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High-resolution naturalness mapping can support conservation policy objectives and identify locations for strongly protected areas in France

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Intact natural landscapes are essential to both biodiversity conservation efforts and human well-being but are increasingly threatened and lack sufficient protection. Bold National and International protected area targets aim to address this problem, yet the question remains – where will these areas be located? Using France as a case study, we present a high-resolution method to map naturalness potential. The resulting map, CARTNAT, performs well at identifying areas which have already been recognised as worthy of strong protection, under both National and International designations, however, only 1% of the top 10% of high naturalness areas in France are currently strongly protected. CARTNAT is already being used to highlight potential sites for new protected areas supporting the French National Strategy for Protected Areas to 2030. We argue that spatially informed participatory decision making of this type has the potential to deliver on national and international protected area policy objectives.

Intact natural landscapes are essential for achieving biodiversity conservation policies which aim to address the twin challenges of climate change and species loss[1]. Researchers working across multiple disciplines have established the critical importance of intact natural landscapes to the continued survival of threatened species[2,3], as well as the life support systems upon which all life depends[4]. Beyond their intrinsic value, these same 'wild' spaces bring additional benefits in terms of human recreation and well-being[5]. Despite growing evidence for their extraordinary value, many ecologically intact wild spaces still lack sufficient protection, and as such are rapidly being lost, meaning that they require immediate large-scale conservation efforts to secure them for the future[6,7].

The Kunming–Montreal Global Biodiversity Framework sets ambitious targets to protect areas of high biodiversity importance and high ecological integrity using inclusive spatial planning[8] and is critical to the success of area-based conservation[9]. Similarly, the EU's biodiversity strategy for 2030 sets the target of placing 10% of European terrestrial land mass under 'strict protection' and emphasises the importance of non-intervention in old growth forests, protected areas, and ecologically intact natural areas in delivering this[10]. Meeting these targets raises a clear challenge—how can policy objectives at the global level translate into effective national action?[4]. Spatially identifying intact natural areas is a key component of any strategy designed to meet global conservation challenges and turn policy into action[11]. Numerous projects have set themselves the challenge of mapping human influence and identifying the remaining wild areas (see for example, refs. 12–14). Global and European level maps of wilderness quality and human influence could potentially be used at the national scale to support protected area policy objectives, but generally lack the spatial nuance in both data and methods to identify regional and local patterns and gradients in wildness. Implementation of the EU biodiversity strategy is the responsibility of the nation states and decision making on national targets

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should be based on the 'best data'[10] (p.18) available, usually nationally produced data sets with full national coverage that are coherent with other National level spatially explicit tools. For mapping to be used effectively in decision making, it also needs to be based on robust methodologies which deliver thematically relevant information of value to national, regional and even local level decision conservation makers and conservation managers[15]. National level maps of wilderness or anthropogenic influence exist for Austria[16], Scotland[17], Denmark[18] and Iceland[19]. Like their global equivalents, they represent wilderness using a continuum from least to most wild and respond to the fuzziness of the 'wilderness' concept by using well established multi-criteria evaluation methods (MCE) to merge remote sensing data on human influence, anthropogenic artefacts and landscape quality into a single thematic map[20]. Whilst these maps include consideration of the perceived naturalness of the land cover they are focused specifically on the idea of human influence, or 'wilderness' as a human perceived attribute of landscapes without extensive human modification. As such they are not specifically designed to address International[8] and EU policy goals[10] focused on the conservation of old growth forests, ecologically intact natural areas, or National targets for biodiverse areas of 'high naturalness'[21].

Furthermore, whilst these existing thematic mapping products integrate high-resolution remote sensing data, the final spatial outputs rarely available at a high enough resolution to support National, regional and local planning. Following the European Parliament's 2009 Resolution on European Wilderness[22], Wild Europe was commissioned to produce a definition of 'wilderness' which could support a standardised approach to the protection and restoration of large ecologically intact areas[23]. In respect of this need for standardised high-resolution mapping focused on identifying ecologically intact natural areas, we developed CARTNAT which maps naturalness potential at 20 m resolution for the entire French Metropolitan territory. CARTNAT mobilises data on the three main components of naturalness: *biophysical integrity*; *spontaneity of process* and *spatio-temporal continuity* (see Fig. 1). These three landscape facets were chosen to capture the plurality of approaches understood by the term naturalness in the literature[24] and were approved by an expert IUCN national working group[25] as appropriate for mapping naturalness at the national scale in France. *Biophysical integrity* describes to what degree the composition of species or habitats in a landscape resemble their undisturbed or native state[26,27]; *spontaneity of process* captures the idea of human influence on the landscape and the degree to which nature is free to evolve in the direction it chooses being 'untrammelled' by human intervention[28,29]; finally *spatio-temporal continuity* refers to the idea that the larger and better connected an area is, and the longer it has remained undisturbed, the more likely it is to contain intact habitats[30–33]. As a conservation decision support tool this tri-facet approach has two clear advantages over previous national mapping initiatives, firstly it is focused on mapping naturalness as a property of the landscape, and secondly in doing so it avoids the challenges that have in recent years dogged the goal of mapping the increasingly politicised anthropocentric concept of wilderness[34]. It also responds to the 2030 CBD targets[8], which highlight, alongside areas of high biodiversity, the importance of both areas of 'high ecological integrity which occur within their natural ranges of variation and can withstand and recover from most disturbances' (in Target 1), as well as the importance of 'connectivity and integrity areas with high ecological integrity which ensures the maintenance of natural species habitats (in Target 2).

We believe that the quantification and mapping of each of these three facets provides a novel description of the entire French metropolitan territory and is well suited as a method to highlight the distribution of potential hotspots of naturalness in France. Highlighting the value of its complete national coverage, we demonstrate the use of CARTNAT as a fast-track search tool to identify potential highly natural areas that are not currently protected, the results from which can be integrated into local and regional level protected areas planning in support of the French National Strategy on Protected Areas to 2030 (SNAP)[35]. In line with the EU Biodiversity strategy, the SNAP aims to strongly protect 10% of the French Continental areas via 'protection forte'. Our objectives were: (1) Develop methods to map naturalness at the national level in metropolitan France, which make use of the best high resolution spatial data available; (2) Test the performance of the resulting mapping in relation to existing protected area networks to validate it's potential as a decision support tool for protected area planning at the local, regional and national level; and (3) Spatially analyse the map to

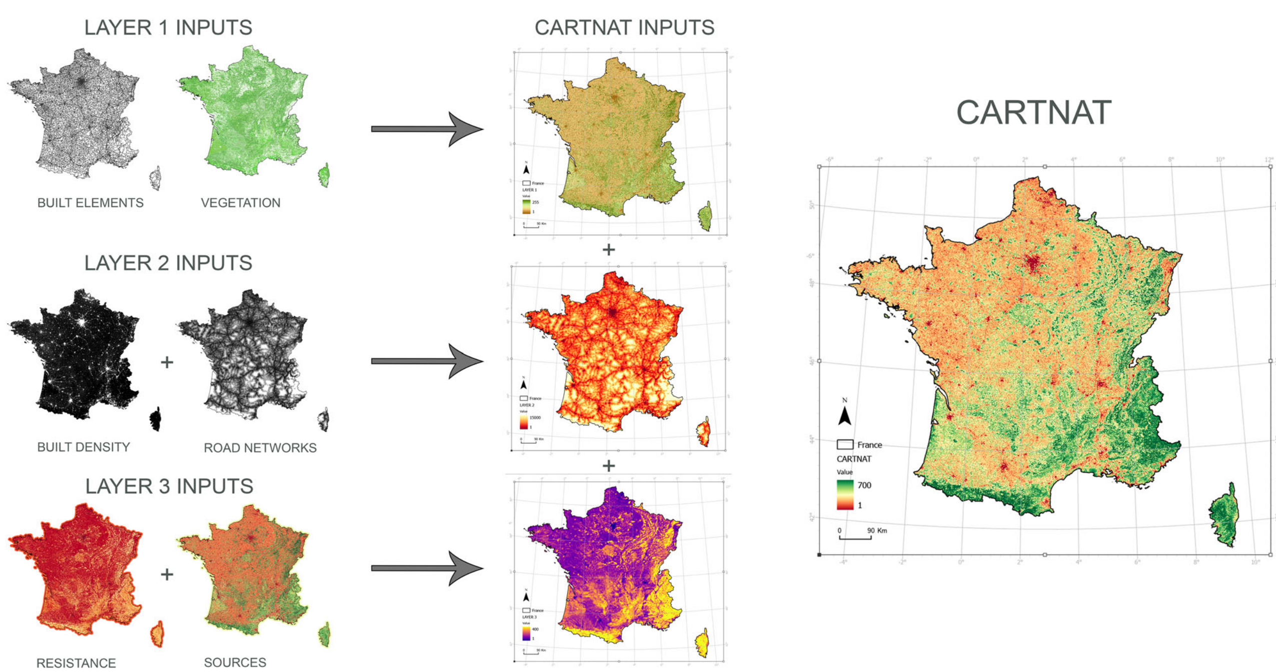

Fig. 1 | CARTNAT three-layer data input model. CARTNAT was built using three spatial component layers that represent the three core components of naturalness: (Layer 1) biophysical integrity; (Layer 2) spontaneity of process and (Layer 3) spatio-temporal continuity. Layer 1 used a weighted overlay to combine spatially explicit data on built elements and vegetation as well as water, crops and proxies for land use (only two layers are shown for ease of representation but see methods and Fig. 6 for full details). Layer 2 combined two spatial models on built density and road type (see methods). Layer 3 modelled ecological flow using a resistance layer and a source layer (see the "Methods" section for more details). Layers 1–3 were then combined to produce Layer 4—CARTNAT.

extract spatial data of relevance to fast-track national level protected area (PA) planning which aims to strongly protect ecologically intact natural areas now that are not currently under a PA designation.

Results

We found that the CARTNAT naturalness map of metropolitan France performs significantly well at identifying areas which have already been recognised as worthy of strong protection, under both French National legislation and IUCN International designations[36,37].

Larger areas of high potential naturalness in green (with higher CARTNAT scores) are predominantly found in mountainous areas such as the Alps and the Pyrenees. These are the areas where the landcover has remained in an intact natural state. This is unsurprising given that topographical factors such as steep slopes and limited road access represent a barrier to intensive land use. Extremes of seasonal climate are another factor limiting intensive land use human activity in these areas. Zooming into the map reveals that there are smaller pockets of high naturalness to be found all over metropolitan France (see Fig. 4 for more details).

The median CARTNAT values for Category I and II protected areas were 516 and 515, respectively. Values for other IUCN Categories were significantly lower: median value for Category III was 355; Category IV 377; Category V 394 and for the null model 305. Comparison of CARTNAT potential naturalness scores for protected areas in mainland France grouped by IUCN category showed a significant difference—Kruskal–Wallis chi-squared = 987.94, $p = 2.45e-211$, df = 5 (see Fig. 2). Between group comparison found significant differences between Ia and groups III, IV, V, and the null model, but not group II. There were significant differences in CARTNAT values between group II and groups III, IV, V, and the null model. This demonstrates that areas identified by CARTNAT as of high naturalness potential correlate well with protected areas already designated under IUCN guidelines for their ecological intactness.

The French protected areas strategy (SNAP) aims to strongly protect 10% of France and the French Government have legally defined those protected area types that offer strong levels of protection[36]. The median CARTNAT values for strong protection normal areas were 397 and 380, respectively. The median value for the null model was 305. CARTNAT mean potential naturalness scores for protected areas in mainland France with a normal level of protection differed significantly from those with a strong level of protection, or the null model: Kruskal–Wallis chi-squared = 1244.77, $p = 5.02e-271$, df = 2 (see Fig. 3). Between group comparisons showed significant differences between all pairwise combinations of the three groups. This demonstrates that areas identified by CARTNAT as of high naturalness potential correlate well with areas already considered worth of strong protection under French legislation.

Naturalness is recognised in France as a key landscape attribute worthy of protection and the definition of naturalness used in the SNAP[35] which aims to strongly protect 10% of France by 2030 is directly based on the definition used in our analysis. We have shown that CARTNAT performs significantly well when tested against existing areas in France considered to be worthy of strong protection[36]. Yet within mainland France, only 0.77% of the top 10% of areas of high naturalness potential identified by CARTNAT are currently strongly protected by a National Designation. Similarly, only 0.53% of the top 10% areas of CARTNAT high naturalness potential areas are protected by a suitable IUCN category (Ia or II). 2.7% of the top 10% of high naturalness areas are not covered by any protected area designation at all. Current estimates suggest around 1.8% of the total area of mainland France is currently protected by a strong designation[38], so these figures seem consistent with what we would expect though it would be highly unlikely to find a direct spatial overlap between the top 10% of CARTNAT and the current strongly protected areas.

With official figures stating that <2% of France is strongly protected, the question remains where the French Government will find the remaining 8% to meet its own 10% target under the SNAP[35] for 2030? With strong protection currently covering less than 1% of the top 10% of those areas identified by CARTNAT as having high naturalness potential, the remaining 9% represent key 'search areas' to meet this national goal

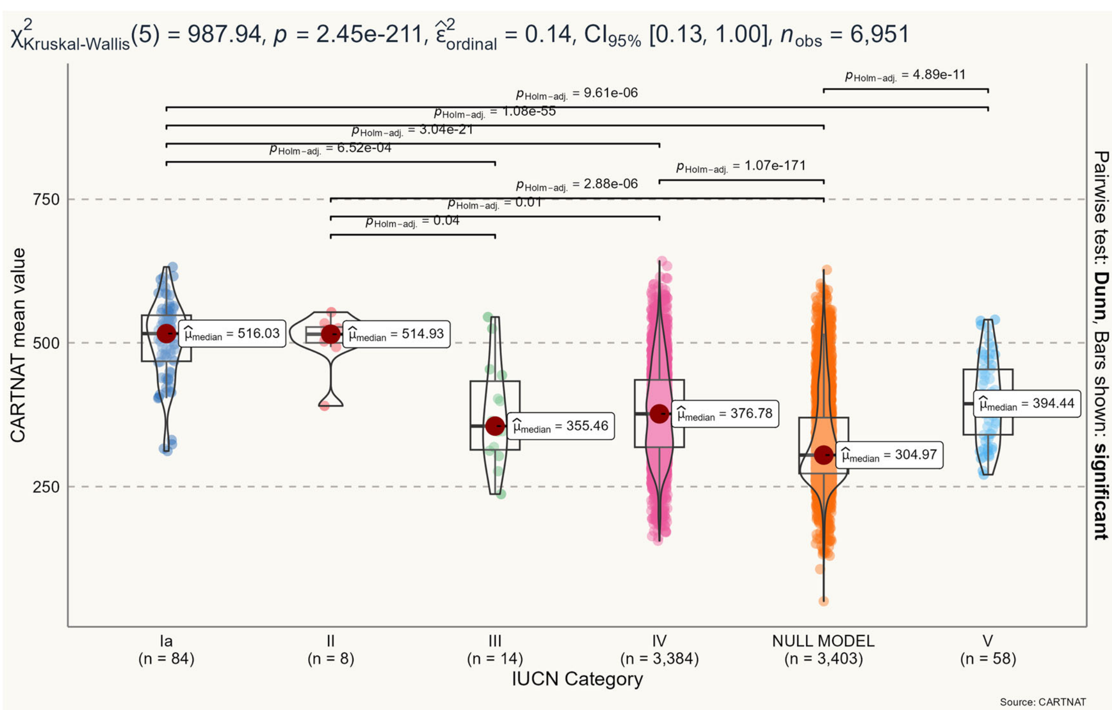

Fig. 2 | Comparison of CARTNAT mean potential naturalness scores for protected areas in mainland France grouped by International Union for the Conservation of Nature protected area category. Groups present in France and shown are as follows: Ia—Strict Nature Reserve, II—National Park, III—Natural Monument or Feature, IV—Habitat/Species Management Area and V—Protected Landscape, as well as the null spatial model. Summary result across all groups is Kruskal–Wallis chi-squared = 987.94, $p = 2.45e-211$, df = 5. Grouping bars then show significant pairwise differences between groups. Ia and II are not significantly different, III–V are not significantly different, and the null model is on its own. Box plots show median values.

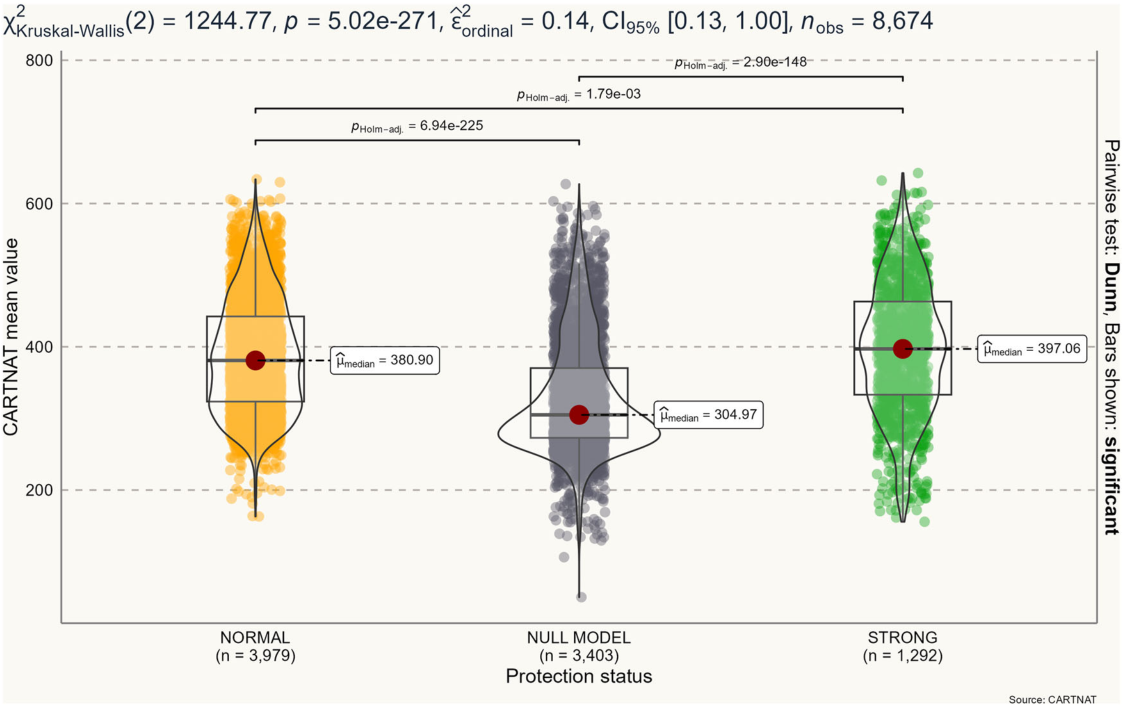

Fig. 3 | Comparison of CARTNAT mean potential naturalness scores for protected areas in mainland France. Comparison of CARTNAT mean potential naturalness scores for protected areas in mainland France grouped by normal and strong protection—defined by the French Government—with the null spatial model. There are significant differences between all three group combinations. Kruskal–Wallis chi-squared = 1244.77, $p = 5.02e{-}271$, df = 2. Grouping bars then show significant pairwise differences between groups. Box plots show median values.

by 2030 (see Fig. 4 for a visual representation of how CARTNAT can support this).

In line with national, European and International objectives, identifying and reviewing these search areas should be a participatory process supported by spatially explicit decision support tools. Within the SNAP this as an iterative process across multiple scales, beginning with National scale definition of objectives and then regional level review with local NGOs and environmental organisations of potential target areas to meet these objectives. This allows local actors to discuss potential options based on expert knowledge, supported by existing spatial data on priority species and habitats. In line with the original aims of the European Parliament's 2009 Resolution on European Wilderness[22], and the Wild Europe definition of wilderness[23], CARTNAT provides this additional standardised spatial data. This supports participatory consultation on existing unprotected areas that are important for priority species and habitats, which are also high naturalness potential, and are therefore obvious candidates for strong protection going forward. Indeed, several regional initiatives are already underway which are testing this participatory approach with local decision makers using CARTNAT as part of the SNAP approach (see Fig. 5. and discussion for examples).

Discussion

By developing a robust high-resolution model to map naturalness potential, that mobilises the best data available at the national scale, our analysis highlights a key methodological process to support National, European and International protected area conservation objectives. Integrating data on the potential naturalness of landcover and landscape connectivity with data on the degree of human influence in those same landscapes allows us to highlight potential new protected areas in a way that can be easily understood by decision-makers and policy makers. Mapping these landscape attributes along a continuum and at 20 m resolution means that local scale nuances in landscape quality can be incorporated into both national and regional scale discussions and planning.

The importance of intact natural landscapes was highlighted in the European Commission's resolution on Wilderness which invited member states to identify and map the remaining *'pristine areas'* in Europe which *'should be regarded as a unique asset and benefit from the highest level of protection [and] should not be diminished or degraded'*[22]. At the national level in France this goal was reinforced and quantified by President Macron, who called for the protection of 30% of the French territory of which a third (10%) should be preserved as areas of *'complete naturalness'*, or *'pleine naturalite'*[21]. Moving beyond policy goals to conservation action, requires a spatially explicit approach based on clear definitions and data models that can accurately represent these definitions as areas on the map. This has been one of the major challenges facing the mapping of intact landscapes, which has been troubled by debates around contested terms such as 'wild' or 'wilderness'[39–41]. These terms are problematic in the European context, where human influence has been more significant, and persisted over longer time frames[42]. To identify a way forward the IUCN French Committee working group on wilderness hosted a series of debates and discussions during the period of 2012–2016 which concluded that a logical way forward was to remove the dominance of the human perspective from these definitions and focus instead on the idea of the naturalness of the landscape[25].

Protected area working definitions of wildness are in fact already dominated by ecological criteria *('be of sufficient size to protect biodiversity; to maintain ecological processes and ecosystem services; characterised by a high degree of intactness: containing a large percentage of the original extent of the ecosystem, complete or near-complete native faunal and floral assemblages …'*[37,43]. In this sense the concept of naturalness is not linked to a human centric view of nature nor dependent on human perceptions of landscape[44]. Based on a review of the literature we have argued that it refers instead to the intrinsic properties of species and habitats and consists of three key components: biophysical integrity; spontaneity of processes; and spatio-temporal continuity[24]. The key advantage of this definition from a mapping perspective is that it allows us to move beyond general descriptions of the idea of naturalness as found in policy, to highlight key landscape facets that can be spatially represented using high-resolution data. In addition, it develops the concept of hemeroby[45] to measure human impact on flora and vegetation and captures the degree to which a habitat is removed from its

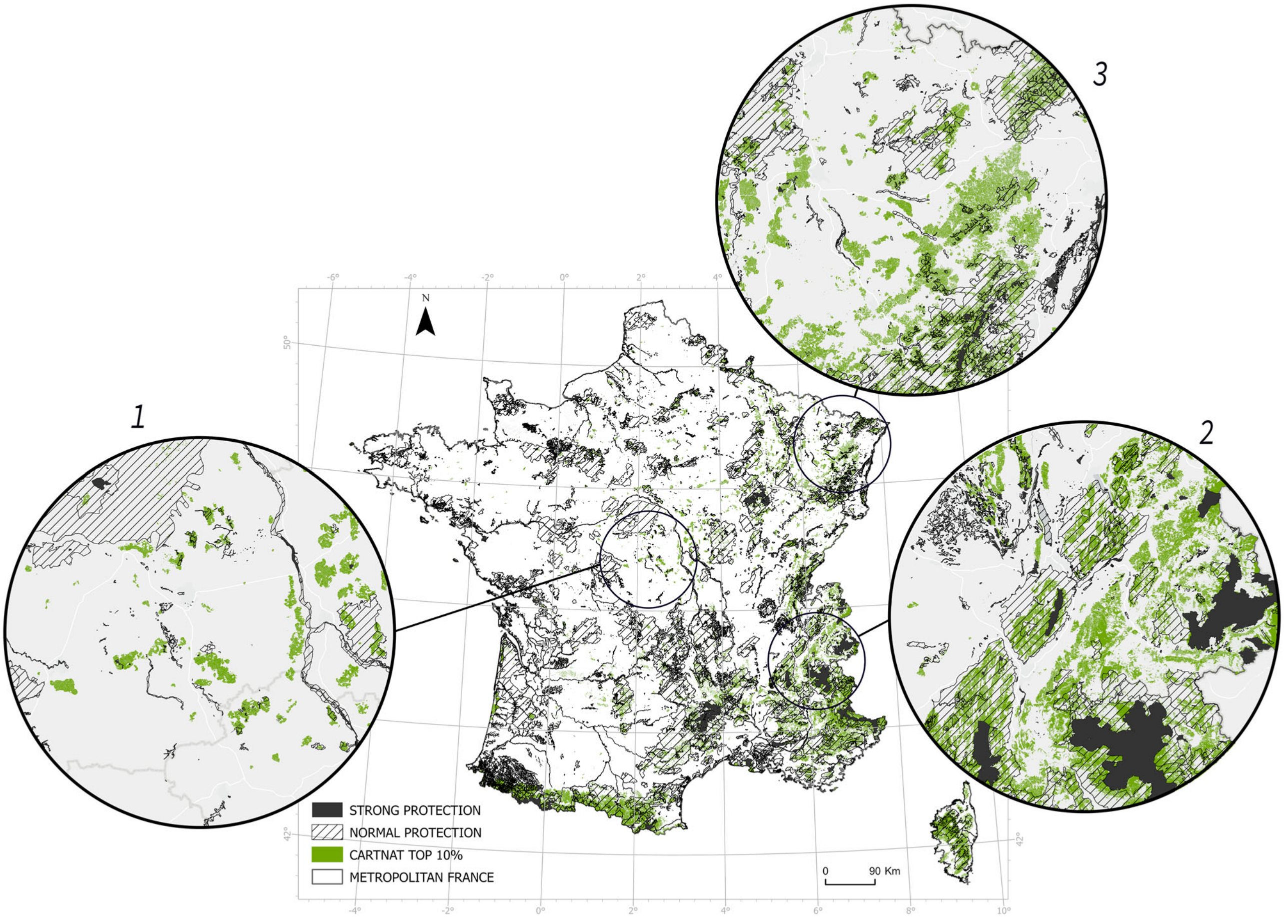

Fig. 4 | Map of mainland France showing high natural potential areas, existing strong protection areas and all other protected areas. Top 10% areas of high naturalness potential areas according to CARTNAT analysis (pale green) compared with existing strongly protected areas in France (dark grey) and all other protected areas in France (hatched fill). Zoom area 1 shows isolated pockets of unprotected high naturalness (pale green) that could be considered for protection and connected together. Zoom area 2 shows an existing cluster of areas of strong protection (dark grey), surrounded by areas of normal protection (hatched fill) and areas of high naturalness (pale green) that could be combined under strong protection to build a network of large intact well protected high naturalness areas. Zoom area 3 shows large contiguous areas of high naturalness (pale green) surrounded by areas of normal protection (hatched fill) which could be candidate areas for a new area of strong protection. Diameter of zoom areas is equal to 175 km (see also Fig. 5 and discussion for details of examples).

'potential natural vegetation' state by human activities[46]. Hemeroby measures the magnitude of anthropogenic modification of a habitat, in relation to its original or potential theoretical composition, taking local biogeographic conditions into account. Integrating hemeroby or biophysical integrity into a map of naturalness allows us to place a landscape along a continuum which ranges from 'artificial' to 'original'. This continuum or landscape gradient aspect of the definition is key from the perspective of national scale mapping, given the lack, limited spatial scope and binary nature of data describing natural or intact habitats[47]. Within France for example, reliable landcover data is available covering the whole of the French mainland at high resolution[48] and specific categories such as vegetation or crop types can be 'weighted' in terms of their position on this continuum based on expert opinion and a review of the literature. This approach avoids the established issue of patchy ecological mapping based only on limited records for the presence of a given species which is more challenging to use as a decision support tool[49].

The advantages of this spatially explicit national coverage are clear when we look at specific policy objectives such as the EU Biodiversity Strategy and the French SNAP. In line with the objective to strongly protect 10% of the French terrestrial area, CARTNAT can be analysed at the national scale to identify the top 10% high naturalness potential areas. Overlaying this top 10% with existing strongly protected areas allows us to have a spatially explicit national vision of potentially important future conservation areas (see Fig. 4). As described above these can form initial search areas where additional data on priority species and habitats can be mobilised as part of a consultation process with local authorities and conservation NGO's. Indeed, there is a clear precedent within protected areas policy for conservation strategies which aim to protect multiple aspects of landscape in this way[37]. As conservation managers face the challenge of accelerating biodiversity loss and climate change, multi-objective optimisation strategies for protected area design have been shown to result in improved overall outcomes[50]. The idea that natural ecological processes—a 'self-willed land'[51]—should be factored into protected areas thinking to solve conservation problems has been gaining ground for some time[52–54]. Protecting existing intact natural landscapes, and implementing passive conservation strategies which allow natural processes to determine ecological trajectories is cost-effective at scale, in contrast to traditional conservation focused on the active restoration and maintenance of specific habitat types via human intervention[55,56]. As a spatially explicit metric, CARTNAT is also compatible with increasingly popular conservation ideas such as passive rewilding which also consider the naturalness of a landscape in terms of a continuum and factor in both connectivity and human influence[57].

This multi-objective approach is now being trialled as part of the initial phases of the SNAP programme, as they move from national scale targets to regional level identification of potential new protected areas. In the Provence-Alpes-Côte d'Azur (PACA) region of south-eastern France this process is led by the Conservatoire d'Espaces Naturels (CEN) and the Conservatoires Botaniques Nationaux (CBN). The high-resolution of

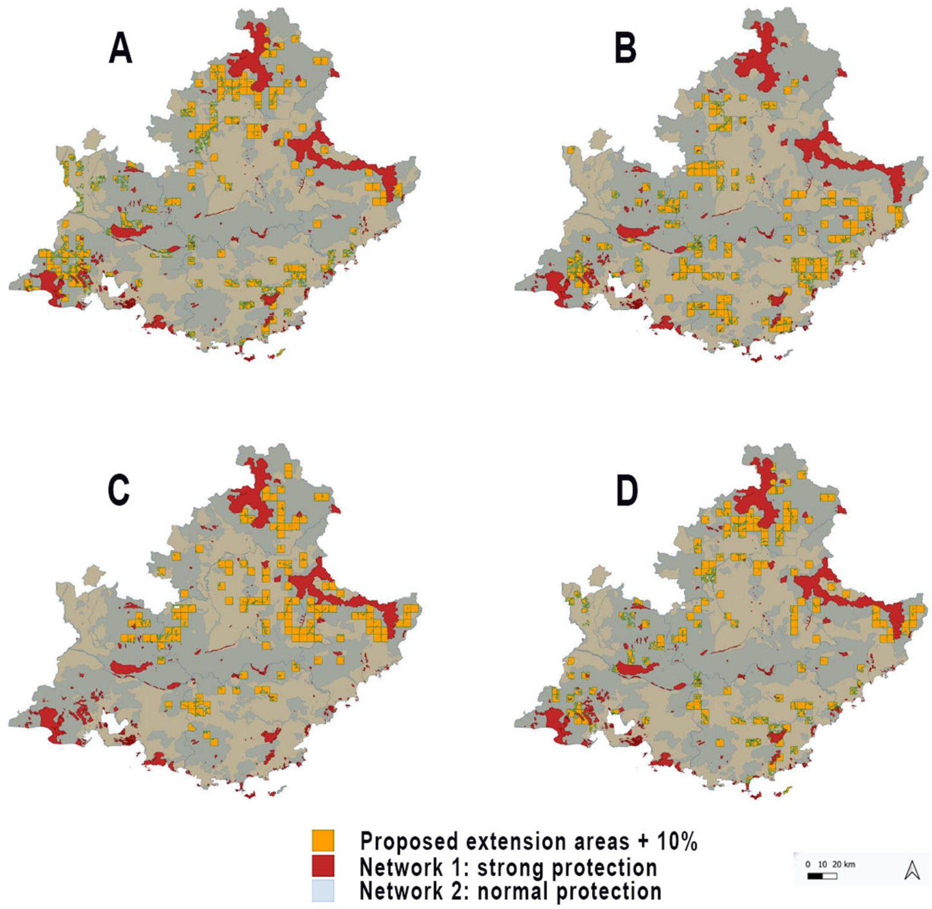

Fig. 5 | Assessment of existing protected areas and scenarios for their future development for the Provence-Alpes-Côte d'Azur region of France. Four scenarios are presented: **A** "Biodiversity Hotspots" which identifies potential areas for the expansion of the existing protected areas network based on biodiversity hotspots for 10 taxonomic groups. **B** "Priority Gaps" which identifies potential areas for the expansion of the existing protected areas network based on priority species and habitat types. **C** "High Naturalness" which identifies potential areas for the expansion of the existing protected areas network based on areas of high naturalness based on CARTNAT; and **D** "Multiple Objectives" which identifies potential areas for the expansion of the existing protected areas network based on a combination of the first three approaches equally weighted. Image courtesy of Sophie Vallée, Conservatoire Botanique National Alpin, and Virgile Noble, Conservatoire Botanique National Méditerranéen.

CARTNAT means that it is possible to query the map at a fine scale along with locally available high-resolution data on biodiversity hotspots and priority habitats, collected from a range of sources including botanical surveys and citizen science programmes. Taking advantage of this, in the PACA region a series of regional map products were developed to inform local decision making on candidate areas for strong protection. (see Fig. 5).

This process of consultation for the SNAP, incorporating CARTNAT along with local species and habitat data, is ongoing at the regional level within the PACA and Auvergne-Rhône-Alpes (AURA) regions. In parallel to these regional level 'hotspot' analyses using local level data, Patrinat have started a national level landscape connectivity analysis of French Protected Areas using CARTNAT along with species and habitat data. Patrinat are the expert group which deliver environmental analyses for the French Government on behalf of the French Natural History Museum (MNHN), the French Office for Biodiversity (OFB) and the National Scientific Research Centres (CNRS). Landscape connectivity is of critical importance to natural ecosystems as suppliers of a wide range of critical ecosystem services such as pollination and pest regulation[58,59]. The progressive fragmentation of the landscape by human land use poses a particular threat to endemic animal species which require large intact natural and well-connected areas[60]. A significant number of conservation projects are predicated on the importance of connectivity to intact natural landscapes and aim to reduce landscape fragmentation[61–63]. Structural and functional connectivity are recognised by environmental legislation within both EU and French national strategies, and conservation targets for protected areas specify that these areas should be well connected via green and blue infrastructure[10,63]. CARTNAT has been chosen to support decision making on PAs connectivity because its design means that areas of high biophysical integrity, where spontaneous natural processes are not impeded, and which are also well-connected, score highly in CARTNAT. The complexity and cost of mapping species specific corridors at national scales, has led to a more generalised approach to connectivity modelling based on ideas of ecological flow and landscape integrity[64,65]. This approach shows promise for identifying corridors of interest for multiple species, especially those that disperse longer distances[66]. Indeed, comparative studies of connectivity modelling approaches have shown that naturalness corridors are more likely than species specific approaches to support a wider range of species, and maintain ecological processes that are essential for long-term biodiversity persistence[67]. Careful design of a "species agnostic" approach based on landscape naturalness produces modelling results better suited to large scale implementation in landscape planning[68]. As we show in Fig. 4, CARTNAT is well suited to identifying the many high potential naturalness areas in France which are not currently protected but which may already act as stepping-stone areas to connect existing protecting areas. Protecting these areas and linking them together using landscape scale conservation strategies such as passive rewilding is an effective and scalable strategy to improve the efficacy of the existing protected areas network[69].

Future developments are planned for CARTNAT which will allow us to more directly integrate additional data focused on target species and habitats. New data on grasslands and natural and semi-natural habitats is now being released which will highlight individual habitat networks —such as freshwater, hedgerows and meadows—within the broader CARTNAT framework[70,71]. Fine scale data on land use intensity and pesticides use are still not available at the national scale for France but new plot level data has been released on organic farming in France which can be used as a proxy to capture a broader range of impacts on the naturalness of the landscape. Initial analysis of data for a range of species has also shown that CARTNAT predicts where species sensitive to human disturbance will be found, validating its potential as a decision support tool for conservation planning for target species communities even when only patchy occurrence data exists[72]. Ongoing research using ecoacoustics has also shown that CARTNAT naturalness values correlate strongly with human cultural values for intact wild landscapes and biological indices[73], highlighting the potential of the soundscape as a framework for integrating social and ecological considerations into spatial planning for PAs. Together these future developments will improve our understanding of how the naturalness of the landscape relates to long-established conservation themes such as priority species and habitats, making it useful for spatial analysis across a broader range of policy objectives. This includes for example IUCN Resolution 127 which calls for a cessation of logging in old-growth forests in Europe[74]. Overall, these developments ensure that CARTNAT will remain a key dataset to support National and regional decision making on the identification of new areas for strong protection in France going forward. The high resolution of CARTNAT also means it will continue to remain useful into the future as the focus in the SNAP shifts to local level decision making and implementation. Beyond France, spatial analytical methods like those used in CARTNAT, which factor in biophysical integrity, spontaneity of processes and spatio-temporal continuity, have the potential to support country-level decision making across Europe in respect of EU Biodiversity strategy targets for 2030[10] and the upcoming EU Nature Restoration Law[75].

Methods

Study extent and development

CARTNAT was developed for the area of Metropolitan France which includes the island of Corsica and is the largest of the European Union countries (~13% of the European Union's surface). It covers an area of nearly 550,000 square kilometres (210,020 square miles) and a population of 65.25 million people. Along with a broad altitudinal range (0–4807 m.a.s.l.) the geographical position of France within mainland Europe and its diverse climate and geology places it at an ecological crossroads spanning four key biogeographical regions including Alpine, Atlantic, Continental and Mediterranean. It is home to 40% of plant species that are to be found in Europe, and 75% of priority threatened habitat types in Europe. Over 25 different types of protected areas are found in France meeting various national, European and international regulations[76].

We used a multi-criteria evaluation (MCE) approach to combine spatial datasets describing properties of the landscape in line with our triple faceted approach to mapping naturalness. Data sources were identified via a search of French data repositories, and through institutional contacts including the French Natural History Museum (MNHN), the National Office of Forests (ONF) and the French National Mapping Authority (IGN). Data models for the three facets were developed in conjunction with expert members of the IUCN working group on Wilderness and Nature Ferale[25,77] (GTWNF). An iterative process of testing the resulting data models on a representative subset of French departments and feeding the results back to the expert group for discussion lasted for the duration of the project, 2016–2020.

Based on this iterative process selected data sets with full coverage of the study area and of thematic relevance to each of the individual layers were retained for use in the production of the three CARTNAT component layers (1) Biophysical integrity, (2) Spontaneity of processes and (3) Spatio-temporal connectivity. Full details of all datasets used and specific weightings for individual classes are included in Supplementary information (see Supplementary Information–Section 1). The three thematic layers were then combined into a final map of naturalness using equal weighting. Here we describe additional information on the individual data layers:

Layer 1—biophysical integrity

Input data included vegetation, buildings, transport networks (roads and rail) rivers and water bodies. For vegetation this included information on natural and managed vegetation such as woodland species (BD Foret 2), crop type (RPG) and naturalness of rivers. All vector data was rasterised at 20 m resolution using ArcGIS Pro[78] and the choice of weightings for the attributes given within individual input layers were based on a review of the literature (see for example, ref. 46), and in consultation with the thematic subgroups of the GTWNF and specific data producers such as the French Geographical Institute (IGN). For each dataset in the biophysical integrity layer, the experts scored each specific component of the dataset in order to build a consensus. To facilitate this process weights were assigned using the range 0 (very low naturalness) to 80 (very high naturalness) and this weighting process was integrated into the ongoing consultation process with the GTWNF. This created an ongoing process for map development for the duration of the project based on expert weighting of input layers and working group review of the results. We note that whilst data on the naturalness of rivers was available, no equivalent data set on the naturalness of water bodies (>7.5 m) is currently available. As a result, while considerable time was given to reviewing the literature and in discussions with experts, it was concluded that a cautious approach should be taken with only a limited set of surface water body types given high naturalness scores (see Supplementary Information—Section 1).

Naturalness of a given forest species varies greatly based on its spatial location within France. In consultation with experts from the forestry commission and botanical research institutes, data on forest cover was pre-processed using a sub-model (GRECO Forest Model) to split France according to a pre-existing classification for large ecological regions within France[79]. A key stage in this process involved a group of five French forestry experts who independently allocated naturalness weightings for a given tree species within the different ecoregions and final weightings were then based on an average across the group (see Supplementary Information—Section 1). An additional spatial model was then built to incorporate the probability that a given area of native forest had remained relatively undisturbed during the last few centuries (high probability natural forest model—HPNFM). This model incorporated spatial data on forest cover in Metropolitan France from the 18th and 19th centuries (Cassini et Etat-Major maps, respectively) as well as data on slope steepness. Slope steepness is strongly linked to the probability of forest exploitation and based on discussion with forestry experts slopes greater than 30% were retained as areas where forest exploitation is far less likely due the challenges and costs of logging. Highest scoring areas in the HPNFM were covered by forest in the 18th century, and in the 19th century, are also on slopes greater than 30% and are still covered by natural forest according to the GRECO forest model. We note that several challenges remain notably that we do not have intermediary data on forest cover between the Cassini and Etat-Major maps and that to date there is no spatially explicit data on forest management, hence the need to use slope as a proxy.

All retained data and the outputs of the sub-models were combined using the mosaic function in ArcGIS Pro[78], which allows for the value of a given pixel in the final layer to be determined by the order in which data layers are processed. Data was written into the raster in the following order: built and linear elements such as roads, land use data, naturalness of rivers and surface water; forest cover (incorporating the HPNFM and GRECO Forest Models); crop types and vegetation. Any remaining small gaps in the data were filled with the OSO-CESBIO-THEIA landcover map for France[80] (see Fig. 6).

Layer 2—Spontaneity of process

Layer 2 aims to measure the degree of human influence on natural processes. In this layer, the spontaneity of processes is understood to be inversely proportional to human influence. Two key indicators were calculated to quantify human influence: building density and distance from roads. The presence of buildings is a well-established proxy for human presence[81]. Building density was preferred to population density because it can be measured in a spatially explicit way. In France, population density is measured by council area and does not allow us to reconstruct the heterogeneity of population density within council areas. All built surfaces in France were included and a density calculation for built-up areas was performed in ArcGIS Pro[78] using the focal statistic tool. This tool calculates for each input cell location a statistic of the values within a specified neighbourhood around it. The radius of density was chosen by an empirical method, and we first tested three distances of

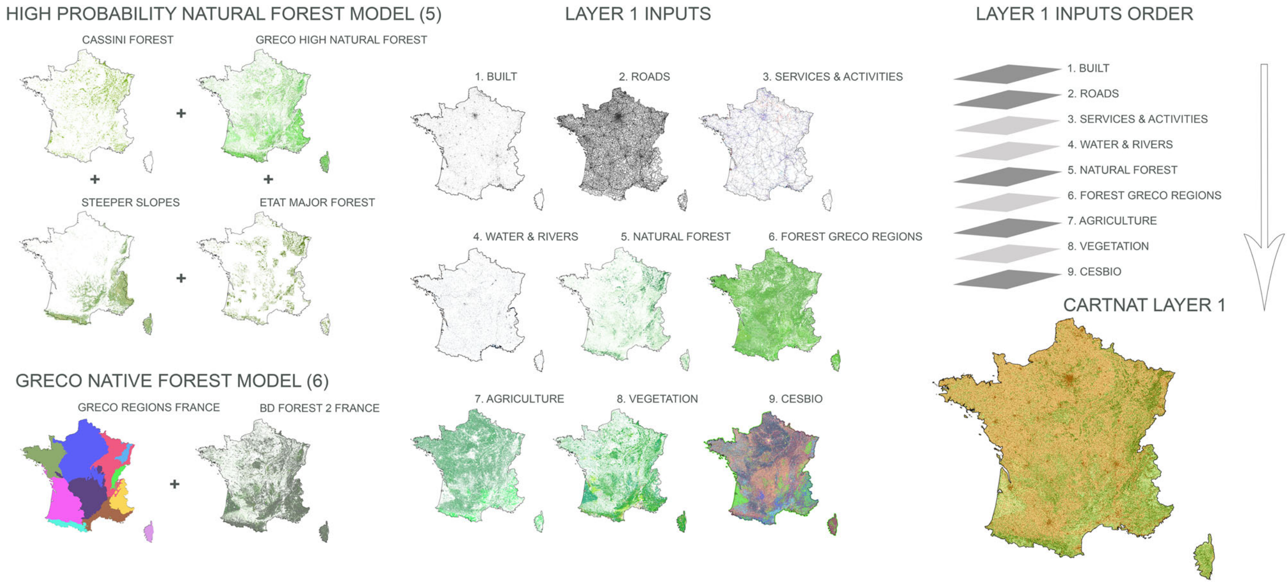

Fig. 6 | Data model for Layer 1 of CARTNAT showing sub-models and component layers. Layer one "biophysical integrity" was built using expert weighting of key spatial layers available at the national scale for France. Where possible spatial layers were improved using sub-models that take advantage of historical data and regional variation based on ecoregions (GRECO native forest model and high probability forest model). Final input layers are shown as well as the priority order in which they were combined to produce the final layer.

radius (500 m, 1 and 2 km) and kept the best compromise between visual representation of reality and the normal distribution of the resulting data.

Road construction allows access to areas that were previously inaccessible, and the presence of roads constitutes a proxy for human influence on areas near to roads[82]. We can therefore assume that the closer a space is to a road, the more this space will be frequented and influenced by humans. To produce an index of road distance, we calculated the Euclidean distance from each point in Metropolitan France to the closest road. To take into account both the type of road and the proximity to several roads, we first computed the distance to the first road by type of road. We used the 'importance index' of the road from the data attribute table as a proxy measure for road traffic. This index is from 1 (most frequented roads) to 6 (for very little used roads)[48]. We then summed the 6 resulting raster layers by weighting each type of road by a weighting coefficient in order to give more weight to the roads with the most traffic. In the final model proximity to a road with a high traffic volume is considered to receive more human influence. The sum of six layers also makes it possible to take into account the cumulative proximity of several types of roads. Combining this with data on built density provides a composite proxy for the likelihood of human influence impacting negatively on the spontaneity of natural processes. The two layers, road distance and built density, were combined with equal weighting to take into account the similar effect of these two proxies on the spontaneity of process. Sensitivity analysis for the equal weighting approach used throughout the CARTNAT spatial model has demonstrated it is a robust strategy for combining these types of thematic layers and has minimal effect on the final result (See Statistics below for overall sensitivity analysis).

Layer 3—Spatio-temporal connectivity

Layer three aims to map the structural connectivity of the landscape, and as such resistance to movement is modelled as a function of landscape naturalness. A connectivity modelling approach that combines a non-species specific, landscape integrity approach with omnidirectional circuit flow modelling can be used to map the wider connectivity of the natural landscape at regional scales[83]. Compared with traditional least-cost modelling approaches, an omnidirectional analysis of relevance to multiple species provides a greater breadth of insights into which landscape features are critical to support conservation policy and wider biodiversity goals[84]. Connectivity was modelled using the Omniscape software package[85] and two input layers—a resistance layer and source layer. The resistance surface was constructed using Layer 1, which was inverted and stretched to 1–1000 in line with the literature[86]. This layer was buffered at the national boundary and terrestrial-marine interface to reduce the impact of artificial edge boundaries on the modelling process[87]. The source input layer, also based on Layer 1, classified all pixels using an equal area approach into 10 classes, where the most natural habitat areas were given the highest weighting (importance) as sources for ecological flow. In line with the aim of mapping the structural connectivity of the landscape, as opposed to a species dispersal modelling goal, a radius of 5 km was chosen to provide a local permeability analysis which models ecological flow and highlights well connected high naturalness areas (see for example, ref. 88). To the knowledge of the authors, Layer 3 represents the first non-species specific spatially explicit connectivity analysis at the national scale in France.

Statistics

For the purposes of analysis, the top 10% of CARTNAT was selected in ArcGIS Pro[78] using an equal area quantile split into ten classes. Data for protected areas was sourced from the World Database on Protected Areas (WDPA)[89]. Strong protection areas were selected from this database based on current French legislation defining those protected area designations which meet the criteria for strong protection[36]. The Extract by mask and statistics tools were used to calculate values for the percentage of CARTNAT high naturalness areas that were covered by strong protection, IUCN categories I–V, or unprotected. Zonal Statistics as Table tool was used to generate mean values for CARTNAT within the protected areas.

The null-model was created using the random point tool in ArcGIS Pro. A series of random points ($n = 5000$) were generated based on the number of protected areas. These points were then buffered out into polygons equivalent in size to the median area of protected areas in the PAs dataset. Polygons intersecting existing PAs were removed and as above the Zonal Statistics tool was to calculate mean values for CARTNAT within the polygons.

All statistical analysis was done using R-Studio[90] and Figs. 3 and 4 were produced using the *ggbetweenstats* package[91].

A sensitivity analysis was conducted to determine the robustness of the final CARTNAT map product to different weightings of the three core input layers in the model design. Given the anticipated use of CARTNAT as a decision support tool for identifying priority areas for protection, a dual-pronged strategy was used. This combined a sensitivity analysis approach which considered four alternative weightings based on potential stakeholder preferences, with a standard Monte Carlo simulation approach with 100 random iterations of the weightings. The stakeholder analysis assessed variation in the identification of the top 10% high naturalness areas based on different stakeholder weightings. The sensitivity analysis demonstrated that the CARTNAT spatial model design was robust to variations in layer input weighting (see Supplementary Information—Section 2).

Data availability

The spatial data for the three input layers for CARTNAT as well as the final CARTNAT mapping product developed by the current study are available for download here: https://doi.org/10.6084/m9.figshare.28430936. Supplementary data on spatial attribute weightings is available in Excel format for ease of use along with high-resolution versions of the figures here: https://doi.org/10.6084/m9.figshare.28304081.

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References

1. Ward, M. et al. Just ten percent of the global terrestrial protected area network is structurally connected via intact land. *Nat. Commun.* **11**, 4563 (2020).
2. Di Marco, M., Ferrier, S., Harwood, T. D., Hoskins, A. J. & Watson, J. E. Wilderness areas halve the extinction risk of terrestrial biodiversity. *Nature* **573**, 582–585 (2019).
3. Pillay, R. et al. Humid tropical vertebrates are at lower risk of extinction and population decline in forests with higher structural integrity. *Nat. Ecol. Evol.* **6**, 1840–1849 (2022).
4. Watson, J. E. et al. Protect the last of the wild. *Nature* **563**, 27–30 (2018).
5. Milner-Gulland, E. J. et al. Accounting for the impact of conservation on human well-being. *Conserv. Biol.* **28**, 1160–1166 (2014).
6. Allan, J. R., Possingham, H. P., Venter, O., Biggs, D., & Watson, J. E. The extraordinary value of wilderness areas in the Anthropocene. In *The Extraordinary Value of Wilderness Areas in the Anthropocene* (eds Goldstein, M. I. & DellaSala, D. A.) *Encyclopedia of the World's Biomes* 158–168 (Elsevier, 2020).
7. Hansen, A. J. et al. A policy-driven framework for conserving the best of Earth's remaining moist tropical forests. *Nat. Ecol. Evol.* **4**, 1377–1384 (2020).
8. CBD. *Kunming–Montreal Global Biodiversity Framework: 23 targets* (CBD, 2022).
9. Maxwell, S. L. et al. Area-based conservation in the twenty-first century. *Nature* **586**, 217–227 (2020).
10. European Commission. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, EU Biodiversity Strategy for 2030* 53, 1689–1699 (European Commission, 2020).
11. Chaplin-Kramer, R. et al. Mapping the planet's critical natural assets. *Nat. Ecol. Evol.* **7**, 51–61 (2023).
12. Sanderson, E. W. et al. The human footprint and the last of the wild: the human footprint is a global map of human influence on the land surface, which suggests that human beings are stewards of nature, whether we like it or not. *BioScience* **52**, 891–904 (2002).
13. Kuiters, A. T. et al. *Wilderness register and indicator for Europe*. Final report Contract No. 07.0307/2011/610387/SER/B.3 (2013).
14. Venter, O. et al. Global terrestrial human footprint maps for 1993 and 2009. *Sci. Data* **3**, 1–10 (2016).
15. Reiner, F. et al. More than one quarter of Africa's tree cover is found outside areas previously classified as forest. *Nat. Commun.* **14**, 2258 (2023).
16. Plutzar, C., Enzenhofer, K., Hoser, F., Zika, M. & Kohler, B. Is there something wild in Austria? In *Mapping Wilderness: Concepts, Techniques and Applications* (Eds Carver, S. J., & Fritz, S.) 177–189 (Dordrecht: Springer Netherlands, 2016).
17. Carver, S., Comber, A., McMorran, R. & Nutter, S. A GIS model for mapping spatial patterns and distribution of wild land in Scotland. *Landsc. Urban Plan.* **104**, 395–409 (2012).
18. Müller, A., Bøcher, P. K. & Svenning, J. C. Where are the wilder parts of anthropogenic landscapes? A mapping case study for Denmark. *Landsc. Urban Plan.* **144**, 90–102 (2015).
19. Carver, S., Konráðsdóttir, S., Guðmundsson, S., Carver, B. & Kenyon, O. New approaches to modelling wilderness quality in Iceland. *Land* **12**, 446 (2023).
20. Comber, A. et al. Different methods, different wilds: evaluating alternative mappings of wildness using fuzzy MCE and Dempster–Shafer MCE. *Comput. Environ. Urban Syst.* **34**, 142–152 (2010).
21. Elysee. Protéger la biodiversité: une ambition française, européenne et mondiale https://www.elysee.fr/emmanuel-macron/2019/05/06/proteger-la-biodiversite-une-ambition-francaise-europeenne-et-mondiale (2019).
22. European Parliament. European Parliament resolution of 3 February 2009 on Wilderness in Europe (European Parliament, accessed 10 December 2023); https://www.europarl.europa.eu/doceo/document/TA-6-2009-0034_EN.html (2009).
23. Wild Europe. *A Working Definition of European Wilderness and Wild Areas* (Wild Europe, accessed 10 December 2023); https://www.wildeurope.org/wp-content/uploads/2023/09/Definition_25062013-update-151120.pdf (2009).
24. Guetté, A., Carruthers-Jones, J. & Godet, L. '«Naturalité»: concepts et méthodes appliqués à la conservation de la nature', *Cybergeo* https://doi.org/10.4000/cybergeo.29140 (2018).
25. Barthod, C. & Lefebvre, T. Le groupe de travail de l'UICN-France « Wilderness et nature férale ». *Rev. For. Fr.* **73**, 323–331 (2022).
26. Anderson, J. E. A conceptual framework for evaluating and quantifying naturalness. *Conserv. Biol.* **5**, 347–352 (1991).
27. Aplet, G., Thomson, J. & Wilbert, M. Indicators of wildness: using attributes of the land to assess the context of wilderness. In *Wilderness Science in a Time of Change*, (eds McCool, S. F., Cole, D. N., Borrie, W. T. & O'Loughlin, J.) RMRS-P-15-VOL-2 89–98 (USDA Forest Service Rocky Mountain Research Station, Missoula, MT, 2000).
28. Scott, D. W. *Untrammeled, Wilderness Character, and the Challenges of Wilderness Preservation*, No.11, 72–79 (Wild Earth, 2001).
29. Machado, A. An index of naturalness. *J. Nat. Conserv.* **12**, 95–110 (2004).
30. Fournier, J. Géographie et écologie du paysage. In Pour une géographie de la conservation (eds Godet, L. & Mathevet, R.) 229–242 (L'Harmattan, 2015).
31. Cateau, E. et al. Ancienneté et maturité: deux qualités complémenta ires d'un écosystème forestier. *C.R. Biol.* **338**, 58–73 (2015).
32. Johansson, L. J. et al. Semi-natural grassland continuity, long-term land-use change and plant species richness in an agricultural landscape on Öland, Sweden. *Landsc. Urban Plan.* **84**, 200–211 (2008).
33. Vallauri, D., Rossi, M. & Cateau, E. "La nature en forêt: qualités clés à conserver". *Rev. For. Fr.* **LXVII**, 157–172 (2015).
34. Locquet, A. & Héritier, S. Interrogation autour de la nature et du sauvage à propos de l'établissement de wilderness areas en Europe. *Cybergeo: Eur. J. Geogr.* (2020).
35. Ministère de la Transition Écologique. Stratégie nationale pour les aires protégées 2030. French National Strategy for Protected Areas 2020–2030 https://www.ecologie.gouv.fr/sites/default/files/2030%20NATIONAL%20STRATEGY%20FOR%20PROTECTED%20AREAS.pdf (2023).

36. French Government. Décret no. 2022-527 du 12 avril 2022 pris en application de l'article L. 110-4 du code de l'environnement et définissant la notion de protection forte et les modalités de la mise en oeuvre de cette protection forte. https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000045551000 (2022).
37. Dudley, N. (ed.) *Guidelines for Applying Protected Area Management Categories* (IUCN, 2008).
38. French Office for Biodiversity OFB. *La stratégie nationale pour les aires protégées* (French Office for Biodiversity OFB, 2023).
39. Cronon, W. The trouble with wilderness; or, getting back to the wrong nature. In*Uncommon Ground: Rethinking the Human Place in Nature* (ed. Cronon, W.) 69–90 (W. W. Norton, New York, 1995).
40. Ridder, B. The naturalness versus wildness debate: ambiguity, inconsistency, and unattainable objectivity. *Restor. Ecol.* **15**, 8–12 (2007).
41. Jørgensen, D. Rethinking rewilding. *Geoforum* **65**, 482–488 (2015).
42. Barthod, C. Le retour du débat sur la wilderness. *Rev. For. Fr.* **LXII**, 57/70 (2010).
43. Rouveyrol, P., Léonard, L. & Hérard, K. *Note sur les concepts de « pleine naturalité » et de « protection forte » pour soutenir la définition de nouveaux objectifs dans le cadre de la Stratégie nationale aires protégées 2020–2030*. Rapport PatriNat. OFB-CNRS-MNHN 44 (UMS PatriNat, 2019).
44. Marris, E. *Rambunctious Garden: Saving Nature in a Post-wild World* (Bloomsbury Publishing, USA, 2013).
45. Jalas, J. Hemerobe und hemerochore Pflanzenarten. Ein terminologischerReformversuch. *Acta Soc. Fauna Flora Fenn.* **72**, 1–15 (1955).
46. Walz, U. & Stein, C. Indicators of hemeroby for the monitoring of landscapes in Germany. *J. Nat. Conserv.* **22**, 279–289 (2014).
47. Génot, J.-C. *La nature malade de la gestion* 239 (Le Sang de la Terre, Paris, 2008).
48. IGN. BD TOPO: la base de données topographiques de l'IGN. French National Geographic Institute. https://geoservices.ign.fr/documentation/donnees/vecteur/bdtopo (2023).
49. Lobo, J. M., Jiménez-Valverde, A. & Hortal, J. The uncertain nature of absences and their importance in species distribution modelling. *Ecography* **33**, 103–114 (2010).
50. Martin, A. E. et al. Multi-objective optimization can balance trade-offs among boreal caribou, biodiversity, and climate change objectives when conservation hotspots do not overlap. *Sci. Rep.* **12**, 11895 (2022).
51. Fisher, M. Self-willed land-can nature ever be free? *ECOS-Br. Assoc. Nat. Conserv.* **25**, 6–11 (2004).
52. Schnitzler, A., Génot, J. C., Wintz, M. & Hale, B. W. Naturalness and conservation in France. *J. Agric. Environ. Ethics* **21**, 423–436 (2008).
53. Steinwall, A. Naturalness or biodiversity: negotiating the dilemma of intervention in Swedish protected area management. *Environ. Values* **24**, 31–54 (2015).
54. Carver, S. Rewilding… conservation and conflict. *Ecos* **37**, 2–10 (2016).
55. Sturm, K. Prozeßschutz-ein Konzept für naturschutzgerechte Waldwirtschaft. *Z. Ökol. Naturschutz* **2**, 181–192 (1993).
56. Fisher, M. et al. *Review of Status and Conservation of Wild Land in Europe*. 148, 131 (The Wildland Research Institute, University of Leeds, UK, 2010).
57. Carver, S. et al. Guiding principles for rewilding. *Conserv. Biol.* **35**, 1882–1893 (2021).
58. Ehrlich, G. et al. Ecosystem services: benefits supplied to human societies by natural ecosystems. *Issues Ecol.* **2**, 1–16 (1997).
59. Mitchell, M. G., Bennett, E. M. & Gonzalez, A. Linking landscape connectivity and ecosystem service provision: current knowledge and research gaps. *Ecosystems* **16**, 894–908 (2013).
60. Spanowicz, A. G. & Jaeger, J. A. Measuring landscape connectivity: on the importance of within-patch connectivity. *Landsc. Ecol.* **34**, 2261–2278 (2019).
61. Soule´, M. E. & Orians, G. E. *Conservation Biology: Research Priorities for the Next Decade* (Island Press, Washington, DC, 2001).
62. Worboys, G., Francis, W. L. & Lockwood, M. (eds) *Connectivity Conservation Management: A Global Guide (with Particular Reference to Mountain Connectivity Conservation)* (Earthscan, 2010).
63. Trame verte et bleue. Trame verte et bleue: Références juridiques. https://www.trameverteetbleue.fr/presentation-tvb/references-juridiques (2023).
64. Theobald, D. M. et al. Connecting natural landscapes using a landscape permeability model to prioritize conservation activities in the United States. *Conserv. Lett.* **5**, 123–133 (2012).
65. Dickson, B. G. et al. Informing strategic efforts to expand and connect protected areas using a model of ecological flow, with application to the western United States. *Conserv. Lett.* **10**, 564–571 (2017).
66. Breckheimer, I. et al. Defining and evaluating the umbrella species concept for conserving and restoring landscape connectivity. *Conserv. Biol.* **28**, 1584–1593 (2014).
67. Krosby, M. et al. Focal species and landscape "naturalness" corridor models offer complementary approaches for connectivity conservation planning. *Landsc. Ecol.* **30**, 2121–2132 (2015).
68. Marrec, R. et al. Conceptual framework and uncertainty analysis for large-scale, species-agnostic modelling of landscape connectivity across Alberta, Canada. *Sci. Rep.* **10**, 1–14 (2020).
69. Carruthers-Jones, J., Gregory, A. & Guetté, A. Natural landscape linkages to rewild protected areas and wildlife refuges. In *Routledge Handbook of Rewilding* (eds Hawkins, S., Convery, I., Carver, S. & Beyers, R.) (Taylor & Francis, 2022).
70. CARHAB. CarHab is a national cartographic modeling program for natural and semi-natural habitats in France https://inpn.mnhn.fr/programme/carhab (2023).
71. Panhelleux, L., Rapinel, S. & Hubert-Moy, L. Natural grasslands across mainland France: a dataset including a 10 m raster and ground reference points. *Data Brief.* **49**, 109348 (2023).
72. Morel, L. Développement d'un indice d'anthropophilie de la faune à partir de CARTNAT. Presentation at the workshop *'Cartographies de naturalité et applications du projet CartNat pour la conservation de la nature en France'*. Marais d'Orx 12–13 December 2022 (2022).
73. Carruthers-Jones, J., Eldridge, A., Guyot, P., Hassall, C. & Holmes, G. 'The call of the wild: Investigating the potential for ecoacoustic methods in mapping wilderness areas'. *Sci. Total Environ.* **695**, 133797 (2019).
74. IUCN. *WCC-2020-Res-127-EN Strengthening the Protection of Primary and Old-growth Forests in Europe and Facilitating their Restoration where Possible* (IUCN, 2023).
75. EU Nature Restoration Law. *Nature Restoration Law: A New Law to Restore Ecosystems for People, the Climate and the Planet* https://environment.ec.europa.eu/topics/nature-and-biodiversity/nature-restoration-law_en (2023).
76. IUCN. *Protected Areas in France: A Diversity of Tools for the Conservation of Biodiversity* (IUCN, 2023).
77. Guetté, A., Carruthers-Jones, J. & Carver, S. *Proposition de méthode de cartographie et de modélisation des espaces français de haute naturalité*. For WWF France, IUCN France and Wild Europe. Final report and delivery of national level wilderness mapping. Data here: https://uicn.fr/aires-protegees/wilderness/ (2020).
78. ESRI. *ArcGIS Pro* (Environmental Systems Research Institute, Redlands, CA, 2023).
79. IGN. Fiches descriptives des grandes régions écologiques (GRECO) et des sylvoécorégions (SER) (IGN, 2023).
80. OSO-CESBIO. *Theia Land Cover SEC land cover maps for Metropolitan France using Sentinel-2A and Sentinel-2B data* (OSO-CESBIO, 2023).
81. Venter, O. et al. Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nat. Commun.* **7**, 12558 (2016).

82. Carver S. J. & Fritz S. (eds) *Mapping Wilderness* 204 (Springer, Dordrecht, Netherlands, 2016).
83. McRae, B. H. et al. *Conserving Nature's Stage: Mapping Omnidirectional Connectivity for Resilient Terrestrial Landscapes in the Pacific Northwest* (The Nature Conservancy, Portland, OR, 2016).
84. Pelletier, D. et al. Applying circuit theory for corridor expansion and management at regional scales: tiling, pinch points, and omnidirectional connectivity. *PLoS ONE* **9**, e84135 (2014).
85. Landau, V. A., Shah, V. B., Anantharaman, R. & Hall, K. R. Omniscape.jl: software to compute omnidirectional landscape connectivity. *J. Open Source Softw.* **6**, 2829 (2021).
86. McRae, B. H. et al. Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology* **89**, 2712–2724 (2008).
87. Koen, E. L., Garroway, C. J., Wilson, P. J. & Bowman, J. The effect of map boundary on estimates of landscape resistance to animal movement. *PLoS ONE* **5**, e11785 (2010).
88. Buttrick, S. et al. *Conserving Nature's Stage: Identifying Resilient Terrestrial Landscapes in the Pacific Northwest* (The Nature Conservancy, Portland, 2015).
89. UNEP-WCMC and IUCN. *Protected Planet: The World Database on Protected Areas (WDPA)* (UNEP-WCMC and IUCN, Cambridge, UK, 2023).
90. R-Studio Team. *RStudio: Integrated Development for R* (RStudio, PBC, Boston, MA, 2023).
91. Patil, I. Visualizations with statistical details: the 'ggstatsplot' approach. *J. Open Source Softw.* **6**, 3167 (2021).

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Author contributions

J. Carruthers-Jones co-led the CARTNAT project as well as the writing, analysis and preparation of the article. A. Guetté co-led the CARTNAT project and supported the writing, analysis and preparation of the article. S. Carver supported the methodological development of the CARTNAT project as well as the writing, analysis and preparation of the article. T. Lefebvre supported the development of the CARTNAT project and advised on policy aspects related to writing. D. Vallauri provided expert input on the forest related aspects of the methodology and the article. L. Debeir provided expert input on the policy related aspects of the methodology and the article. T. Aykroyd provided expert input on the policy related aspects of the methodology and the article. C. Barthod provided expert input on the policy and forest related aspects of the methodology. P. Cavallin provided expert input on the policy related aspects of the methodology. S. Vallée provided expert input on the use of CARTNAT in conservation and related figure for the article. F. Benest provided expert input on the forest related aspects of the methodology. E. Cherel provided expert input on policy. Z. Kun provided expert input on wilderness conservation and the policy related aspects of the methodology. O. Debuf provided support on the figure design.

Competing interests

The authors declare no competing interests.

Additional information

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