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Ecosystem services modeling as a tool for defining priority areas for conservation

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Dedicatória

Ao meu irmão, que sempre me inspirou a me aventurar por essa área…

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Ecosystem services modeling as a tool for defining priority areas for conservation

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Abstract

Ecosystem services have gained importance in conservation science in the last decade. As conservationists often have difficulty obtaining financial and social support for protected areas that do not demonstrate their benefits for society, ecosystem services provide further justification for appropriate management and conservation of natural systems. With spatial and quantitative information, land use decisions can incorporate areas with the best trade-offs and win-wins between services, biodiversity conservation and economic activities. Here, we take as our region of study the Iron Quadrangle, an important Brazilian mining province and a conservation priority area located in the interface of two biodiversity hotspots, the Cerrado and Atlantic Forest biomes. We used InVEST software and a set of GIS procedures to quantify and spatialize ecosystem services – habitat quality, carbon stock and sediment retention – and evaluated the overlap between them. In addition, we proposed a method to indicate priority areas with synergism between ecosystem services and biodiversity conservation. We also improved the habitat quality model with a topography parameter, and used a model that consider the tree mortality caused by edge effects in the estimative of carbon stock. We found low spatial congruence between the services modeled, mostly because of the pattern of sediment retention distribution. The method allowed us to successfully achieve a preliminary spatial plan for ecosystem services priority areas in the region, with 13% of the study area indicated as priority for the maintenance of key ecosystem services. Among those priority areas, 30% are within already established strictly protected areas and 12% are in sustainable use protected areas. We considered ecosystem services analysis very important in the Iron Quadrangle region because of increasing mining pressures that could generate high social and economic externalities costs. An ecosystem services approach is increasingly needed, as human population and the economic activities continue to grow. Following the transparent and highly replicable method shown in this study, conservation planners can better determine which areas fulfill multiple goals and can locate the trade-offs in the landscape.

Keywords

InVEST; Iron Quadrangle; conservation planning; sediment; biodiversity; carbon stock

Introduction

Ecosystem services are the benefits provided by natural ecosystems for humans [1,2]. Among them are the provision of food, wood, water quality, climate regulation, wildlife-based tourism and pollination of crops. This concept has garnered great importance in conservation science in the last decade [3]. The Millennium Ecosystem Assessment, an international scientific collaboration, has reported a widespread decline in ecosystem services across the world [2]. The research emphasized the urgent need to incorporate services in decision-making process in order to ensure human well-being, presently and in the future. In this context, the Conference of Parties (COP 10) to the Convention on Biological Diversity (CBD) established a global strategic plan for biodiversity in which, among others, the protection and the restoration of ecosystem services are targets to be accomplished until 2020 [4].

The ecosystem services approach supports biodiversity conservation. Conservationists often have difficulty to obtain financing and social support for protected areas that do not demonstrate their benefits for society [5,6]. Normally, the areas defined as priority are rich in species and concentrate high levels of endemism [7–9], as well as within a well connected and highly conserved context [10]. In most cases, the development and implementation of this strategy is unrelated to the economic and social debate; however, their integration could reduce the conflicts and trade-offs between them [11]. Services provide further justification for appropriate management and conservation of natural systems, and for more financial support for these two activities [5,12]. Furthermore, the ecosystem services approach has the potential to preserve areas outside legally protected reserves, which is an important feature in face of the global proliferation of disturbed landscapes [2,13,14]. These areas are usually maintained through payments for environmental services (PES), in which beneficiaries pay landowners for the conservation and maintenance of ecosystems and their services [15]. This is a promising way to align social and economic development with protection of natural environments and their ecological processes.

Aiming to improve recognition and application of ecosystem services in the decision-making process, important elements that need to be prioritized are the understanding, modelling and mapping of these services, linking them to human well-being [16]. Spatial prioritization is considered an important step of biological conservation planning [17].

With spatial and quantitative information, land use decisions could incorporate areas with the best trade-offs and win-wins between services, biodiversity conservation and economic activities [18]. Those are very important tools for decision-making, especially in conflict regions where the natural surroundings are greatly affected by the main economic activity, such as mining. According to Seppelt *et al.* [19], the recent studies on mapping and quantifying ecosystem services are concentrated in a few countries (50% of 153 reviewed works are located in only six countries), and are lacking in research on tropical areas. The works that sought to analyze the overlap between biodiversity rich areas and areas providing services are still incipient and have conflicting results [14,18,20–22]. This suggests a need to extend this kind of research, mostly in places where current human activity can harm the conservation of the natural capital.

Here, we take as a region of study the Iron Quadrangle, located in southeastern Brazil. Besides being an important mineral reserve for the country [23], the Iron Quadrangle is also a conservation priority area [24]. Located in the interface of two Brazilian biodiversity hotspots, Atlantic Forest and Cerrado [8], the Iron Quadrangle has a high endemism level for amphibians and plants, high vertebrates richness, a large extension of ironstone outcrops, one of the country's most threatened geologic formations [24,25] and important groundwater and watersheds for human population.

Therefore, the region has characteristics – biodiversity, endemism, human demand for services and economic pressures on the environment – that illustrate the need to incorporate human well-being and economic externalities into conservation science. Focusing on modeling and mapping habitat quality (a biodiversity indicator), carbon stock and sediment retention, the aims of this work were: 1) Quantify and spatialize these ecosystem services; 2) Identify which parameters influence the ecosystem services model; 3) Evaluate the overlap and the synergism between ecosystem services and biodiversity; 4) Indicate priority areas for ecosystem services and biodiversity conservation. We expect that habitat quality has a positive correlation with ecosystem services and that each model parameter has a different influence on the models.

Methodology

Study area

The Iron Quadrangle has about 7000 km^2 and is located in the central-east region of Minas Gerais state, Brazil (Fig. 1). The Iron Quadrangle is responsible for approximately 67% of Brazil's measured iron ore production [23], and is submitted to increasing global demand for iron and steel [26]. The Iron Quadrangle is located within two of Brazil's major watersheds, Rio Doce and Rio São Francisco. A subtropical latitude climate prevails, characterized by a dry winter and rainy summer, where places with higher rainfall indices have an annual mean of almost 2000 mm, and those with lower rainfall indices have an annual mean of 1400 mm [27]. The altitude ranges from 586 to 2087 m.a.s.l. Many vegetation types occur in the Iron Quadrangle, varying from tropical semideciduous forest to rupestrian grasslands, due to the high geodiversity, different soil types and altitudinal/climate gradients [28,29]. We chose the Iron Quadrangle as a study region due to its high levels of biodiversity and endemism, the occurrence of relatively large natural areas, the presence of relevant watersheds providing water for one of the largest urban centers in Brazil, and due to the increasing anthropogenic pressures associated mostly with mining activities and urban expansion [25,26].

Fig. 1 – Map of the study area. Map representing the Iron Quadrangle's selected watersheds, the digital elevation model with its altitude range and the main ridges. The inset illustrates the location of the study area within Brazil and Minas Gerais.

For the study area delimitation, we used the digital elevation model (DEM) available for the region, obtained from the "Advanced Spaceborne Thermal Emission and Reflection Radiometer" (ASTER GDEM). Using digital and automatic processing, we delimited watersheds in the region with the GRASS GIS software [30]. Each watershed had a minimum area of 36 km^2. During this digital processing, we generated data on flow direction, flow accumulation and definition of the drainage network (for more details see [31]. After that, we selected 80 watersheds, using the criterion of being inside the Iron Quadrangle area, the availability of maps and other necessary information for subsequent analysis. The total area summed approximately 6500 km^2 and contains the alignments of

Serra do Curral to the north, Serra de Ouro Branco to the south, Serra da Moeda to the west, Serra do Gandarela and Serra do Caraça to the east (Fig. 1).

Modeling key ecosystem services

The InVEST model as baseline

For mapping and quantifying habitat quality and ecosystem services, we used InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), a GIS tool developed by Stanford and Minnesota Universities, World Wildlife Fund and The Nature Conservancy [32]. This geospatial tool helps to evaluate land use change impact on ecosystem services [33,34]. As cited by Nelson *et al*. [35] "InVEST is a suite of service models that use production functions to convert maps of land use and land cover (LULC), land management, and biophysical conditions into maps of service supply". It uses mostly free available data and, therefore, has a generalization characteristic that is important to cover different landscapes, situations and needs. As InVEST software not fulfilled all our needs to model the ecosystem services of interest, we developed a set of GIS tools to complete the tasks (see below).

Land use and land cover map

To obtain a LULC map for the study area that would serve as an input to all models, we mosaicked and manually edited the maps provided by Vale S.A. company, which were elaborated in 2008 [36,37]. Using ArcGIS 10.2 software [38] for visual analysis, we chose the best maps for each class in each watershed, having as reference Landsat 8 OLI images from 2013, obtained from *United States Geological Survey* website (USGS), and RapidEye images from 2009, provided by Minas Gerais Institute of Forestry (IEF-MG). We combined different spectral bands and produced several image compositions to facilitate visual identification of LULC classes (see the definition of classes in S1 Table). Then, we fixed a 1:20,000 scale, performed a new visual analysis using manual edition and generated a more accurate LULC map.

We validated the LULC map through ground truth points collected (total of 471 points) throughout the entire region. Field routes were predetermined, aiming to cover the majority of watersheds. In order to quantify the classification's accuracy, we generated a confusion matrix using the cover classes from our map and from the ground truth points and calculated omission and commission errors. We aimed to have overall classification accuracy greater than 80%. S2 Table presents the results of this matrix.

Habitat quality

Biodiversity *per se* is not considered an ecosystem service, but it is well recognized as important to ecosystem processes and to maintenance of several ecological functions and services such as primary production, disease and pest control [1,39]. The InVEST model assumes a positive relationship between habitat quality and biodiversity [32]. We consider habitat quality as a proxy for quantity and quality of available resources, which means the ability of a natural environment to promote appropriate conditions for the persistence of individuals and populations. We assumed that habitat quality decreases with the proximity of anthropic land use, but varied the intensity of this decrease according to the land use class. In the model, we defined which LULC classes were considered as habitat using a binary system in which zero corresponded to the threat LULC classes and one to the habitat LULC classes. Additionally, we assigned different weights or intensities to LULC classes according to their habitat quality degradation capacity (w_r). To address this parameter, we consulted with 16 specialists that had knowledge about the study area and about different organisms groups (mammals, birds, amphibians, reptiles and plants). We asked them to evaluate the LULC classes according to their threat intensity level, giving them values from zero to ten (see S3 Table). This approach is called expert knowledge and is increasingly used in landscape ecology analysis [40–42]. We used the *Delphi* method [43], in which the questionnaire with a text description of the survey was sent to experts via e-mail. Based on the responses, we calculated the average threat intensity value for each group of organism studied. The experts received the summary of results with a request to review their initial position, keep it the same if they were sure of their answers or, if not, change their previous evaluation. Based on the revised information, we calculated the median of all intensity values obtained per threat. In addition, the InVEST model considers the distance between the threat's source and the habitat. The intensity of impact on habitat quality caused by a specific threat decreases with distance according to a decaying exponential function (see Equation 3). We obtained the maximum influence distance by the same specialist surveys.

As the Iron Quadrangle has a relatively high altitudinal range, its hills and mountains can be seen as geographic barriers for the impacts caused by some LULC threats (S1 Fig.). We adapted the InVEST model to incorporate hilly conditions as a barrier to threat propagation. As it is not implemented within InVEST/ArcGIS, the new procedures were coded within GRASS GIS. First, we used the slope (in degrees, derived from a digital elevation model, 30 m of spatial resolution) and its cosine to correct the distance from the threats (d_a), accounting for the ups and downs of relief:

$$d_a = 30 / \cos\theta \tag{1}$$

where the number 30 is due to the raster resolution, and θ is the slope in degrees (see S1 Fig.). Then, we did the maximum relief curvature analysis in GRASS GIS to identify the position where the relief became a barrier to threat propagation. To calculate maximum relief curvature, we input a 500 m radius of influence around every pixel, considering maximum relief curvature higher than 20% as a barrier to threat propagation. Based on the maximum distances found in the expert consultation, we put a value of 300 on the remaining pixels to simulate a geographic barrier in which the distances following it would be too great for any impact to be significant. We summed the maximum curvature and the "d_a" rasters to obtain a "distance cost surface" for the subsequent analysis, i.e., we created a new relief distance raster that attenuated the impact factor of threats where a relief barrier exists. Lastly, with this new raster, we did a cost distance model in ArcGis software treating each one of the threats as a source. With this, we obtained a "cost-relief-distance" (d_c) for each pixel. To summarize, "d_c" is equal to the cost distance model (CDM) of the sum of "d_a" and the maximum curvature raster (mcr):

$$d_c = CDM\left(d_a + mcr\right) \tag{2}$$

Considering the LULC raster map of the study area, the impact (i_{rxy}) of pixel (y) with a certain threat class (r) over a habitat pixel (x) is given by equation:

$$i_{rxy} = \exp\left(-\left(\frac{2.99}{dmax}\right)d_c\right) \tag{3}$$

where "d_c" is the obtained cost-relief-distance between the pixels and "dmax" is the maximum influence distance.

Impacts have low accessibility to protected areas, which usually have some kind of management project and administration policy for their protection. Brazil's National System of Conservation Units (SNUC) provides categories for protected areas established in the country's territory [44], which can be divided in strictly protected areas (IUCN Categories I-III) and sustainable use protected areas (IUCN Categories IV-VI). We defined lower accessibility (β_x) for all impacts (with value 0.5) in strictly protected areas, decreasing the impact influence in those areas. One of the strictly protected areas was omitted from this evaluation, as it is a very recently created national park (October 2014 – Gandarela National Park) and lacks a management project and administration. However, we defined all evaluated habitats as equally susceptible to all sources of threats.

Thus, the total level of threat (D_{xj}) in a particular pixel (x) with a given habitat class (j) is given by the equation:

$$D_{xj} = \sum_{r=1}^{R}\sum_{y=1}^{Yr}\left(\frac{Wr}{\sum_{r=1}^{R} Wr}\right) i_{rxy}\beta_x \quad (4)$$

The habitat quality (Q_{xj}) in a given pixel (x) is given by the equation:

$$Q_{xj} = 1 - \left(\frac{D_{xj}}{D_{xj} + 0.5}\right) \quad (5)$$

Carbon stock

In this study, we modeled carbon storage according to the amount of four main reservoirs: i) the aboveground living plant biomass; ii) belowground biomass, which includes the roots of these plants; iii) soil organic components, that represents the largest terrestrial carbon reservoir [45]; iv) dead organic matter present in the litter. We used average data available in the literature for each LULC class (S4 Table). We sought data that were from the same watersheds or had vegetation, climate and soil features similar to the study area. We considered only terrestrial environments. For the forest class, it is described in the literature that edge effects reduce the aboveground and belowground biomass by increasing tree mortality in the first 100 meters [46–49]. We went beyond InVEST model and took this into consideration by reducing the biomass under edge effects and, therefore, carbon stocks according to what is found in restoration areas in the region [49]. The belowground biomass (BGB) of forest and urban classes were calculated according to the equation described by Pearson *et al*. [50]:

$$BGB = \exp(1.0587 + 0.8836 \times \ln AGB) \quad (6)$$

where AGB is the aboveground biomass. We assumed that 50% of the stock biomass is carbon [51].

Sediment retention

Sediment retention was estimated using the universal soil loss equation (USLE) [52], which consider LULC information along soil proprieties, rainfall data and elevation.

Thus, the annual soil loss due to water runoff (A), measured in ton/ha/year, is given by the equation:

$$A = R \times K \times LS \times C \times P \quad (7)$$

where R is the rainfall erosivity (MJ/ha/(mm/h)), K (ton/MJ/ha/(mm/h)) is the soil erodibility factor, LS is the slope length-gradient factor, C is the crop management factor and P is the support practice factor. The last three factors are dimensionless.

The rainfall erosivity index was calculated using the program NetErosividade [53]. The program allows calculating the annual erosivity for any location in the state of Minas Gerais from data interpolation performed using neural networks. We choose the method proposed by Foster *et al*. [54] to calculate the kinetic energy and the erosivity index EI_{30}. The map had a coarse resolution (900 m) but was the only available map covering the whole region. In our case, we considered that precipitation rates did not vary significantly on a finer spatial scale than the one obtained, but did so on a temporal scale during one year [27]. We obtained the soil erodibility rate (which indicates the susceptibility of soil particles to be detached and carried by the rain) from studies in the literature for each soil type found in the region. The soil type map was provided by Vale S.A., at the scale 1:50,000 [36,37]. The values for crop management and support practice factors were also taken from the literature (see S5 and S6 Tables), considering areas with similar characteristics; these practices were previously observed in the field. We obtained the LS factor from the digital elevation models cited for the delimitation of the study area. As the vegetation also retains eroded upstream sediment, the model also predicts a value of filtering sediments [32]. This field corresponds to the capacity of each LULC class to retain sediment coming from above the terrain and should be understood as relative values, reflecting the idea that one class can retain more sediments than another. We chose the values according to the relative density of vegetation found in each LULC class.

Data analysis

We performed three steps to analyze the models' outputs: 1) Verified the parameters that most influence each model; 2) Checked for the overlap between the models' output; 3) Created a prioritization method for those areas that overlapped. These analyses were made in ArcGIS and R software (R Core Team, 2013). For the first step, we perform a sensitivity analysis to quantify how the variance of model parameters influences the ecosystem service maps. We estimated the strength of influence of explanatory variables on habitat quality, carbon stock and sediment retention using sensitivity analysis [55]. This was made through the standardized regression coefficient (*src*) analysis, which estimates the average, standard errors and 95% confidence interval of the relative contribution of each explanatory variable on each response variable – habitat quality, carbon stock and sediment retention [55]. The *src* varies between -1 and +1, with values near zero representing variables with low or null influence to response variable (i.e. ecosystem service maps). For the habitat quality model, we used as explanatory variables the impact of each LULC threat and the accessibility factor. For the carbon stock, we used each one of the carbon pools. For the sediment retention, we used the USLE parameters and the sediment filtration factor. To prepare a table with a response (ecosystem services) and explanatory variable (model parameters), we randomly selected ten thousands pixels of our entire region for analyzes.

As each service uses a specific unit of measure, they were not directly comparable. In the second step, we rescaled the three service maps from zero to 100, following the formula:

$$Z_i = \frac{X_{ij}}{Xmax} \times 100 \tag{8}$$

where "X_{ij}" is the score for ecosystem service "i" in pixels "j", "Xmax" is the maximum score for ecosystem service "i" across all pixels and "Zi" is the new score for that pixel. Only for the sediment retention results did we previously log-transform the data, because the amplitude of result values was too high. To assess the spatial correlation between the model results, we calculated Pearson's correlation coefficients for each pair of services. We then assessed the ability to bundle the results of each model: Following Wendland *et al*. [14], we summed the areas containing overlap of pixels with more than a 0% value of each service, 15% and so forth, up to 90% or more.

For the third step, we selected for overlap the 20% of pixels that had the biggest scores (on the zero to 100 range) of each model's output. Next, we took only pixels where the overlap of at least two models occurred. As biodiversity conservation is an important aim in our prioritization analysis, we chose an organism dispersal capacity approach to create a spatial aggregation index for each one of the pixels that did overlap. With this method, the resultant conservation priority areas could increase the landscape's connectivity, i.e., the degree to which the landscape facilitates organism movement among resource patches [56]. Thus, we used a 250 m radius focal statistical analysis, using the selected overlapped pixels as input and giving to each one as core equivalent to the number of neighboring pixels within this radius. We chose this distance because of the ocelot (*Leopardus pardalis*) movement capacity in an inhospitable landscape matrix, the ocelot being a felid specie sensitive to habitat loss that occurs in our study region [57,58]. Therefore, we obtained a priority gradient for conservation and for future projects of payments for environmental services, ranging from low priority (pixels with low aggregation/connectivity) to high priority (pixels with high aggregation/connectivity).

Results

The LULC map had a global accuracy of 82% (S2 Fig. and S2 Table). We excluded from this analysis the LULC classes with less than 2% of the total study area (Table 1). We found that habitat classes (cerrado, forest, rupestrian grasslands, and water bodies) accounted for 70% of the study area, which confirm that, in general, the region is well conserved. Nevertheless, many natural habitats are suffering direct pressure from human disturbed LULC classes. For instance, we have more forest edge area than we have interior forests.

Table 1 – Area and the percent of the total study area correspondent to each land use land cover (LULC) class.

LULC name	Area (Km^2)	Percent of the total area
Agricultural fields	13.44	0.21
Cerrado	962.96	14.83
Eucalyptus plantations	316.56	4.88
Forest	1249.63	19.24
Forest edges	1637.97	25.23
Mining areas	189.80	2.92
Pasture	893.93	13.77
Roads network	120.44	1.85
Rupestrian grasslands	623.87	9.60
Urban areas	436.85	6.73
Water bodies	47.91	0.74

In this table, forest and forest edges are considered separately.

The three ecosystem services presented great variation in the Iron Quadrangle (Fig. 2). The habitat quality model ranged from zero to 0.99 (mean= 0.52 and standard deviation ±0.35). Despite the high anthropogenic impact of many areas devoted to eucalypts, pastures and mining activities, there are some places with relatively high habitat quality that promote appropriate conditions for sensitive species like the ocelot *Leopardus pardalis* [57]. Carbon stock varied from zero to 255.8 tons/ha (144.6 ±69.22). The $\log_{10}$ of the sediment retention model had values between zero and 61.7 tons/ha/year (6.7 ±7), meaning that sediment retention was a diffuse ecosystem service, with few areas providing very high rates of retention, and many areas providing medium to low rates.

Fig. 2 – Ecosystem services resultant maps. Iron Quadrangle's outputs maps and their quantitative variation for each one of the models: habitat quality at the top, carbon stock (tons of carbon/ha) in the center and sediment retention (tons/ha/year) below. The three insets show the same zoomed area for its respective model.

Sensitivity analysis

The main factors influencing habitat quality were the amount of pastures (src= -0.44 ±0.01) and urban areas (src= -0.37 ±0.01), both with strong negative influence (Fig. 3A). In addition, the sensitivity analysis showed that the accessibility layer had low or null influence (src= -0.06 ±0.01), mostly because the strictly protected areas already have low impact influence from threat LULC classes in the study region. For the carbon stock model, the aboveground stock (src= 0.72 ±0.01) had the strongest influence in the model results variation (Fig. 3B), mostly because of the great differences in natural vegetation types in the region, ranging from grass lands (low aboveground biomass) to forests (high aboveground biomass). The results for the sediment retention model (Fig. 3C) showed a stronger influence of the LS factor (src= 0.3 ±0.02), and intermediate influence of K factor (src= 0.2 ±0.01) and sediment filtration (src= 0.17 ±0.01).

Fig. 3 – Sensitivity analyses of the parameters used in three models, measuring their influences in output ecosystem services maps. A) Standardized regression coefficient (src) for the habitat quality model, where ACCESS is the accessibility parameter of anthropic land use land cover class impacts in conservation units, and the others are impacts caused by eucalyptus plantations (EUC), pasture (PAS), mining areas (MIN), urban areas (URB), road network and agriculture fields (AGR). B) The src values for the

carbon stock model, where DOC is the dead organic carbon, SOC the soil organic carbon and BGB e AGB are correspond to the carbon stock in below- and aboveground biomass. C) The src values for the sediment retention model, where FILT is the sediment filtration parameter and R, K, CP and LS are the USLE factors.

Synergism and conservation priorities

The three services modeled had different spatial distributions, as shown by the correlation coefficients in Table 2, although we found some areas with either high or low value to multiple services. Bundling the three services, we found weak spatial overlap between all three after a value of 15% or more of each service (Fig. 4). This overlap reached zero near 45% or more of each service. Considering the overlap between sediment retention and the other two services separately, we found the same pattern. Notwithstanding, there was strong spatial overlap of up to 60% for biodiversity and carbon, showing a higher synergism of those two models' results.

Table 2 – Correlation Coefficients for each pair of models.

Correlation Coefficients	Habitat Quality	Sediment Retention
Carbon Stock	0.55	-0.07
Habitat Quality	1	0.10

The coefficients were obtained through Pearson's correlation.

Fig. 4 – Sum of the total area that overlapped when the services are bundled together in each one of the minimum percentiles. "C" is the carbon stock service, "S" the sediment retention and "H" the habitat quality.

We produced a map of priority areas for conservation, which is shown in Fig. 5. These areas correspond to 13% (826 km^2) of the study region. About 30% of these priority areas are already in strictly protected areas (counting the one recently created, the Gandarela National Park) and 12.2% are in sustainable use protected areas. As there are many kinds of sustainable use protected areas in Brazil, this study only considered the ones that assure a minimum biological conservation status [44], as do the private reserves of natural heritage (RPPN in Portuguese acronym) and the National/State Forest (FLONA/FLOE). Also of interest in Fig. 5 is the presence of priority areas with high connectivity that are not within any existing protected areas.

Fig. 5 – Gradient of priority areas and the conservation units present in the study region. Pixels nearer the red color have a high aggregation index and the ones near the blue color have a low value for the same index.

Discussion

We successfully achieved a preliminary spatial plan for priority areas in the region, which has the potential to reduce conflicts between socioeconomic and conservation interests. The method presents a promising alternative to find the synergism between ecosystem service and biodiversity protection, providing an opportunity to consider ecosystem services as a new argument for supporting decision making in a conservation framework and, at the same time, incorporating human needs and demands in the priority areas planning process [2,18]. Our study demonstrated that, even with limited information available, we could quantitatively access and analyze areas with high capacity for providing ecosystem services throughout the space. Following the transparent and highly replicable method described in this study, conservation planners can better determine the areas within the landscape that provide multiple goals and trade-offs. The ecosystem services approach is increasingly necessary, as the human population and economic activities continue to grow [2].

One key aspect of this process was to determine how ecosystem services and biodiversity could be bundled together. We found low congruence between sediment retention and the other two models' results – carbon stock and habitat quality – mostly because the sediment retention model had the majority of pixels with intermediate values spread across the landscape. The Iron Quadrangle also has a very rugged topography. As this model is sensitive to the LS factor, we argue that it could have reduced the spatial correlation with the other two models. Despite this fact, the sediment retention service is important because it highlights areas where landowners need to preserve riparian vegetation, particularly under rugged terrain conditions. The Brazilian National Forest Code already determines the sizes for riparian forest buffers to be preserved by landowners [59], but this is not always accomplished [60], and thus, environmental liabilities have a negative impact on sediment retention services.

The correlation of terrestrial carbon and biodiversity is still controversial, having different patterns in different scales and landscapes [22,61–64]. In this study, carbon stock had a high congruence with biodiversity when compared to sediment retention. This is because the remaining forest fragments are large enough to have forest blocks that do not suffer from edge effects and are located in regions that are topographically protected from the impacts of anthropic land uses. The maintenance of those areas could be a target for economic incentives, such as the Warsaw Framework for Reducing Emissions from Deforestation and Forest Degradation, known as REDD+ [65]. For this, the government and landowners have to demonstrate emission reductions through improved carbon stocks, forest protection and/or sustainable management, comparing it to a "business-as-usual" scenario.

It is important to notice that our relief-factor applied to the habitat quality model reduced the impact of anthropic areas in the habitats LULC classes. In areas of very rugged topography such as the Iron Quadrangle, we have to consider the geographical barriers for these impacts and think beyond the linear distances. We argue that we have taken an important step towards the improvement of the InVEST habitat quality model, which received only a few updates of early versions ([66] compared to [32]). For this, we merely added the digital elevation model as an input, maintaining the simplicity and replicability of the model since this information is readily available and already used in other InVEST models. This model should be validated to ensure its efficacy.

Among the priority areas found in our analysis, 42.2% overlapped with protected areas. The ones that overlapped with strictly protect areas could have financial support through payments for those ecosystem services. Usually, these reserves and parks lack financial support and management projects [5], do not always contain nearby deforestation [67], and suffer pressures from local community because they have high opportunity cost [9,11,68,69]. Ecosystem services are already helping to solve those problems in some parts of the world [12,69–71] and can assist in this case. In private reserves, landowners could earn additional income based on the valuation of social benefits derived from ecosystem services, incorporating the positive externalities into the value of their protected areas for sustainable use. For areas that did not overlap with any conservation units, yet have high aggregation indices, we recommend implementation of strictly protected natural reserves (IUCN Category Ia). Those areas are extremely important for maintaining landscape connectivity and are large enough to conserve high rates of ecosystem services, permitting many sensitive species to persist. The areas around them and around those with lower connectivity indices could be sustainable use protected areas, due to adequate management aiming at future ecosystem services provision. Together, our priorities areas and the conservation units of the Iron Quadrangle cover 20% of the study region, more than the eleventh terrestrial environment target established by the Aichi Biodiversity Targets for 2020 [4].

We considered ecosystem analysis very important in the Iron Quadrangle region because of increasing mining pressures [26] that could generate high social and economic externalities in the region. The productive mining sector is expanding in the study area and creating new open pit mines, leading to losses in vegetation and soil carbon stocks as well as more erosion and siltation of rivers, triggering problems for populations downstream, despite losses in groundwater recharge ([72,73]. This is worrying if we consider that 43% of water consumption for the state's capital metropolitan area depends on the flow of rivers in the region [74].

Quantifying other services in the landscape is necessary to better understand the opportunities for financial and social support for conservation. Services that provide direct benefits, such as timber production or food provision, can have many trade-offs for biodiversity conservation [2]. Moreover, we need to account for the additionality of ours priority areas [14,75], because if they are already going to be preserved or not deforested in the future, they do not need to be prioritized and the economic resources can be allocated to other places [76]. This could be done with projections of probable future scenarios that encompass stakeholders needs and deforestation rates [33,77–80]. Finally, it is also important to quantify and spatially analyze the demand for services [76]. In the case of the services described here, the scale and location of service provision is not the same as its beneficiaries. Carbon has a local supply and global beneficiaries, and sediment retention has supply and demand in different spatial regions on the landscape. We believe that the spatial integration of biodiversity targets, ecosystem services provision and direct beneficiaries of pristine habitats could provide stronger arguments in conservation policies in conflict regions.

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Supporting Information

S1 Table - Land use land cover (LULC) class names and descriptions found in the Iron Quadrangle region.

LULC class name	Description
Agricultural fields	Mosaic cropland (50-100%) / vegetation (grassland/shrubland/forest) (0-50%)
Cerrado	Brazilian savanna vegetation/natural grasslands/shrubland
Eucalyptus plantations	Mosaic eucalyptus plantations (50-100%) / vegetation (grassland/shrubland/forest) (0-50%)/
Forest	Open-Closed (>40%) semi-deciduous Atlantic Forest
Mining areas	Areas with opencast mines. Includes buildings, associate industrial infrastructure, and small water bodies created by mining.
Pasture	Mosaic pasture (50-100%) / vegetation (grassland/shrubland/forest) (0-50%)
Roads network	Highways and roads. Minimum width of 30 meters.
Rupestrian grasslands	Shrub and grasslands, typical from altitudes ranging from 900 to 2000 meters.
Urban areas	Mosaic of Buildings, roads and artificial surface areas (50-100%)/vegetation within urban areas (<50%)
Water bodies	Natural and anthropic made water bodies

Data used for mapping and as input in the three models – habitat quality, carbon stock and sediment retention.

S2 Table - Confusion matrix for the land use land cover map.

	Cerrado	Rupestrian grasslands	Eucalyptus	Forest	Mining areas	Pasture	Urban areas	*Total*	Commission Errors
Cerrado	36	1	2	3		5	2	*49*	0.27
Rupestrian grasslands	6	47	2	2	1	1		*59*	0.20
Eucalyptus	1		38	2	1	2		*44*	0.14
Forest	6	6	9	118		10	2	*151*	0.22
Mining areas	3	1			17			*21*	0.19
Pasture	3		6	1	1	90	2	*103*	0.13
Urban areas	2					2	40	*44*	0.09
Total	*57*	*55*	*57*	*126*	*20*	*110*	*46*	*471*	
Omission Errors	0.37	0.15	0.33	0.06	0.15	0.18	0.13		0.82

Using only the LULC class that had more than 2% of the total study area . The columns represent the number of ground truth points and the lines represent the pixels classification in this study. The commission and omission errrors are the proportion of the errors in the lines and columns respectively.

S3 Table – Habitat quality model input parameters.

LULC Name [a]	Intensity	Maximum Distance (Km)
Agricultural fields	7.5	1
Eucalyptus	6.5	1
Mining areas	10	3
Pastures	7	1
Roads network	7	1
Urban areas	7.5	3

The intensity and maximum distance for each land use land cover class considered as threat and obtained by specialist consultant (n=16).

[a] Refer to S1 Table for LULC classes descriptions

S4 Table – Inputs values used in the carbon stock model.

LULC Name[a]	Aboveground Biomass	Belowground Biomass	Soil Organic Carbon (40 cm)	Dead Organic Carbon
	Mg ha^{-1}			
Agriculture fields	7.2	1.9	62.44	1.1
Cerrado	2.7	15.088	90.684	0.96
Eucalyptus	56.7	9.9	74.3	7.4
Forest	134.0	27.6	90.6	3.6
Forest edges	69.0	13.2	90.6	3.6
Mining areas	0.0	0.0	0.0	0.0
Pasture	2.9	7.7	94.6	1.1
Roads network	0.0	0.0	0.0	0.0
Rupestrian grasslands	2.8	15.088	90.684	0.96
Urban areas	15.0	3.8	41.0	0.0
Water bodies	0.0	0.0	0.0	0.0

Data for soil organic carbon, dead organic carbon, aboveground biomass and belowground biomass carbon by land use land cover (LULC) class, obtained from literature[b]

[a] Refer to S1 Table for LULC classes descriptions

[b] References: [1–10].

S5 Table – Mean values for K factor (erodibility) used in the universal soil loss equation (USLE) for each soil type, obtained from literature[a]

Soil type	K
Argisol	0.04450
Cambisol	0.02314
Gleysol	0.03585
Red Latosol	0.00962
Yellow-red Latosol	0.01717
Fluvic Neosol	0.042
Litholic Neosol	0.045
Quartzipsamment Neosol	0.1448

[a] References: [11–16]

S6 Table - Sediment retention model input table.

LULC Name[a]	C	P	Sediment Filtration (%)
Agricultural fields	0.18	0.4	40
Cerrado	0.042	1	70
Eucalyptus	0.016	1	70
Forest	0.012	1	95
Mining areas	1	1	0
Pasture	0.052	1	50
Roads network	1	1	0
Rupestrian grasslands	0.042	1	60
Urban areas	0.1	1	3
Water bodies	0.01	1	10

For universal soil loss equation (USLE): cover and management factor (C), support practice factor (P) and sediment filtration factor by each land use land cover (LULC) class, obtained from literature[b]

[a]Refer to Supp. Mat. S Table1 for LULC classes descriptions

[b]References: [17–19]

S1 Fig. – Representation of geographical barriers reducing impacts from land use land cover threat classes and of correction of distance from the threats (d_a). The gradient in the red arrows represent the impact reduction with the distance from its source (urban area or pastures). The slope in degrees was use to obtain the d_a distance, also reducing impact intensity in the natural land use land cover class (forest in this case).

S2 Fig. – Land use land cover map obtained for the Iron Quadrangle study region, showing each one of the classes found in the mapping process.

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Figures:

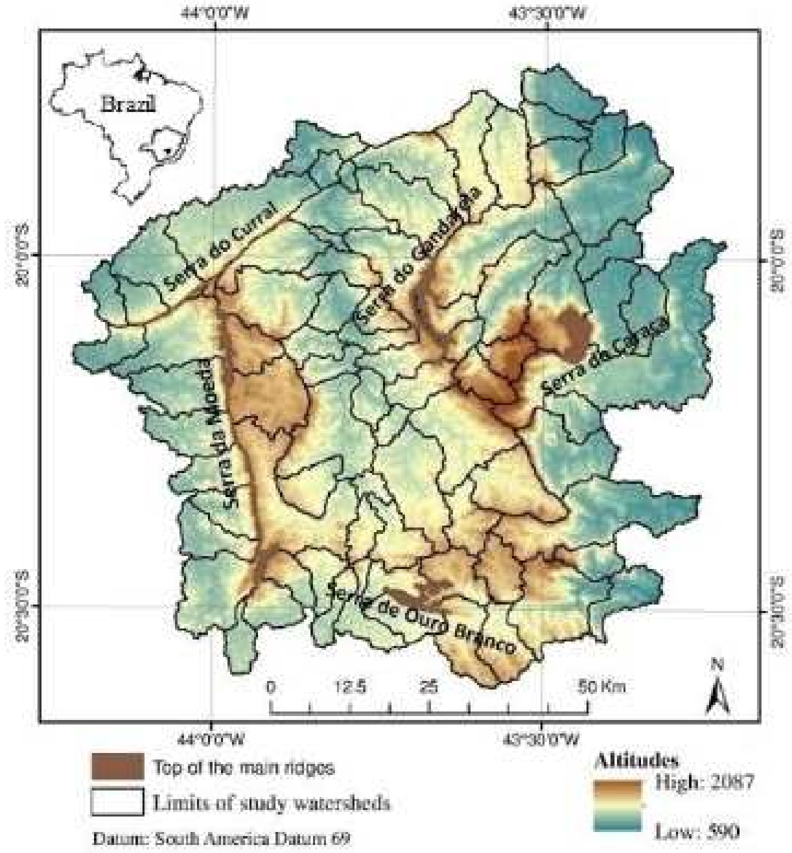


Figure 1

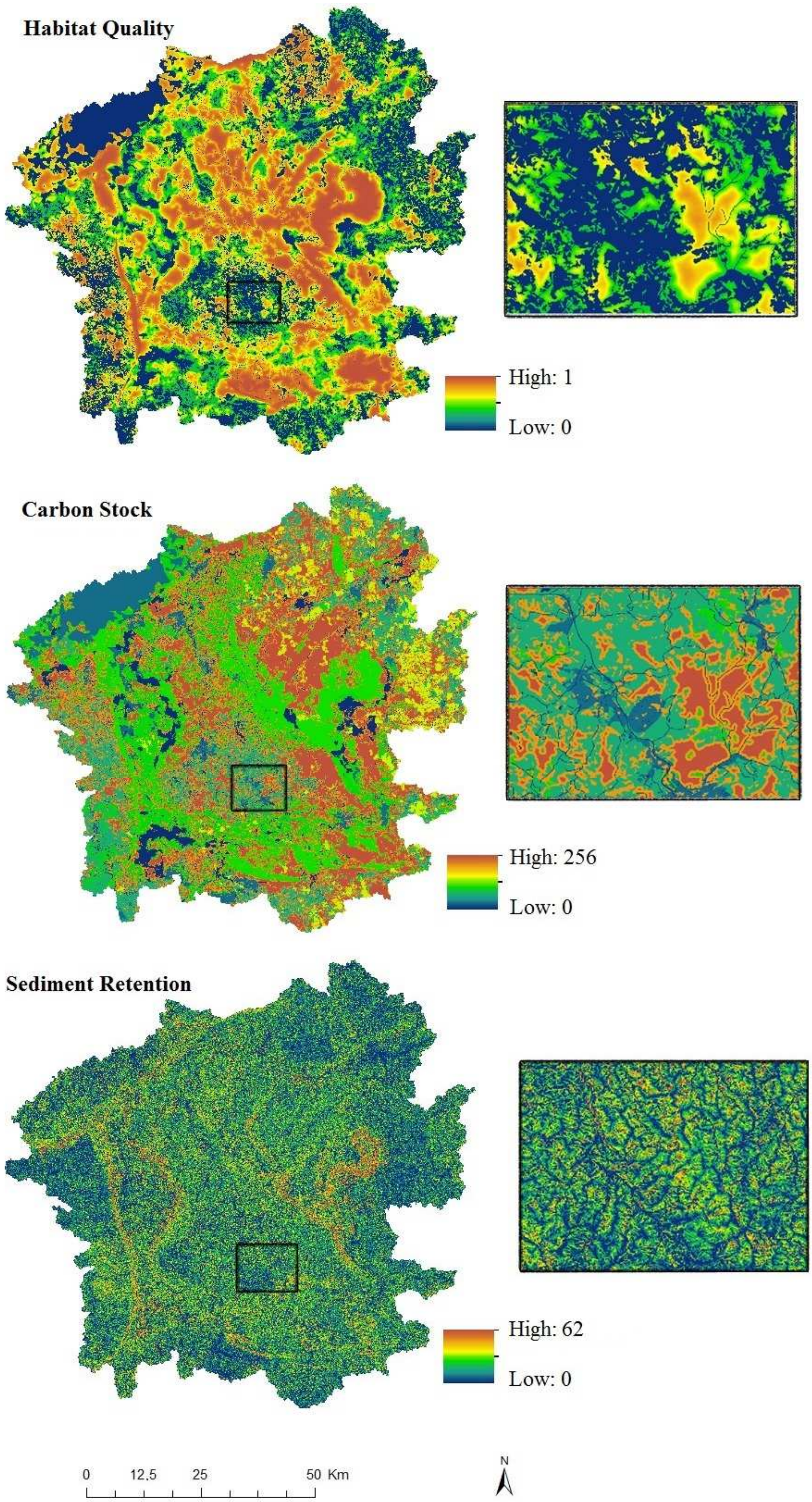

Habitat Quality
High: 1
Low: 0
Carbon Stock
High: 256
Low: 0
Sediment Retention
High: 62
Low: 0
0
12,5
25
50 Km
N

Fig. 2

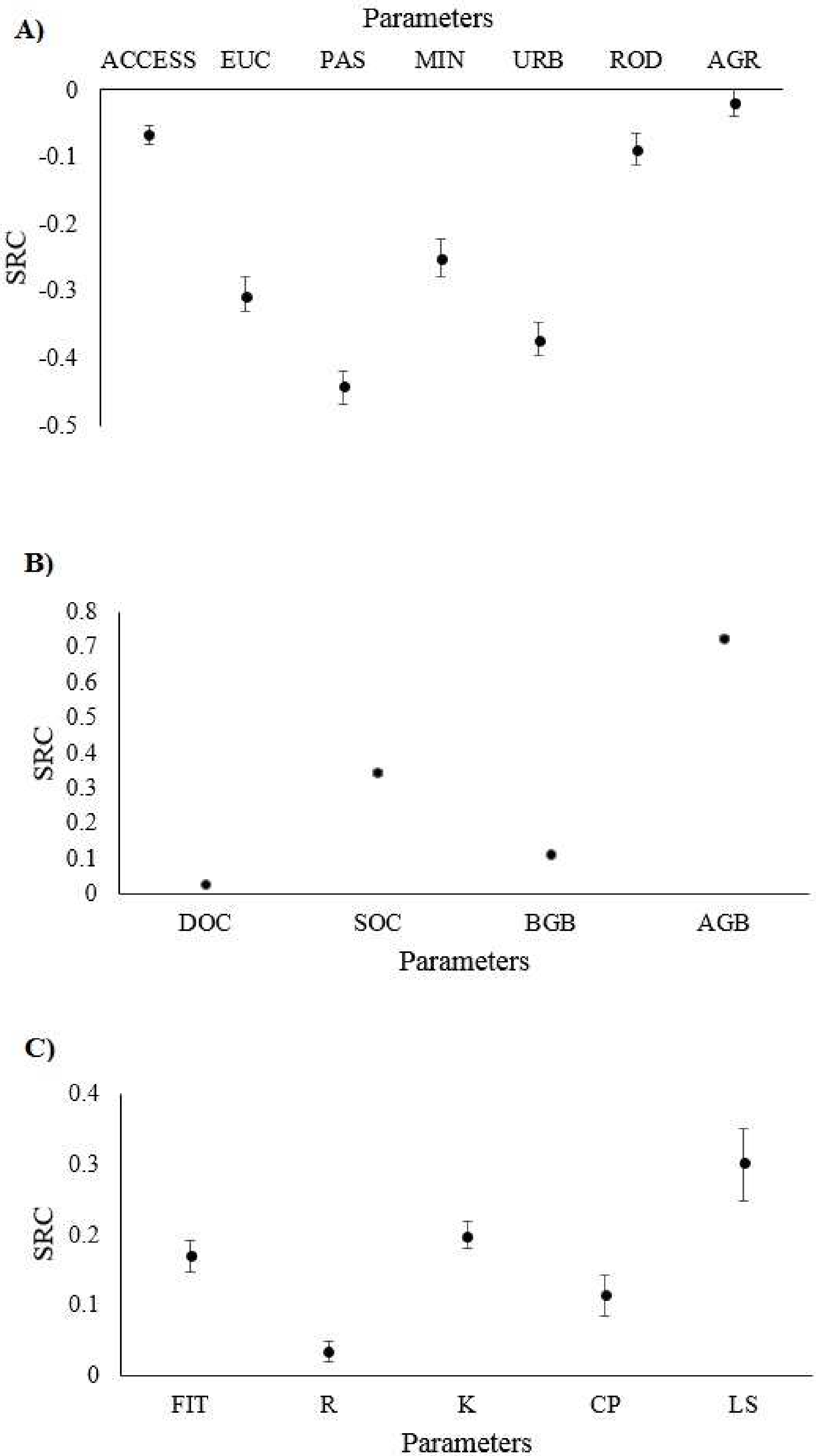
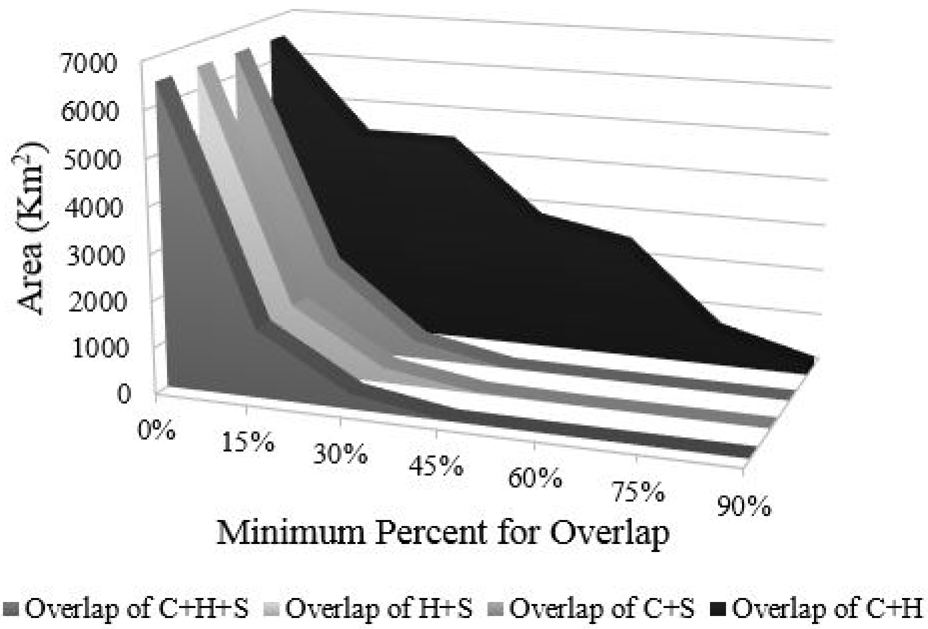

A)
Parameters
ACCESS
EUC
PAS
MIN
URB
ROD
AGR
0
-0.1
-0.2
-0.3
-0.4
-0.5
SRC
B)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
SRC
DOC
SOC
BGB
AGB
Parameters
C)
0.4
0.3
0.2
0.1
0
SRC
FIT
R
K
CP
LS
Parameters

Fig. 3



7000
6000
5000
4000
3000
2000
1000
0
Area (Km^2)
0%
15%
30%
45%
60%
75%
90%
Minimum Percent for Overlap
Overlap of C+H+S
Overlap of H+S
Overlap of C+S
Overlap of C+H

Figure 4

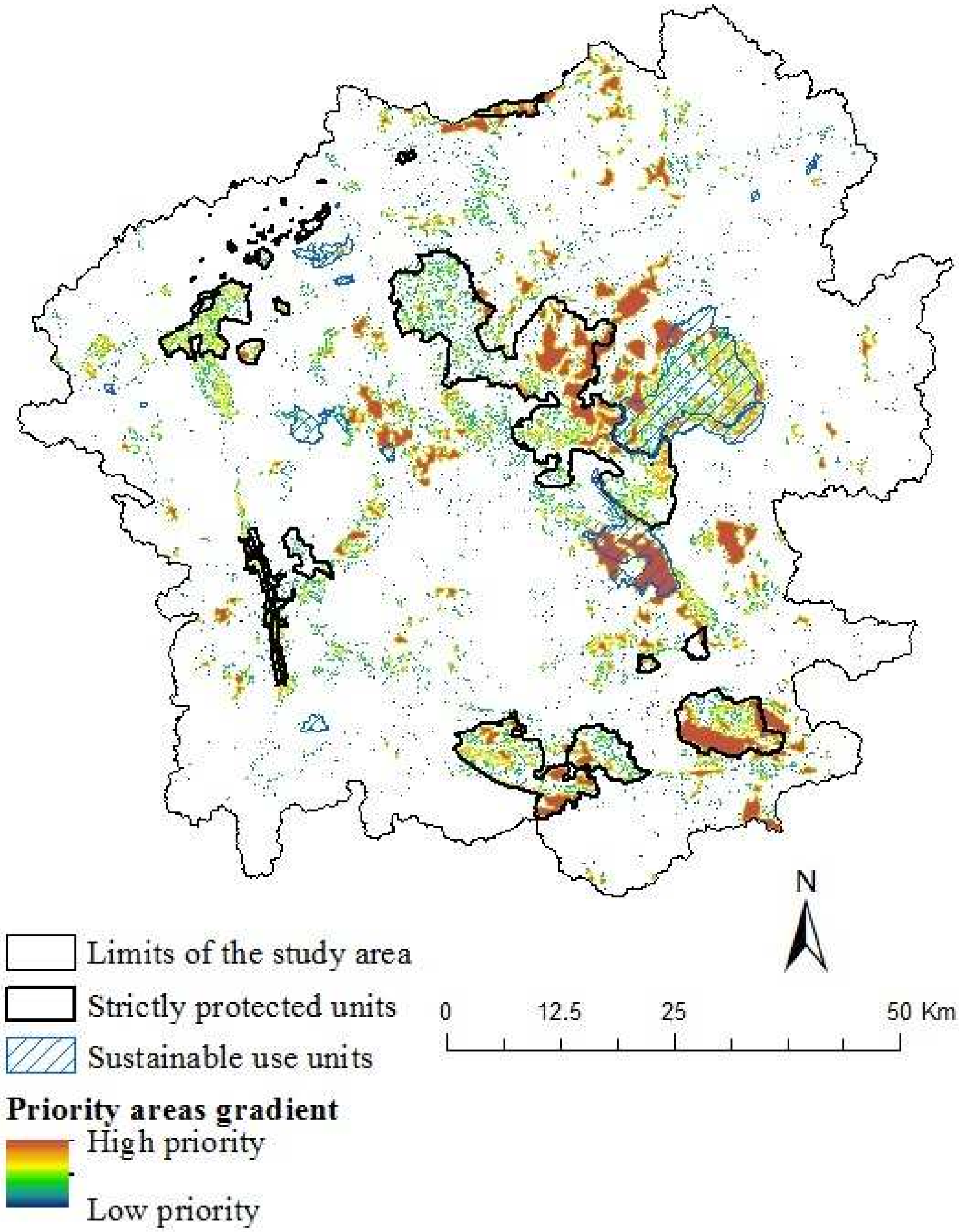
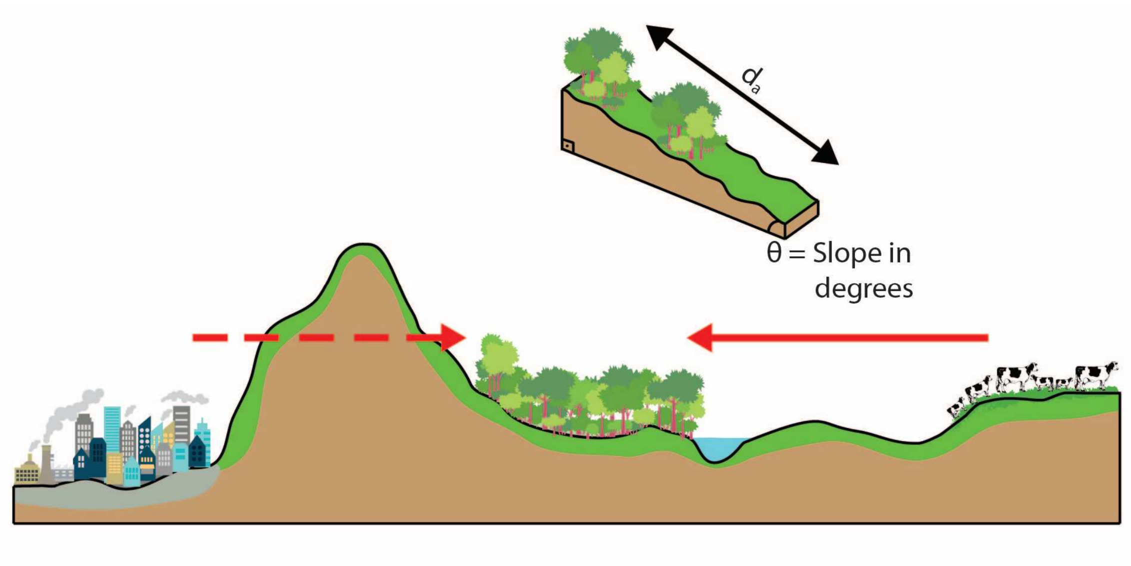
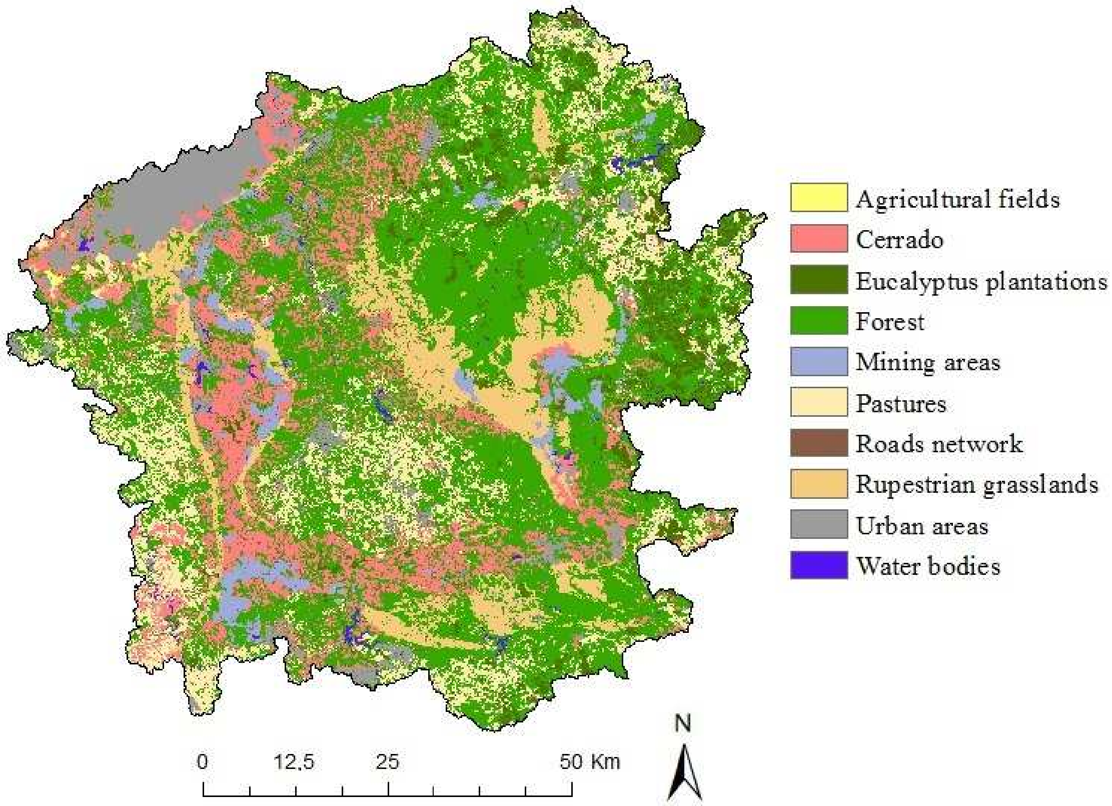

N
Limits of the study area
Strictly protected units
Sustainable use units
0
12.5
25
50 Km
Priority areas gradient
High priority
Low priority

Figure 5



S1 Figure



S2 Figure.