeneity (standard deviation (SD) of 377 €/ha/yr) as well as the highest mean value (326 €/ha/yr) of the three productive land types. In the majority of the grid cells, allocated arable land rents fall between 5 and 400 €/ha/yr (Figure 4). Considerably higher values are found in Italy and the Netherlands, in contrast Portugal stands out due to lower values (Figure 5). These spatial differences correspond with differences in land rent. The highest NUTS 2 arable land rents are in Friuli-Venezia Giulia, an Italian province in the Po valley where arable land rent is approximately 2,600 €/ha/yr. Further, agricultural land rents are generally high across Italy (mean, 1,164 €/ha/yr), in comparison to the average land rent in Europe (326 €/ha/yr). The province of Flevoland in the Netherlands also has high land rents (1,721 €/ha/yr). In contrast, Portugal is characterised by rather low arable land rents, particularly in the Algarve (NUTS 2 arable rent, 3 €/ha/yr) and Alentejo regions (NUTS 2 arable rent, 5 €/ha/yr). These low arable rents could be due to inaccuracies introduced when converting the Portuguese agricultural land rents from total per region into the regional average per hectare (see Section 4.2.2.1).

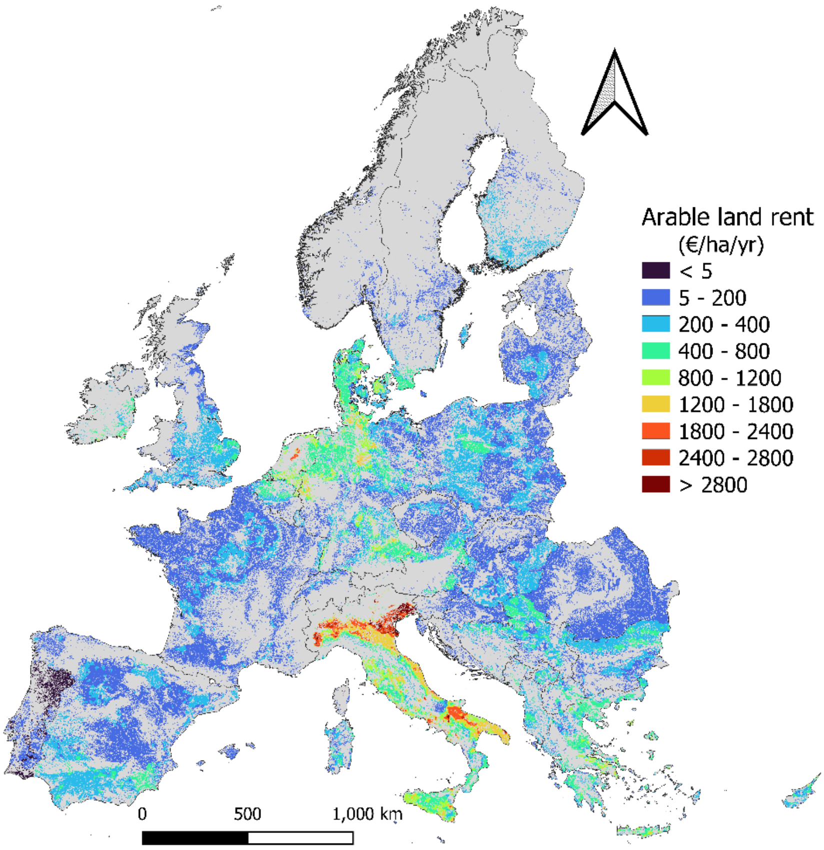

Figure 3: Opportunity cost layer for arable land in (€/ha/yr).

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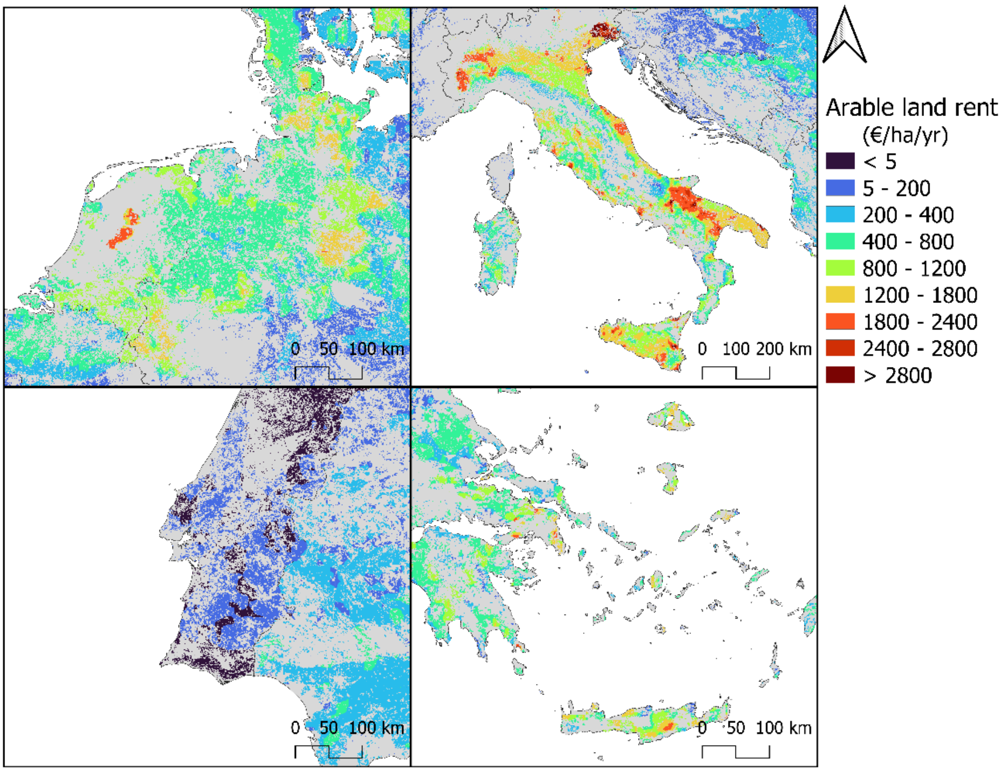

Figure 4: Hot and cold spots of opportunity costs for arable land in Europe in (€/ha/yr).

Top left panel shows high arable land rents in the Netherlands and in the surrounding areas in Germany. Top right panel shows very high arable land rents in Italy, particularly in the Po valley, in Puglia, and across Sicily. Bottom left panel shows areas of very low arable land rents in Alentejo and the Algarve. Bottom right panel shows high arable land rents in mainland Greece, the Greek islands, and Crete.

Considering the large swathes of arable land, mainland France shows little variation in arable land opportunity cost, which could be explained by the coarse land rent source data (NUTS 0 level). This finding also indicates that variation in land rent drives the outcome of the allocation procedure more than variation in crop yield, given that the monetary yield varies considerably across France, from 1,541 €/ha/yr in Brittany (Bretagne) to 3,577 €/ha/yr in Pays de la Loire (*Figure A 4*).

5.2. Pastoral land opportunity cost layer

The pastoral land opportunity cost layer (Figure 6) shows considerable heterogeneity (SD 257 €/ha/yr) and an average land rent value of 264 €/ha/yr, albeit both less than the arable land opportunity cost layer (Figure 4). Similar to the arable land opportunity cost map, the Netherlands and Italy (the Po valley and Tuscany) show hotspots of high land rent values. Relatively high values are also found in Southern Ireland, with pastoral land rent falling between 400 and 800 €/ha/yr, driven by the relatively high pastoral land rent of the region (426 €/ha/yr).

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The southern regions of Portugal display low pastoral land rents, similar to the patterns in the arable land opportunity cost map (Figure 5 and 7). The congruence of these low values in this region of Portugal in both agricultural maps is due to the low Portuguese agricultural land rent values, which are not differentiated between arable and pastoral lands. Also, Norway is characterised by low pastoral land rents across the country (Figure 7), where shrubland, a land type that typically is not associated with high levels of pastoral farming productivity, dominates the landscape (Figure 3). This aligns with the low average NUTS 2 permanent grassland rents of the region (8 €/ha/yr).

When comparing the agricultural (arable and pastoral) land rents with the Eurostat (2023e) output of the agricultural industry dataset, we can see agreement for high ranking nations for 2021 such as Italy (~61,000 million € agricultural production value at producer price), Germany (~59,000 million €), and the Netherlands (~30,000 million €), but our maps do not highlight France as a land with markedly high agricultural opportunity costs, despite it having the greatest value (~81,000 million €). This disparity of agricultural production value and proportionally allocated land rents in France could be attributed to the empirical agricultural land rent of 149 €/ha/yr, which does not discriminate between the arable and permanent grassland lands.

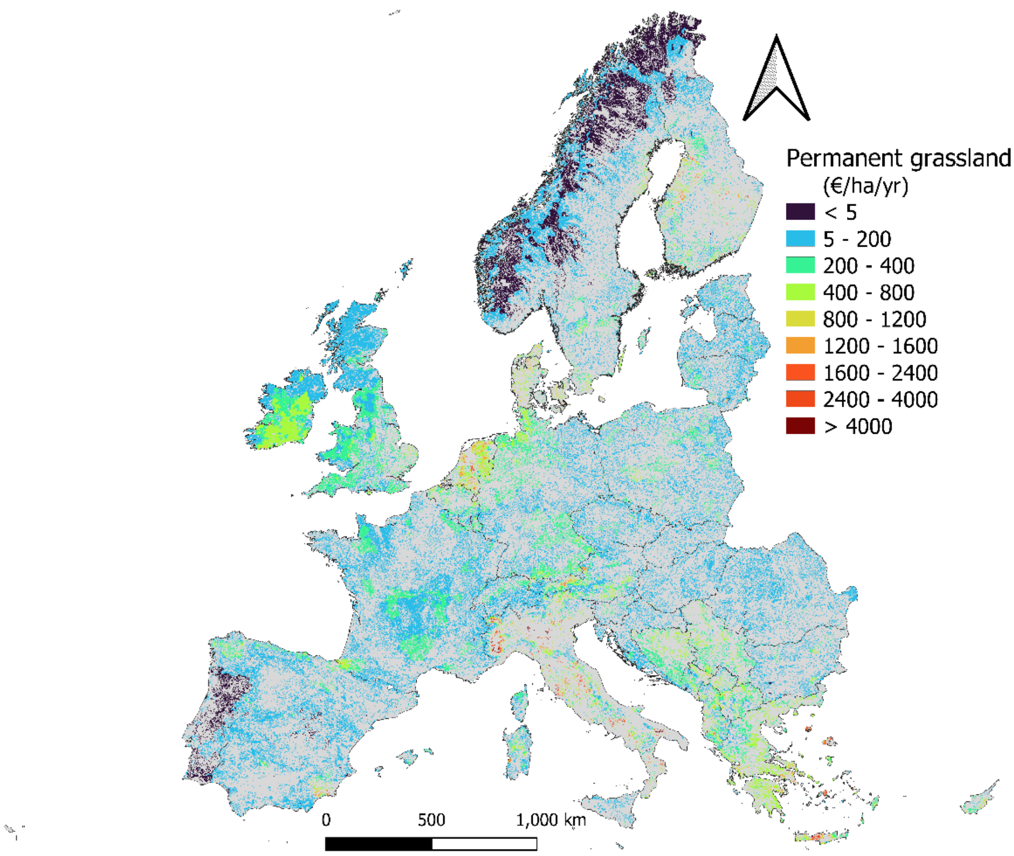

Figure 5: Opportunity cost layer for pastoral land in Europe in (€/ha/yr).

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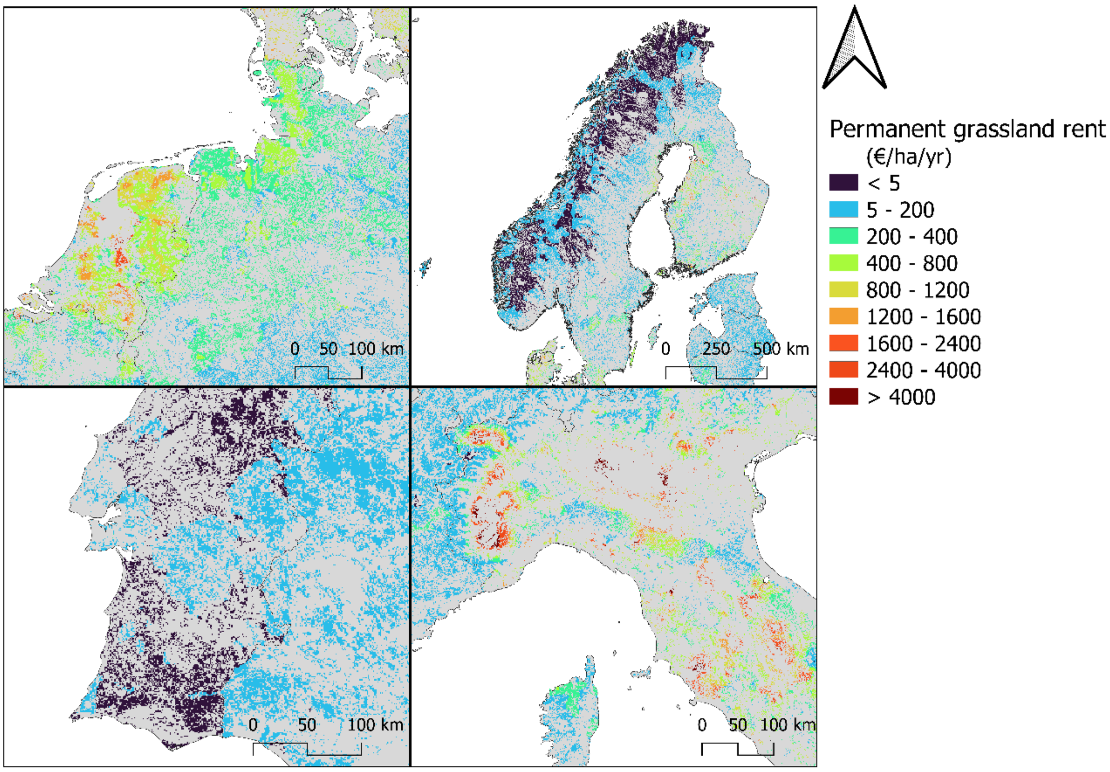

Figure 6: Hot and cold spots of opportunity costs of pastoral lands in Europe in (€/ha/yr).

Top left panel shows high pastoral land rents in the Netherlands and in the surrounding areas in Germany. Bottom right panel shows very high permanent grassland land rents in Italy, particularly in the Po valley and Tuscany. Bottom left panel shows areas of very low permanent grassland land rents in Alentejo and the Algarve. Top right panel shows large areas of very low permanent grassland land rents in Norway and Sweden.

5.3. Forestry land opportunity cost layer

The forestry opportunity cost map represents the lowest land rent values in comparison to the other opportunity cost maps, with a mean of (66 €/ha/yr) (Figure 8). Besides the relatively high forestry opportunity cost values in the Landes forest in the southwest of France, countries in central Europe such as Germany, Czechia and Poland show patches of high forestry land rent. These high values are driven by high NUTS regional land rents, with Czechia having by far the highest forestry land rent in Europe (Czechia: 272 €/ha/yr). The forested area in Sweden only shows much lower land rent values (34 €/ha/yr), a result that goes against our expectations given the high levels of total woody biomass production according to Verkerk et al. (2015) (Figure 9).

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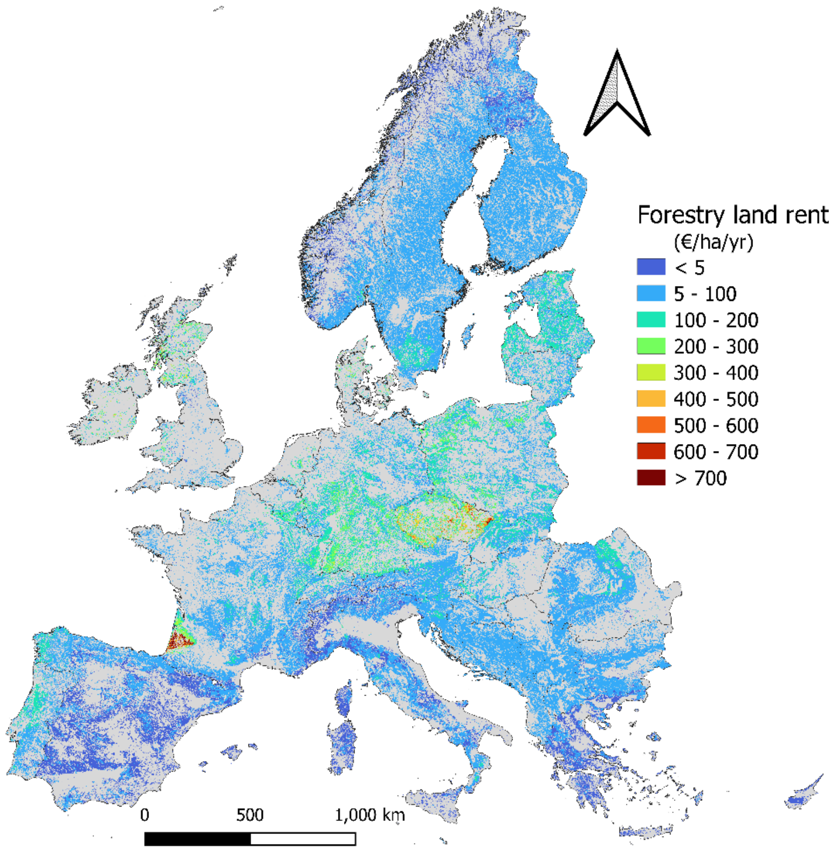

Figure 7: Opportunity cost layer for forestry land in Europe in (€/ha/yr).

The forestry rent per hectare values are based on the national rental rate times the national total forestry revenue (including both timber and forest nontimber resources) (World Bank, 2021) and the total forest area as defined in the ELS map (Dou, 2021). We explain the stark difference between these two per hectare forestry rent values due to the greater size of the forested areas in Sweden compared to Czechia and the greater woody biomass production intensities in Czechia compared to Sweden. According to the ELS map (Figure 2), the forested area in Sweden is approximately 11 times greater than the forested area in Czechia and a greater proportion of the forest is low-intensity (Dou, 2021). These forest area values were used to derive a per hectare forest rent value and so, despite the total forest rent being ~1.5 greater in Sweden than in Czechia according to the World Bank (2022), the calculated per hectare forest rent in Sweden is significantly lower. A validation of the forest rent dataset with local values in Sweden and Czechia would provide more insight into the accuracy of the input per hectare forestry rent values.

In Scotland, there are many small clusters of high levels of forestry land rent, which mirror the small clusters of highly productive forest as shown by Verkerk et al. (2015) (Figure 8). Much of the mountainous regions in Europe (the Pyrenees, the Alps, the Apennines and the Dinaric

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Alps) show very low levels of proportionally allocated forestry land rents. This commonality could be due to the relatively low levels of accessibility as compared to the flat terrain and low-lying Landes forest, being much more accessible to forestry activities.

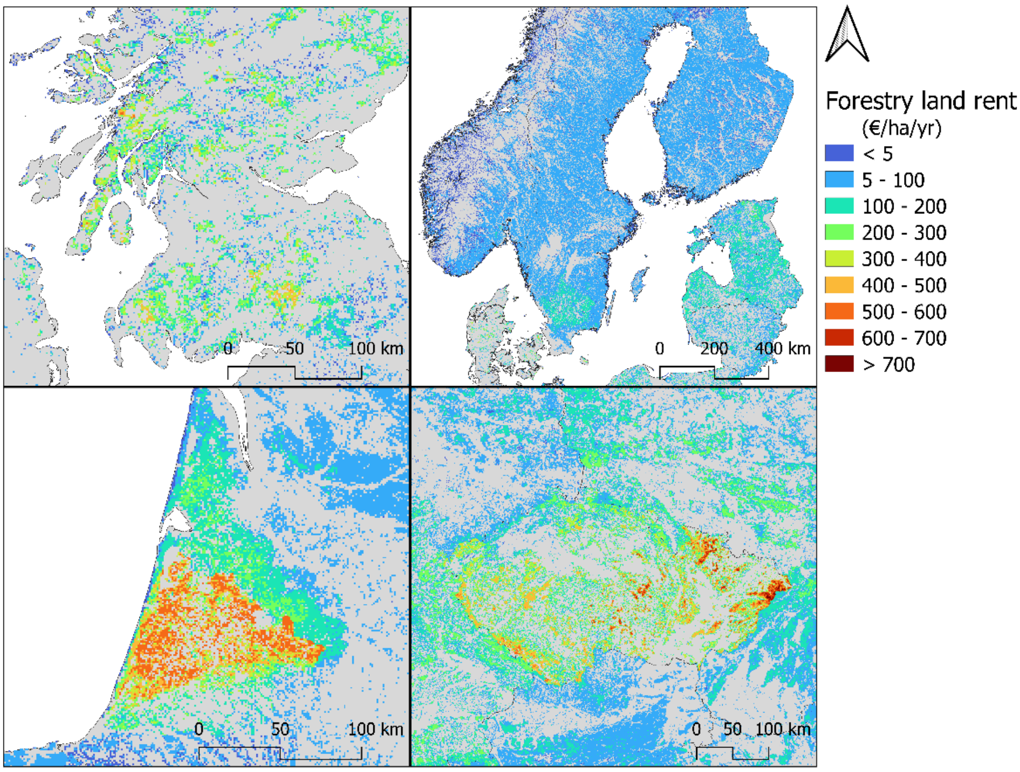

Figure 8: Hotspots of opportunity costs of forestry land in Europe in (€/ha/yr).

Top left panel shows scattered areas of high forest land rents in Scotland. Top right panel shows consistent areas of moderate forestry land rents in Scandinavia, Estonia and Latvia. Bottom left panel shows large areas of very high forestry rents in the Landes forest in the southwest of France. Bottom right panel shows multiple spots of very high forestry land rents in Czechia.

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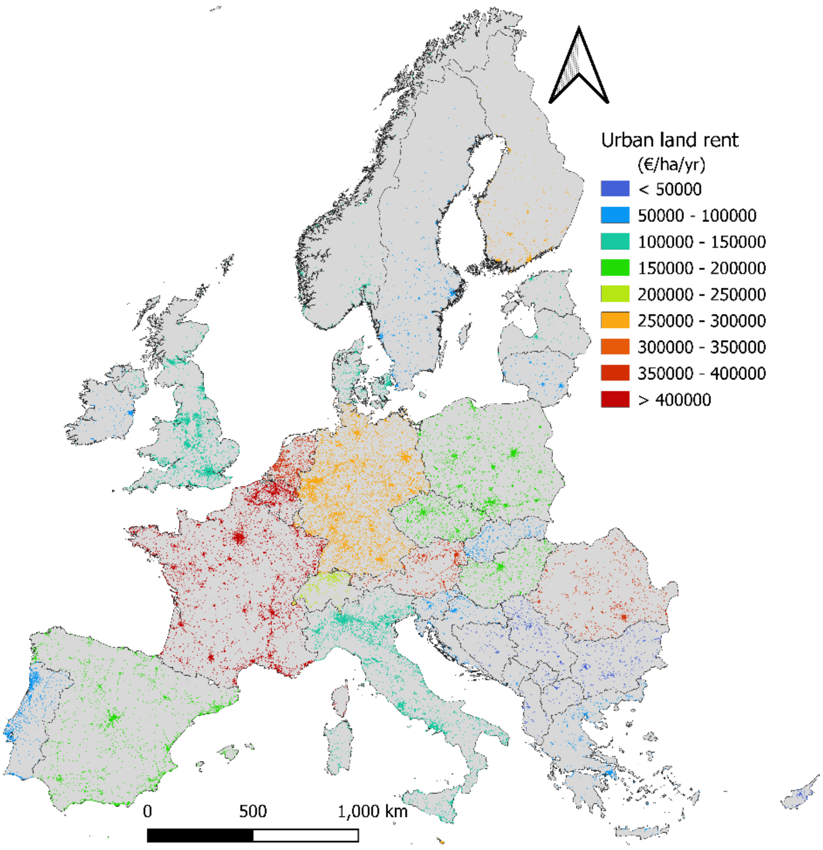

Figure 9: Opportunity cost layer for urban land in Europe in (€/ha/yr).

5.4. Urban land opportunity cost layer

The average urban land opportunity cost value (~230,000 €/ha/yr) is considerably higher (~750 times) than the mean arable opportunity cost value. This is to be expected since the residential rent values that the urban land opportunity cost values are based off are exceedingly higher than the arable land rent values. France leads with the highest average urban land opportunity cost (~500,000 €/ha/yr), whereas Bosnia and Herzegovina has the lowest average urban land opportunity cost value of (~€6,400 €/ha/yr). Furthermore, the urban land opportunity cost map (Figure 9) shows the greatest homogeneity compared to the agricultural and silvicultural land opportunity cost maps. This reflects that no proportional allocation was performed and therefore the values are the same for all urban areas in the same country. We explored the effect of reducing the urban land opportunity costs in rural settlements by an urban-to-rural reduction factor (~38). The resulting difference is highlighted in Figure 10 which shows how the rural areas surrounding Paris have a markedly lower urban land opportunity cost when the urban land opportunity cost reduction factor is applied . This urban-to-rural reduction factor offers a broad estimate of the differences in residential rates between urban and rural areas. However, since it is only based upon the rent relationship between two UK urban and rural settlements, it is not necessarily a representative reduction

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factor of the whole of Europe. With empirical rural residential rent data across Europe, nation-specific reduction factors could be derived to estimate more accurate urban-to-rural rent reductions across the respective European nations.

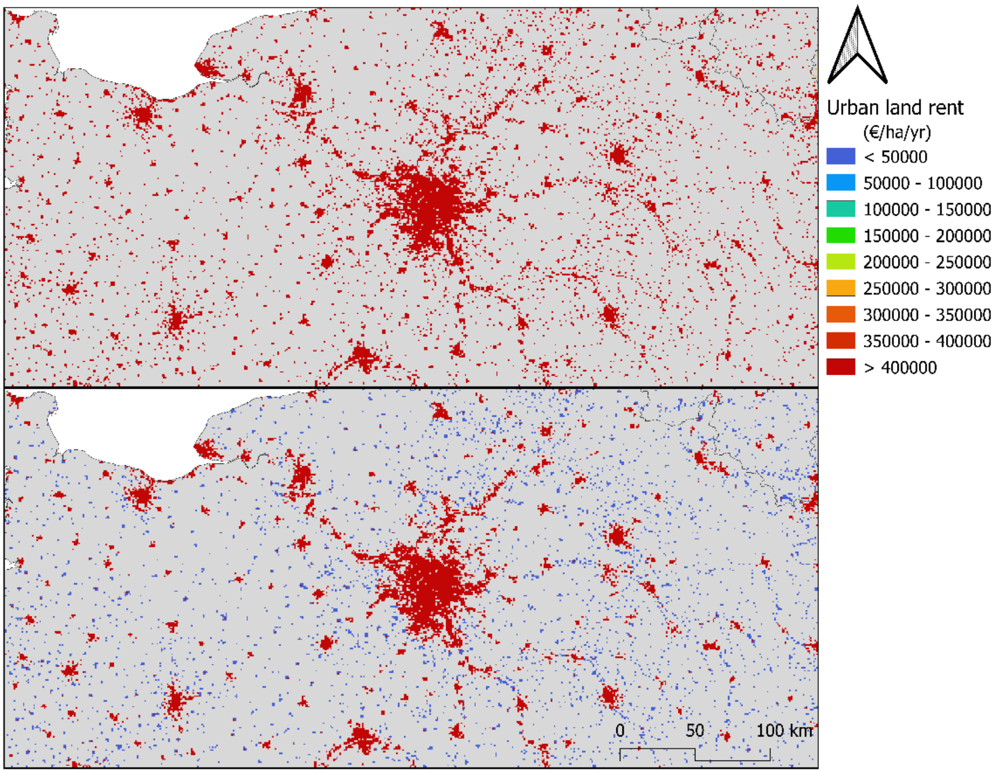

Figure 10: Opportunity cost for urban land in Paris and surrounding areas in (€/ha/yr).

Top panel shows the urban land rents map without a distinction between urban and rural settlement areas as shown in Figure 9 . Bottom panel shows the urban land rents map with a distinction between urban and rural areas.

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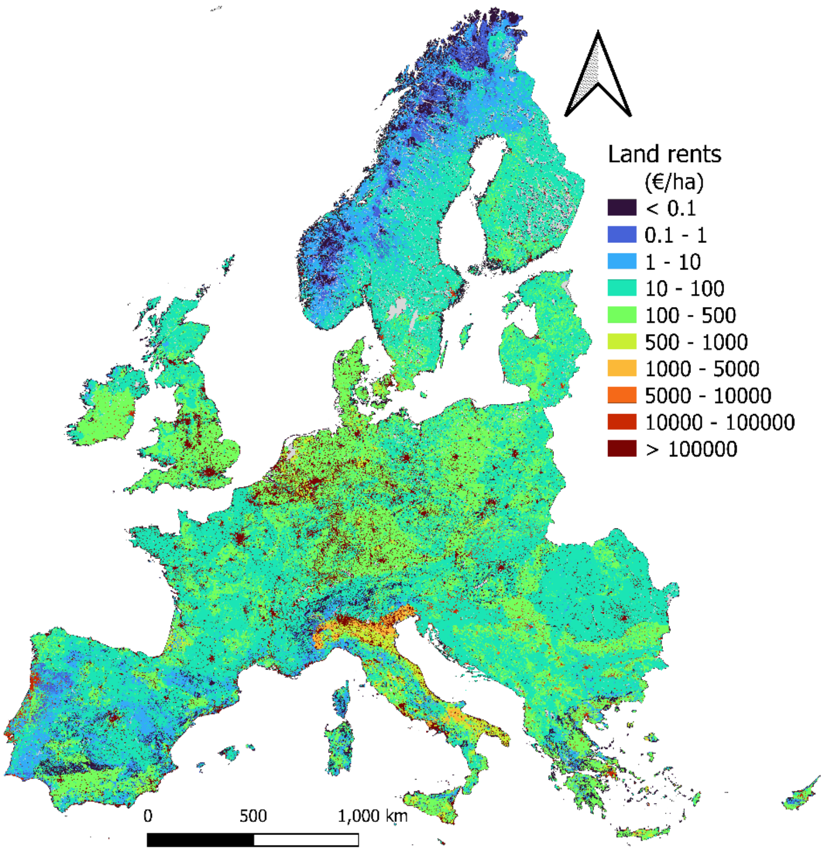

Figure 11: Combined opportunity cost layers in Europe in (€/ha/yr)

5.5. Combined opportunity cost layer and z-score standardised layer

Aggregating land rents across all land subdivisions from the ELS map (besides water bodies), we see that the urban land classes stand out with the highest rents (Figure 9). The Z-score standardisation mirrors this disparity between urban land class rents and the rest of the land classes and shows a positive skew of data (Figure 12). On the lower end of the scale are generally the mountainous regions (Scandes, Pyrenees and Alps). Considerably close to the urban rents, however, are the agricultural land rents in the Po Valley of Italy as well as in the Italian province of Puglia. The combined layer naturally shows the greater heterogeneity since it is the synthesis of all the individual opportunity cost layers. Furthermore, we note that the countries with more detailed information on cost in our dataset (e.g. Italy and Germany) show greater heterogeneity than the countries with relatively poor quality of data from our data compilation (e.g. Western Balkan states). The combination of the individual opportunity cost layers could be improved by aggregating based upon the proportions of the different land cover classes within the mixed land systems, instead of using an equal weight average.

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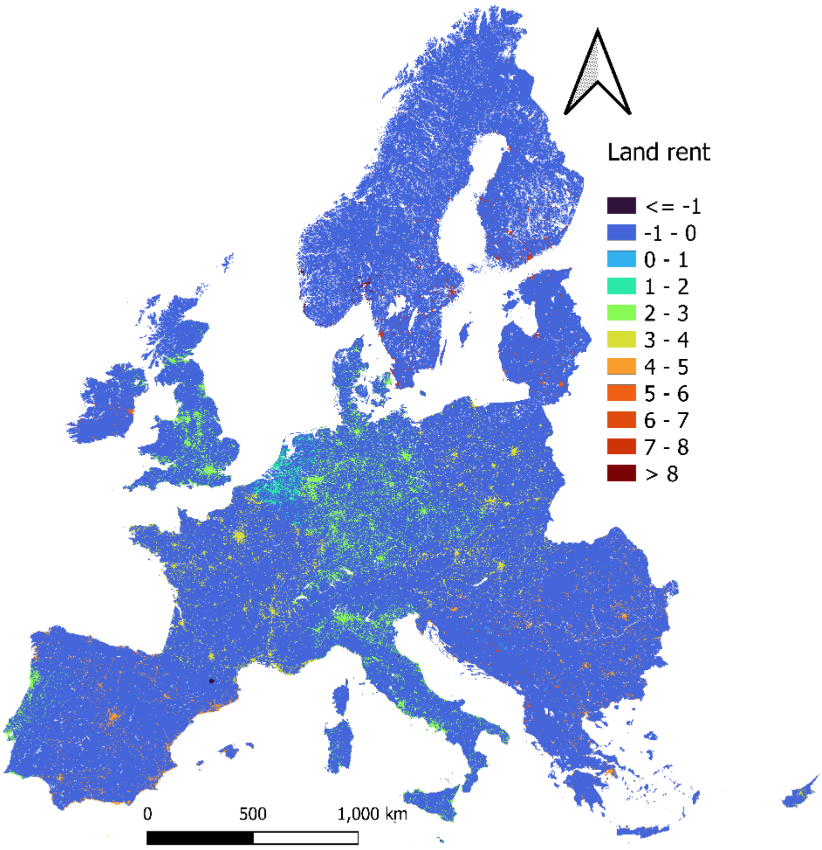

Figure 12: Z-Score standardised land rents of Europe.

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6. Conclusion

We present here gridded opportunity costs maps for arable, pastoral, forest, and urban lands across Europe. Overall we note higher opportunity costs in urban lands followed by arable and pastoral land opportunity costs and lastly, forestry land opportunity costs. We combined the individual opportunity cost layers into a single opportunity cost map using the average value of each land type per grid-cell. We also offer a zero-mean intranational standardised layer to reduce the prioritisation bias to countries with a lower rent values. It is important to refer that several datasets with different coverage, units and resolution were combined to produce the different opportunity costs layers. The availability of consistent spatially explicit datasets at the European level of land rents and agricultural yields would result in improved opportunity costs layers. We also note that these opportunity cost layers lack sufficient validation from empirical datasets, a procedure that represents future improvements of the layers, once such data has been acquired. These layers have been designed for integration into a European wide spatial conservation prioritisation. To enhance the cost of conservation analysis, management and restoration cost layers that distinguish between restoration or management actions could be used in combination with the opportunity cost layers. The develop of management and restoration layers represents an area of future research, since the empirical dataset on these costs is not consistent and lacks important detail on the actions associated with costs. Conservation support offers another research area for cost analysis improvement. Although the opportunity cost layers produced in this analysis have room for improvement, they represent a first step in consistently estimating conservation cost across Europe.

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8. Annexes

Table A 1: Types of conservation costs.

From Naidoo et al. (2006).

Conservation Cost	Definition
Acquisition costs	Acquisition costs are costs of acquiring property rights to a parcel of land. Acquisition of property rights can be total (i.e. the land and title are sold to a conservation agent) or partial. Partial transfers of property rights include short-term land rental, conservation easements, and contracts between conservation agents and landowners that exchange money for land management that enhances conservation value.
Management costs	Management costs are those associated with management of a conservation program, such as those associated with establishing and maintaining a network of protected areas. Management costs can be fixed, and therefore independent of the amount of conservation activities pursued (e.g. regardless of how much land is protected in an area, an office will need to be opened and a minimal amount of staff hired); or variable, and therefore proportional to the amount and type of conservation intervention.
Transaction costs	Transaction costs are those associated with negotiating an economic exchange. In a terrestrial conservation context, the costs over and above the price of a transfer of property rights to a given parcel of land. These include the costs of searching for properties, negotiating with individual landholders and obtaining approval for title transfer. Transaction costs can be substantial; for example, carbon sequestration projects involving afforestation or reforestation can be beneficial for conservation, but high transaction costs often limit their viability.
Damage costs	Damage costs are those associated with damages to economic activities arising from conservation programs; for example, damages to crops and livestock from wild animals living in protected areas adjacent to human settlements can result in significant losses in income. In other cases, direct wildlife attacks might physically harm or kill humans, resulting in further economic losses.
Opportunity costs	Opportunity costs are costs of foregone opportunities; that is, they are a measure of what could have been gained via the next-best use of a resource had it not been put to the current use. In terrestrial protected areas where extractive uses are forbidden, the opportunity cost represents the highest-value extractive use for that land. When purchasing land or conservation easements from private land owners, payments will reflect the value of lost opportunities. With public land or with regulation, direct financial obligations might be divorced from the value of lost opportunities. From a social perspective, it is important to include opportunity costs to track the full set of consequences of conservation planning.

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Table A 2: Overview of reviewed literature.

Includes a breakdown of author, year, cost categorisation according to categories by Naidoo et al. 2006 (if specified in the paper), cost variable, and method of total cost aggregation.

ID	Author	Year	Cost categorisation	Cost variable	Total cost aggregation method
1	Barbosa et al.	2018	Management costs	Land cover-associated restoration costs	Weighted according to land type and degradation level
2	Cameron et al.	2008	Opportunity costs	Population	Weight and ranked costs
				Distance to village	
				Subsistence gardens	
				Cash crop potential	
				Small-scale logging potential	
				Plantation parcel	
				Mining licenses	
				Forestry potential	
				Plantation suitability	
				Distance to airstrips	
				Distance to road	
				Forestry license	
				Mining license	
				Distance to village	
3	Carwardine et al.	2008	Transaction costs	Flat administrative cost for each parcel	Monetary summation
			Not specified	Native vegetated area as a spatially homogenous cost	
			Acquisition costs	Land price	
			Not specified	Agricultural production (NPV)	
4	Chomitz et al.	2005	Opportunity costs	Land price	Regression
5	Cunningham et al.	2021	Opportunity costs	Urban and agricultural land use	Standardisation
6	Di Minin et al.	2017	Not specified	Land suitability for agriculture and forestry	Weight and ranked costs
			Not specified	Land price	
7	Doelman et al.	2020	Opportunity costs	Agricultural land rents	Weighted
			Not specified	Monitoring costs	
				Conversion costs (planting initial trees)	
8	Duran et al.	2014	Not specified	Agricultural production	Weighted
9	Fastre et al	2021	Opportunity costs	Farming suitability	Summation
			Transaction costs	Naturalness of planning unit	
10	Jung et al.	2021	Not specified	Land area	Weighted

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ID	Author	Year	Cost categorisation	Cost variable	Total cost aggregation method
11	Karimi et al	2023	Opportunity costs	Urbanisation level	Weighted
12	Moilanen et al.	2011a	Opportunity costs	Agricultural production	Weighted
				Urban area (development priority area proxy)	
13	Moilanen et al.	2011b	Management costs	Land use-associated management costs	Weighted
14	Mu et al.	2022	Not specified	Engineering cost	Overlay analysis
			Opportunity costs	Agricultural production potential	
			Not specified	Eco-compensation costs	
15	Müller et al.	2020	Opportunity costs	Agricultural land rents	Land rents arithmetic mean
16	Naidoo and Adamowicz	2006	Opportunity costs	Forest conversion probability	Regression
				Land rent	Averaged according to land use
17	Rodewald et al.	2019	Not specified	Land value	Monetary summation
18	Schleupner and Schneider	2013	Opportunity costs	Land rent	Weighted
			Not specified	Naturalness of wetland site	
				Neighbouring land use (hemerobic index)	
19	Strassburg et al.	2020	Opportunity costs	Agricultural production	Monetary summation
			Not specified	Restoration costs	
20	Nolte	2020	Land acquisition	Land price	Regression

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Table A 3: Overview of land systems and corresponding land categories used for the opportunity cost layers.

Land system	Sub-division	Description	Land category: Urban land	Forestry land	Arable land	Pastoral land	Unproductive land
Settlement systems	1.1 Low-intensity settlement	Low-medium density, far away from urban cores	X				
	1.2 Medium-intensity settlement	Medium density or adjacent to urban core	X				
	1.3 High-intensity settlement	High imperviousness	X				
Forest systems	2.1 Low-intensity forest	High probability as primary forest and low/medium wood production		X			
	2.2 Medium-intensity forest	Low probability as primary forest and medium wood production		X			
	2.3 High-intensity forest	Low probability as primary forest and high wood production		X			
Cropland systems	3.1 Low-intensity arable land	Low inorganic fertiliser input, small field size			X		
	3.2 Medium-intensity arable land	Medium inorganic fertiliser input, medium field size			X		
	3.3 High-intensity arable land	High inorganic fertiliser input, large field size			X		
	3.4 Low-intensity permanent crops	Vineyards, olive groves, fruit gardens, with understory vegetation, this class also has mixed annual and permanent crops			X		
	3.5 High-intensity permanent crops	Vineyards, olive groves, fruit gardens, without understory			X		
Grassland systems	4.1 Low-intensity grassland	Low density of livestock, low inorganic fertiliser input, and low mowing frequency				X	
	4.2 Medium-intensity grassland	Medium density of livestock, medium use of inorganic fertiliser, and medium mowing frequency				X	
	4.3 High-intensity grassland	High density of livestock, high inorganic fertiliser input, and/or high mowing frequency				X	
Shrub		Areas dominated by shrub land cover or similar				X	
Rocks and bare soil		Areas dominated by rocks, bare soil, or similar					X
Mosaic systems	7.1 Forest/shrub and cropland mosaics	Areas with small parcels of forest/shrubs and cropland		X	X	X	
	7.2 Forest/shrub and grassland mosaic	Areas with small parcels of forest/shrubs and grassland		X		X	

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Land system	**Sub-division**	**Description**	**Land category**				
			Urban land	**Forestry land**	**Arable land**	**Pastoral land**	**Unproductive land**
	7.3 Forest/shrubs and bare mosaics	Areas with small parcels of forest/shrubs and bare land		X		X	
	7.4 Forest/shrubs and mixed agriculture mosaics	Areas with small parcels of forest/shrubs and mixed areas of cropland and grassland		X	X	X	
	7.5.1 Low-intensity agricultural mosaic (cropland and grassland)	Low density of inorganic fertiliser input, small field size, and low livestock density			X	X	
	7.5.2 Medium-intensity agricultural mosaic (cropland and grassland)	Medium use of inorganic fertiliser, medium field size, and medium livestock density			X	X	
	7.5.3 High-intensity agricultural mosaic (cropland and grassland)	High inorganic fertiliser input, large field size, and/or large livestock density			X	X	
Snow, water, wetland systems	8.1 Glaciers	Areas dominated by glaciers, wetland, or water body					X
	8.2 Water body						X
	8.3 Wetland					X	

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Table A 4: IMAGE world regions and constituent countries.

Only countries included in this analysis are listed.

Region	Countries (ISO codes)
Western Europe	Austria (40), Belgium (56), Denmark (208), Finland (246), France (250), Germany (276), Greece (300), Ireland (372), Italy (380), Luxembourg (442), Malta (470), Netherlands (528), Norway (578), Portugal (620), Spain (724), Sweden (752), Switzerland (756), United Kingdom (826)
Central Europe	Albania (8), Bosnia and Herzegovina (70), Bulgaria (100), Croatia (191), Cyprus (196), Czech Republic (203), Estonia (233), Hungary (348), Latvia (428), Lithuania (440), Macedonia, Poland (616), Romania (642), Serbia and Montenegro (891), Slovak Republic (703), Slovenia (705)

Table A 5: Crop categories selected from MapSPAM.

These are crops that are produced in Europe according to FAOSTAT (2023b) and for which crop prices were available.

Crop name	Code	Crop name	Code	Crop name	Code
Banana	bana	Other Pulses	opul	Sweet Potato	swpo
Barley	barl	Pigeon Pea	pige	Temperate Fruit	temf
Bean	bean	Pearl Millet	pmil	Tobacco	toba
Chickpea	chic	Potato	pota	Tropical Fruit	trof
Coconut	cnut	Rapeseed	rape	Vegetables	vege
Cotton	cott	Rest Of Crops	rest	Wheat	whea
Cowpea	cowp	Rice	rice	Yams	yams
Groundnut	grou	Sesame Seed	sesa		
Lentil	lent	Small Millet	smil		
Maize	maiz	Sorghum	sorg		
Other Cereals	ocer	Soybean	soyb		
Other Fibre Crops	ofib	Sugar beet	sugb		
Oilpalm	oilp	Sugar cane	sugc		
Other Oil Crops	ooil	Sunflower	sunf		

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Table A 6: Mapping of MapSPAM crops onto the crop categories distinguished by FAOSTAT and EUROSTAT.

Code concordance tables matched using Yu et al. (2020) and the Manual on the economic accounts for agriculture and forestry EAA/EAF 97(European Commission & Statistical Office of the European Communities, 2000).

MapSPAM	FAOSTAT			EUROSTAT		
	Name	Code	Group	Name	Code	Comments
Wheat	Wheat	15	Cereals	Wheat and spelt	01100	-
Rice	Rice	27	Cereals	Rice	01600	-
Maize	Maize	56	Cereals	grain maize, fodder maize	01500; 03100	-
Barley	Barley	44	Cereals	Barley	01300	-
Pearl Millet	Millet	79	Cereals	Cereals (including seeds)	01000	-
Small Millet	Milletb	79	Cereals	Cereals (including seeds)	01000	-
Sorghum	Sorghum	83	Cereals	Cereals (including seeds)	01000	-
Other Cereals	Other Cereals ++	68, 71, 75, 89, 92, 94, 97, 101, 103, 108	Cereals	Oats and summer cereal mixtures	01400	-
Potato	Potato	116	Roots & Tubers	Potatoes for consumption; Industrial potatoes; Potato seeds; Fodder potatoes	73600; 73700; 73800; 73900	Excluded: "Potatoes (including seeds)"
Sweet Potato	Sweet Potato	122	Roots & Tubers	Potatoes for consumption	73600	-
Yams	Yam	137	Roots & Tubers	Potatoes for consumption	73600	-
Bean	Beans, Dry	176	Pulses	haricot beans	73500	-
Chickpea	Chickpea	191	Pulses	dried pulses	73300	-
Cowpea	Cowpea	195	Pulses	dried pulses	73300	-
Pigeon Pea	Pigeon Pea	197	Pulses	dried pulses	73300	-
Lentil	Lentils	201	Pulses	dried pulses	73300	-
Other Pulses	Broad Beans ++	181, 187, 203, 205, 210, 211	Pulses	dried pulses	73300	-
Soybean	Soybean	236	Oilcrops	haricot beans	73500	-
Groundnut	Groundnut, With Shell	242	Oilcrops	Oil seeds and oleaginous fruits (including seeds)	02100	-
Coconut	Coconut	249	Oilcrops	Oil seeds and oleaginous fruits (including seeds)	02100	-
Oilpalm	Oil Palm Fruit	254	Oilcrops	Oil seeds and oleaginous fruits (including seeds)	02100	-
Sunflower	Sunflower Seed	267	Oilcrops	Oil seeds and oleaginous fruits (including seeds)	02100	-
Rapeseed	Rapeseed, Mustard seed	270, 292	Oilcrops	Oil seeds and oleaginous fruits (including seeds)	02100	-
Sesame Seed	Sesame Seed	289	Oilcrops	Oil seeds and oleaginous fruits (including seeds)	02100	-

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MapSPAM	FAOSTAT			EUROSTAT		
	Name	Code	Group	Name	Code	Comments
Other Oil Crops	Olives ++	260, 263, 265, 275, 280, 296, 299, 333, 336, 339	Oilcrops	Olive	06500	-
Sugarcane	Sugar Cane	156	Sugar Crops	Sugar beet	02400	-
Sugarbeet	Sugarbeet	157	Sugar Crops	Sugar beet	02400	-
Cotton	Seed Cotton	328	Fibres	Fibre plants	02910	-
Other Fibre Crops	Other Fibres ++	773,777, 780, 782, 788, 789, 800,	Fibres	Fibre plants	02910	-
Other Fibre Crops	Other Fibres ++	809, 821	Fibres	Fibre plants	02910	-
Tea	Tea	667	Stimulates	-	-	-
Tobacco	Tobacco	826	Stimulates	-	-	-
Banana	Banana	486	Fruits	-	-	-
Tropical Fruit	Oranges ++	490, 495, 497, 507, 512, 567, 568, 569, 571, 572, 574, 577, 587, 591, 600, 603	Fruits	sweet oranges; mandarins; lemons; clementines	06210; 06220; 06230; 76200	-
Temperate Fruit	Apples ++	515, 521, 523, 526, 530, 531, 534, 536, 541, 542, 544, 547, 549, 550, 552, 554, 558, 560, 592, 619	Fruits	desert apples; desert pears; peaches; grapes; tomatoes; apricot; cherries; strawberries; currants; gooseberry	06110; 06120; 06130; 06400; 04120; 75500; 75600; 75900; 76000; 76100	-
Vegetables	Cabbages And Other Brassicas ++	358, 366, 367, 372, 373, 388, 393, 394, 397, 399, 401, 402, 406, 407, 414, 417, 420, 423, 426, 430, 446, 449, 459, 461, 463	Vegetables	cauliflower; cabbages; fennel; endives; artichokes; courgettes; cucumbers; onions, shallots	04110; 74200; 74500; 74300; 74400; 74800; 74700; 75100	-
Rest Of Crops	All Individual Other Crops (e.g., Spices, Tree Nuts, Other Sugar Crops, Mate, Rubber)	161,216, 217, 220, 221, 222, 223, 224, 225, 226, 234, 671, 677, 687, 689, 692, 693, 698, 702, 711, 720, 723, 748, 754, 836, 839		walnuts; hazelnuts	75700; 75800	-

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Table A 7:Regional statistics of empirical and proportionally allocated land rents per NUTS 0 (forestry land) and NUTS 2 (agricultural land) region.

The convergence of the mean values of the empirical land rent dataset and the regional average of the proportionally allocated dataset reflects a successful proportional allocation procedure.

Productive land type	Empirical land rent (€/ha/yr)	Proportionally allocated land rent (€/ha/yr)	
	Mean	Mean	SD
Arable land	343.16	326.22	±377.05
Permanent grassland	249.29	263.72	±257.27
Forestry land	65.25	66.01	±67.86

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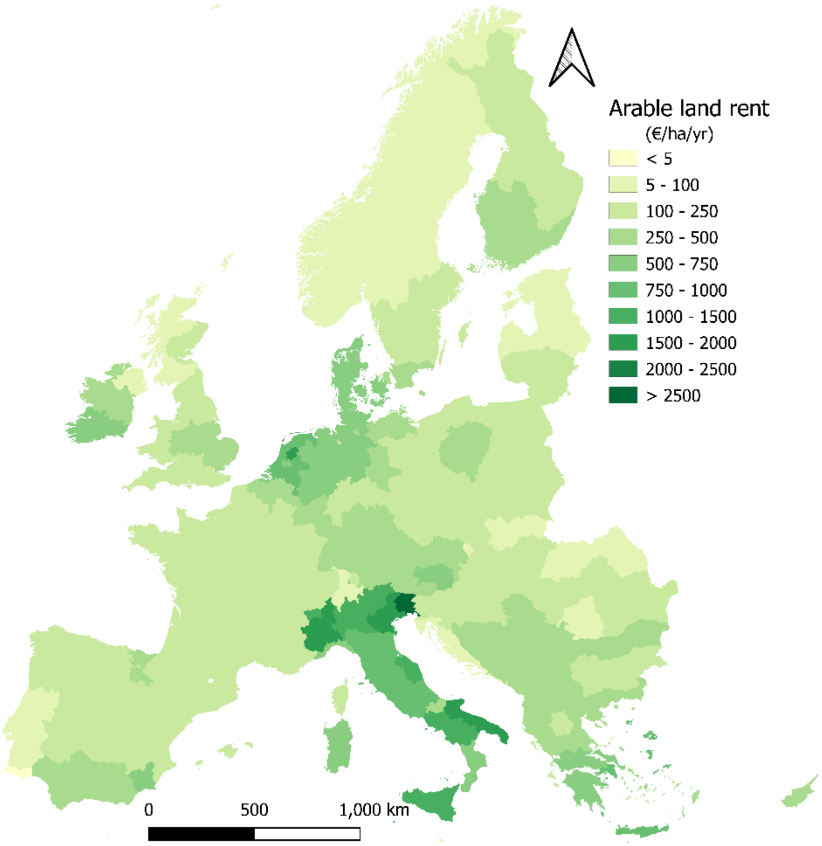

Figure A 1: Land rent for arable land in €/ha/yr.

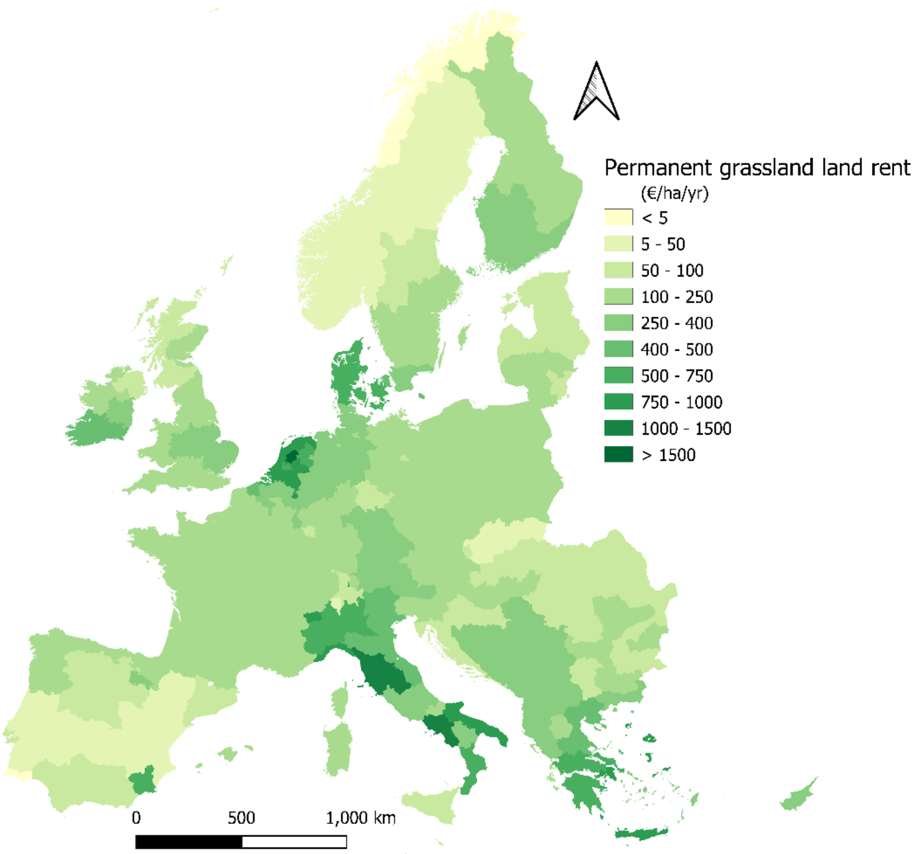

Figure A 2: Land rent for pastoral land in €/ha/yr

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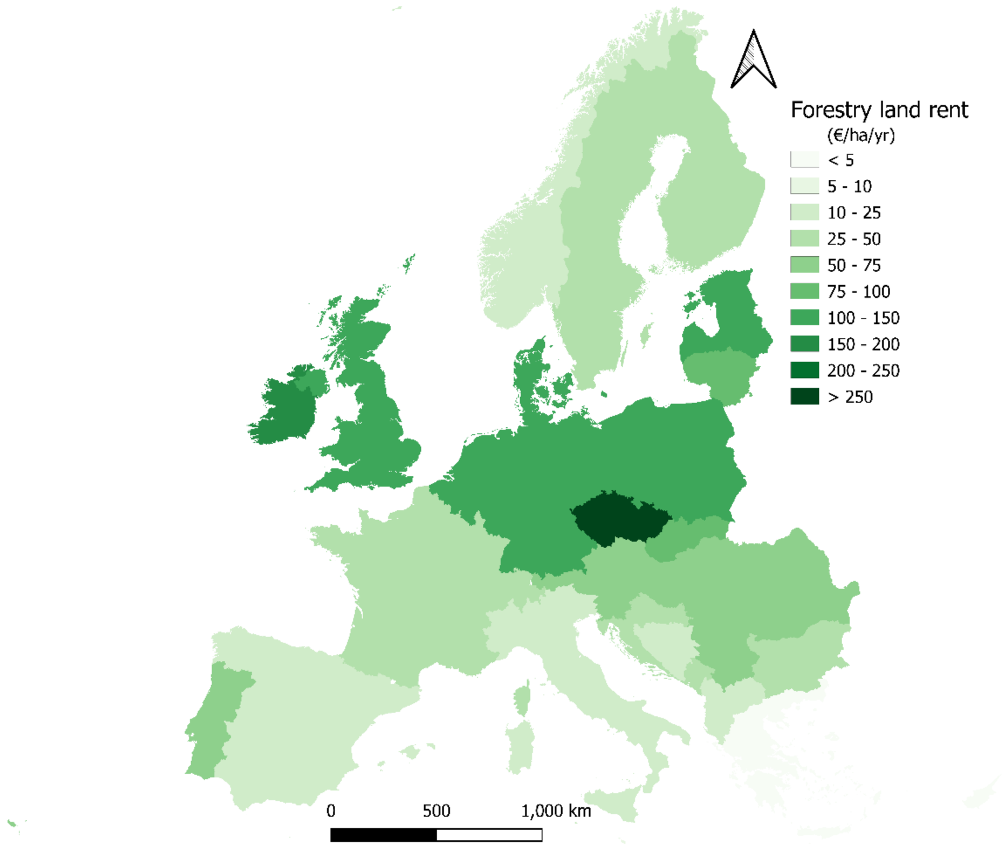

Figure A 3: Land rent for forestry land in €/ha/yr.

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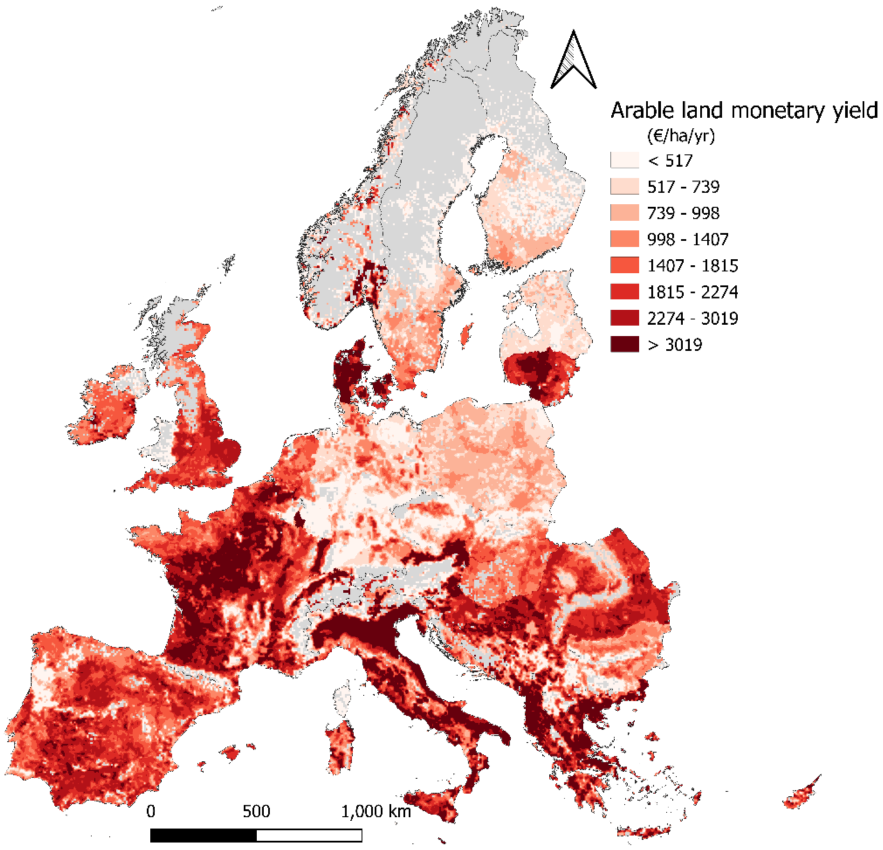

Figure A 4: Monetary yield for arable land in €/ha/yr.

To optimise visualisation of heterogeneity, the values are categorised into eight quantile classes.

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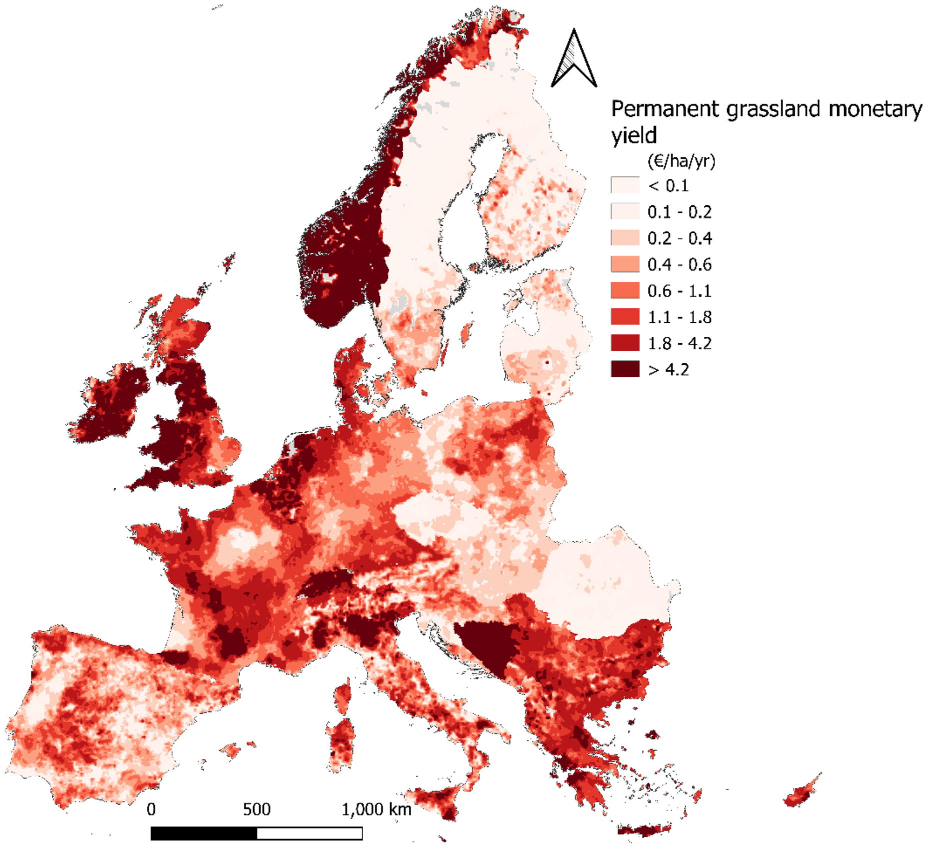

Figure A 5: Monetary yield for pastoral land in €/ha/yr.

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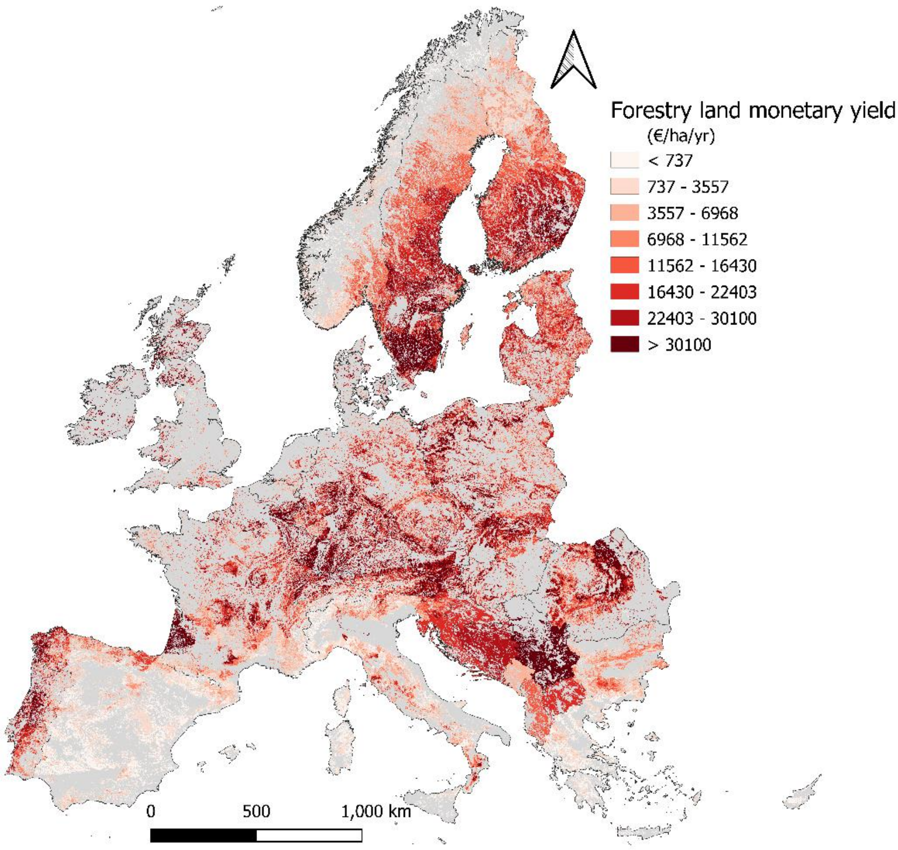

Figure A 6: Monetary yield for forestry land in €/ha/yr.

To optimise visualisation of heterogeneity, the values are categorised into eight quantile classes.

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More information about the project:

NaturaConnect has 22 partner institutions: International Institute for Applied System Analysis (project lead; Austria); German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig (project co-lead; Germany); Associacao Biopolis (Portugal); BirdLife Europe (Netherlands); Birdlife International (United Kingdom); Centre National De La Recherche Scientifique (France); Doñana Research Station - Agencia Estatal Consejo Superior De Ivestigaciones Cientificas (Spain); Europarc Federation (Germany); Finnish Environment Institute (Finland); Humboldt-University of Berlin (Germany); Institute for European Environmental Policy (Belgium); Netherlands Environmental Assessment Agency (Netherlands); Rewilding Europe (Netherlands); University of Evora (Portugal); University of Helsinki (Finland); University of Natural Resources and Life Sciences, Vienna (Austria); University of Rome La Sapienza (Italy); University of Warsaw (Poland); Vrie University of Amsterdam (Netherlands); WWF Central and Eastern Europe (Austria); WWF Romania and WWF Hungary.

NaturaConnect aims to design and develop a blueprint for a truly coherent **Trans-European Nature Network** (TEN-N) of conserved areas that protect at least 30% of land in the European Union, with at least one third of it under strict protection. Our project unites universities and research institutes, government bodies and non-governmental organizations, working together with key stakeholders to create targeted knowledge and tools, and build the capacity needed to support European Union Member States in realizing an ecologically representative, resilient and well-connected network of conserved areas across Europe.

https://naturaconnect.eu/

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