Hierarchical priority setting for restoration in a watershed in NE Spain, based on assessments of soil erosion and ecosystem services

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Abstract

Maintaining and enhancing ecosystem services through the restoration of degraded ecosystems has become an important biodiversity conservation strategy. Deciding where to restore ecosystems for the attainment of multiple services, is a key issue for future planning, management and human wellbeing. Most restoration projects usually entail a small number of actions in a local area and do not consider the potential benefits of planning restoration at broad regional scales. We developed a hierarchical priority setting approach to evaluate the performance of restoration measures in a semi-arid basin in NE Spain (the Martín River Basin, 2,112 km^2). Our analysis utilized a combination of erosion (a key driver of degradation in this Mediterranean region) and six spatially explicit ecosystem services data layers (five of these maps plotted surrogates for soil retention and accumulation, water supply and regulation and carbon storage, and one plotted a cultural service, eco-tourism). Hierarchical maps were generated using a Geographic Information System that combined areas important for providing a bundle of ecosystem services, as state variables, with erosion maps, as the disturbance or regulatory variable. This was performed for multiple scales, thereby identifying the most adequate scale of analysis and establishing a spatial hierarchy of restoration actions based on the combination of the evaluation of erosion rates and the provision of ecosystem services. Our approach provides managers with a straightforward method for determining the spatial distribution of values for a set of ecosystem services in relation to ecological degradation thresholds and for allocating efforts and resources for restoration projects in complex landscapes.

Keywords: Basin management, Mediterranean, Spatial prioritization, Semiarid landscape, GIS, Planning.

1. Introduction

Soil erosion is a major threat to the continued provision of ecosystem services in large parts of the world (Brown 1981), particularly in arid and semiarid areas (Gisladottir and Stocking 2005; García-Ruiz 2010). The future global change scenario corroborates the negative effects of increasing drought in Mediterranean regions on vegetation (Schröter et al. 2005), with runoff and sediment yields increasing in association with decreasing plant cover (within threshold) (Quinton et al. 1997). These suggested scenarios are likely to result in greater amounts of soil being exposed to water and wind erosion (López et al. 1998). Additional factors that determine the predominance of erosion include the spatial scale, slope, rainfall magnitude-frequency-duration characteristics, the initial soil moisture content and soil biological activity (Cammeraat 2002). Intensive agriculture and mining are land-use activities that cause serious environmental problems and increased erosion across vast areas. These activities cause serious environmental problems and erosion across vast areas and result in enforced critical trade-offs for the associated societies (Zhang et al. 2007; Bernhardt and Palmer 2011; Carreño et al. 2011).

A key issue in semiarid environments is determining how to prioritize areas for restoration to optimize erosion control. However, the challenge is how to combine this goal with the improved provision of vital ecosystem services, particularly water-related services reduce negative consequences for human development (Reynolds et al. 2007). Emerging policies are focused on ecosystem services and their inclusion in measures aimed at restoration and control of erosion. This emergency policy focus on ecosystem services represents a significant shift in the approach at the objectives of restoration (Bullock et al. 2011). Different organizations have set targets for ceasing biodiversity losses and the degradation of ecosystem services and restoring them ‘so far as feasible’ (European Commission 2011, MA 2003). To meet these policy objectives, there is growing interest in the development of tools and methods for identifying and evaluating ecosystem services and incorporating these measures into policies related to landscape planning, management and the allocation of environmental resources (Ruiz-Navarro et al. 2012; de Groot et al. 2010). This is particularly the case with regard to degraded areas and when attempting to understand trade-offs that arise related to land use and land cover planning (Rodríguez et al. 2006).

Mapping of ecosystem services has been identified as a useful aid in decision making during the allocation of efforts aimed at land use planning and management, particularly for the restoration of degraded areas (Reyers et al. 2009; Pert et al. 2010; Carreño et al. 2011). To obtain a complete understanding of the services provided in a study area, research should ideally be conducted at multiple, nested scales, as environmental effects may be uncorrelated across scales (MA, 2003). The extent to which ecosystem services can be integrated into basin-scale restoration projects that are focused on reversing these trends remains largely untested, despite the recent and growing number of studies focused on this broader topic (Fisher et al. 2009).

To understand how landscapes affect and are affected by biophysical and socioeconomic activities, we must be able to quantify spatial heterogeneity and its scale dependence (i.e., how patterns change with scale) (Wu 2004). Hierarchy theory is applied to the development and organization of landscape patterns and is best understood if tested across spatial and temporal scales (Bourgeron and Jensen 1993). Disturbance events such as soil erosion, which maintain landscape patterns and ecosystem sustainability, are also spatial-temporal scale-dependent phenomena (Turner et al. 1993). Acknowledgment of this situation is critical for the development of management strategies aimed at ecosystem sustainability (McIntosh et al. 1994). Watershed risk analysis procedures can be used to consider the effects of rehabilitation treatments on watershed-level hazards, the consequences of inaction and the resources at stake (Milne and Lewis 2011). The combined analysis of areas that are important for the supply or provision of a suite of services employing erosion maps representing multiple scales should provide useful information for the establishment of priority areas for the restoration of watersheds (Orsi et al. 2011; Su et al. 2012; Trabucchi et al. 2012b). Historic restoration efforts have been primarily focused at a single scale (such as on stands or stream reaches) (Bailey et al. 1993; Milne 1994) and have relied on site-level information to direct restoration actions (Bohn and Kershner 2002). As a result, many restoration programs lack the ability to scale up their findings. This situation has prompted the call for the adoption of a multi-scale approach in planning ecological restoration policies (Ziemer 1997; Hobbs and Harris 2001; Comín 2010). Here, each restoration activity should be evaluated across a hierarchy of scales ranging from a broad region to an individual site, as the success of a local project depends on how well that project contributes to a comprehensive restoration strategy (Ziemer 1999; Palik et al. 2000). Landscape-level empirical studies are required for determining the kinds of scaling relationships that may exist and how variable or consistent they are (Wu 2004).

The aim of this study is to present a simple approach for targeting and prioritizing sites for land management and restoration actions in a Mediterranean semiarid region. We focused on the potential benefits of restoration across a hierarchy of spatial scales through the inclusion of both ecosystem services and erosion maps. We assessed the congruence between ecosystem services and erosion rates at different spatial scales, creating hierarchical maps to derive assessment units for the evaluation of the ecological status of the entire region. This procedure allowed us to assess resource management and restoration and to determine whether patterns in the relationship between these two contrasting characteristics and the criteria for establishing spatial priorities for restoration are maintained across spatial scales.

2. Methods

2.1. Study area

The Martín River Basin is a 2,112 km^2 watershed located in the south-central region of the Ebro River Basin in Aragón in NE Spain (Fig. 1). The altitude in this area ranges between 143 and 1620 m above sea level and the annual average precipitation is 360 mm yr^{-1}. The Martín Basin is a water-limited semiarid environment in which water availability restricts rangeland production as well as dryland and irrigated farming, which are the basis of the local economy.

The basin is composed of two distinct regions: the north and south. In the lowlands in the north, dry cereal cultivation dominates and the soils are predominantly regosols, rendsina-lithosols, calcic cambisols and yermosols. These soils are prone to erosion when inappropriate land use management practices are applied, particularly on steep slopes (FAO-UNESCO 1988),. Centuries of overgrazing and deforestation in this region, combined with its dry climate and wind erosion (López et al. 1998), have resulted in large-scale degradation.

Whereas, in the highlands located in the southern part of the basin, grasslands, shrublands and hardwood conifers dominate the landscape. In this region, mining became the predominant economic activity beginning in the early twentieth century, including the mining of coal (Lignite or brown coal), iron, gypsum, lead and salt. Since the boom in 1980's surface mining (when there were 17 mines in operation in this region), the activity has strongly declined. Only three mines are cirrently in operation, and a recent Global Financial Crisis in this economic activity has forced economic restructuring (Comín et al. 2009). Some of these mines have been abandoned (due to the absence of an obligation for companies to restore them until 1985) and some have been restored over the last 10 years using a variety of different techniques. The mines cover an area of the total basin of 27.2 km^2 (0.8%) (Comín et al. 2009). The runoff from mined areas varies and is influenced by the restoration status (see Trabucchi et al., 2012a). Forests previously found along floodplains have been replaced by horticulture, which has impacted river channel dynamics. The remaining natural vegetation cover here accounts for less than 30% of the total cover and occupies a band of less than 10 m wide along most rivers and canyons in the basin. Only certain sections exhibit native forest fringes along channels and these are narrow and discontinuous, being dominated by *Populus*, *Salix*, *Betula*, *Ulmus* and *Tamarix* bushes and reed beds (Hydrologic plan-report DGA, ftp://oph.chebro.es:2121/BulkDATA/DOCUMENTACION/DirectivaMarco/Martin).

2.2. Data

2.2.1 Ecosystem services

Five ecosystem services were selected based on key environmental characteristics required for the ecological functioning and biophysical potential of the Martín Basin. This set includes five supply-side-focused regulatory service surrogates: soil retention, soil accumulation, water supply, water regulation and carbon storage. A cultural service defined as potential recreation and ecotourism services was added to our suite of surrogate of services due to the presence of a cultural park that crosses the central part of the basin through paths in a high-value natural and cultural landscape (for further details, see M. Trabucchi’s PhD thesis). The services considered in this study are universally important: both soil and water resources are highly stressed, especially in semiarid Mediterranean areas, whereas carbon sequestration benefits the global community. Due to some consideration given to our study area, we were unable to focus on demand-side issues and beneficiaries.

Ecosystem service bundles were evaluated in terms of their area of production and overlap with one another, forming a unique map with values ranging from 0 to 6 following the majority rule, which is one of the most commonly used methods for aggregating categorical data in ecology (Wu 2004). To keep our methodology as simple as possible, we did not consider the flow of a service, evaluating only its presence or absence and each raster cell was reclassified as having a 1 (presence) or 0 value (absence). Finally, a congruence analysis was undertaken to compare erosion and ecosystem service areas using the combined potential within the raster calculator of the spatial analyst in ArcGIS (Environmental Systems Research Institute 2008). The grids of the mean erosion per geographical unit and ecosystem services were summed to obtain attribute tables. For each geographic unit, the relationship between the mean erosion value as a pressure factor and the ecosystem service bundle as a state factor was plotted to investigate possible patterns for prioritizing restoration efforts at different scales. A brief description of how each service was mapped is provided in the following sections.

2.2.1.1. Surface water supply

This service was defined as the capacity of a unit of the study area to deliver surface water for human use to other parts of the basin. The surface water supply is a function of the quantity of water provided for direct use by humans. The Spanish Integrated Water Information System (SIA, http://servicios2.marm.es/sia/visualizacion/lda/recursos/superficiales_escorrentia.jsp) mapped important areas for delivering a water supply at 1km cell size as total runoff. The raster layer was resampled at 20 m cell size (Trabucchi et al. submitted). In a semiarid area such as the Martín Basin, adequate management of areas to retain natural vegetation cover is vital for ensuring water base flows, improving water quality and retaining both nutrients and sediments (Scanlon et al. 2002).

2.2.1.2. Water flow regulation

Regulation of water flows reduces the impact of floods and droughts also affects aquaticbiodiversity on downstream land areas as well as soil erosion. Vegetation cover plays a key role in the delivery of this service, typically resulting in lower surface flows to nearby waterways. The recharge area for the entire Ebro Basin has been mapped for the Ebro River Basin Authority (CHE) as mm/year per 350 m cell (see CHE

http://iber.chebro.es/sitebro/sitebro.aspx). This layer was used as a surrogate for evaluating this service, as it represents the amount of water that does not run off. The greater the amount of water infiltration into the soil, the greater the capacity for regulating surface water flows. Trabucchi et al. (submitted) extracted and resampled the data from this study using a 20 m cell size.

2.2.1.3. Carbon storage

Carbon storage data were extracted from the DGA-CITA database regarding the CO_2 stored in woody vegetation in Aragón (Spain) and the role of forests as a CO_2 sink (unpublished 2008 http://www.aragon.es/estaticos/GobiernoAragon/Departamentos/MedioAmbiente/Areas/03_Cambio_climatico/06_Proyectos_actuaciones_Emisiones_GEI/estudio.pdf). The data are expressed in metric tons of

CO_2 equivalents (T CO_2-eq) for different woody vegetation types and were calculated using national forest map (1:50000), plant diameter from the third National Forest Inventory map and allometric equations. This polygon layer was converted to a 20 m cell size raster layer to facilitate calculation.

2.2.1.4. Soil retention

Trabucchi et al. (submitted) mapped soil retention in the Martín Basin using a 20 m cell size, based on plant cover information and erosion estimations obtained from Trabucchi et al. (2012a). As stated in this previous report, to avoid errors in soil erosion estimation, we masked areas with a slope >30º (i.e., the angle of repose for most loose sediments) with an erosion value of 0 and we employed aerial photographs to delineate rocky areas where little sheet or rill erosion normal occurs. Soil retention was then categorized in areas with low and very low potential erosion and a vegetation cover of at least 30%. We assume that the potential for this service is relatively low in areas with little natural vegetation cover. Areas prone to irreversible degradation were defined as areas with a high or very high erosion potential and a continued vegetation cover of less than or equal to 30% of the soil surface.

2.2.1.5. Soil accumulation

We used the organic matter content as a surrogate for soil accumulation, as soil depth is positively correlated with soil organic matter (Yuan et al. 2006) and even small changes in the total C content can have disproportionately large impacts on key soil physical properties (Powlson et al. 2011). The functions performed by deep soils include retaining nutrients, facilitating water infiltration and storage (Kemper 1993), preventing sheet erosion and maintaining the water quality in nearby water bodies (de Groot et al. 2002). These are all crucial for the maintenance of ecosystem integrity in erosion-prone basins such as the Martín Basin. For the study area, Trabucchi et al. (submitted) extracted data from Jones et al. (2005) on organic carbon contents (OCTOP) from the European Soil Database using a 1 km resolution grid cell size and resampled these data at a 20 m cell size. The data are expressed as a percentage of the organic carbon content in the surface horizon.

2.2.1.6. Potential recreation and ecotourism services

Recreational and ecotourism services are the non-material benefits people obtain from ecosystems. Landscapes and the visual experience they offer have considerable value for society and are often the primary tourist attraction within an area, as well as contributing to the wellbeing of its residents (Brabyn and Mark 2011). The Martín watershed is popular for recreational uses due to its wide open spaces and scenery (http://www.parqueriomartin.com). We used key tourism areas that need to be maintained in an attractive form, such as hiking and mountain biking routes with a high heritage and natural value, from the Cultural Park of the Martín River (2011) and generated their viewsheds in a geographic information system (GIS) which are the elements visible to the human eye walking along the routes. While we acknowledge that many other cultural aspects and values exist within this region, these tourism routes and viewsheds capture the potential for attracting visitors and providing socio-economic benefits to the local populations, which are key factors for socio-economic development and could have a major regulating impact on the area. Finally, a raster layer with a resolution of a 20 m cell size was generated.

2.2.2. Priority soil erosion areas

Soil erosion is counteracted by structural aspects of ecosystems, especially vegetation cover and associated root systems (Gyssels et al. 2005). Structural properties can be recreated through restoration actions, which, in turn, can create synergy among numerous ecosystem services (Bennett et al. 2009). Furthermore, areas vulnerable to erosion, as determined by rainfall, soil depth and texture, need to be identified and managed appropriately to retain soil, vegetation cover and associated service synergies. An erosion model based on RUSLE (Renard et al. 1997) coupled with GIS, allowed the identification of risk areas associated with erosion thresholds at multiple scales, where soil conservation practices were identified. Previously Trabucchi et al. (2012a) mapped erosion risk using the RUSLE model in the study area using a 20 m cell size, which is recognized as the most appropriate scale for estimating soil losses in semiarid areas (Ruiz-Navarro et al. 2012). This map was reclassified according to three thresholds: 0-12 t ha^{-1} yr^{-1}, 12-17 t ha^{-1} yr^{-1} and > 17 t ha^{-1} yr^{-1}, that are important for soil formation (Rojo 1990) and represent a critical range of acceptable limits for plant colonization in reclaimed Mediterranean environments, particularly for restored slopes in the study area (Moreno-de las Heras et al. 2011). Exceeding the highest threshold (>17 t ha^{-1} yr^{-1}), results in irreversible soil degradation. The mean erosion value for each subwatershed level was generated for multiple scales using a ArcGis zonal statistics tool (Environmental Systems Research Institute 2008). To identify the erosive risk at each subwatershed level, we classified areas that presented proportionally higher standard deviations. A high standard deviation in a subwatershed corresponding to a low or medium mean erosion level in the same area indicates a concentrated erosion point inside the subwatershed. Examples of such points include mines, landslide sites and areas of intense human impacts or natural severe erosive processes, which can be easily identified using the mean erosion vs. standard deviation relationship. In contrast to these areas, we identified areas that showed relatively low standard deviations or values similar to the mean values as representing widespread erosion inside the subwatershed (Fig. 2), possibly due to sparse vegetation cover or similar related factors. The relationship between the mean erosion rate per geographic unit (subwatershed level) and its standard deviation was plotted and investigated for the different scales in the Martín River Basin to facilitate the prioritization of restoration measures and to understand erosion distribution patterns at different scales.

2.3. Regional multi-scale spatial analysis

2.3.1. Delineation of subwatersheds among different spatial aggregation levels

To perform a multi-scale analysis of erosion and ecosystem services, we distributed the basic information on these variables, available at a 20 m^2 cell size, at three levels, or scales of pixel aggregation, moving gradually towards a finer resolution. We used the watershed tool in GIS to perform this analysis. Following this approach, we created three drainage networks for the Martín Basin with different numbers of subwatersheds, which are described here.

We use three pixel spatial aggregations suitable for prioritization restoration actions, specifying the limit of pixels for flow accumulation, these being 20000 (level 1), 2000 (level 2) and 1000 (level 3).

The spatial arrangement of the Martín Basin at subwatershed level 1 contained 67 subwatersheds (Fig. 2 a), which presented a minimum area of 1.27 km^2, a maximum of 120.9 km^2 and an average of 28 km^2. The second subwatershed, level 2, included 655 subwatersheds (Fig. 2 b), with a minimum area of 0.007 km^2, a maximum of 12.1 km^2 and an average of 2.87 km^2. Finally, subwatershed level 3 consisted of 2534 subwatersheds (Fig. 2 c), with a minimum area of 0.006 km^2, a maximum of 4.15 km^2 and an average of 0.75 km^2. These subwatersheds are the functional ecological units for the delivery of the majority of our selected suite of ecosystem services, determining erosion dynamics and planning of restoration actions. Classifying assessment units directly assists in resource management, including restoration.

Ecosystem service bundles and erosion maps were reclassified and summarized for every subwatershed level to create a new prioritization classification consisting of a combination of erosion rate thresholds and a number of services (Fig. 4).

2.3.2. Comparison of management units

To investigate service delivery and erosion at the finest scale, we selected two subwatersheds from the first level presenting contrasting topographic features and land use practices as a case study. Our selection was made to facilitate the assessment and utility of our multi-spatial level approach for prioritizing restoration measures. Subwatershed number 4, located in the northern lowland region and subwatershed number 63, located in the south mountainous area (Fig. 2 a), were selected for this analysis. They were further investigated at the second and third levels (Fig. 5) to determine the optimal management area for planning restoration policies and to develop an understanding of how patterns of congruence change with scale. Subwatershed number 4 is a fairly homogeneous area that is mostly used for dryland and irrigation agriculture but also contains some remnant patches of shrubland. The erosion rate here was calculated to be 0.2 ± 64 t ha^{-1} $year^{-1}$. In contrast, subwatershed number 63 contains a mix of conifer and hardwood forest, shrubs, grassland-scrublands, abandoned and restored mines, and dry agriculture areas. It has a calculated erosion rate of 0.5±165 t ha^{-1} $year^{-1}$.

3. Results

3.1. Erosion patterns across subwatershed levels

The landscape heterogeneity of the Martín Basin is a key determining factor explaining the erosion patterns in the region, with the northern area being predominantly flat and the southern area being mountainous, showing a considerable increase in slope, altitude and rainfall patterns. Contrasting the three spatial levels provides us with insights regarding how changes in spatial detail can facilitate the targeting of degraded areas. For example, in Fig. 2a, we are able to clearly identify areas with high erosion values grouped in the south and a large portion of the northern area showing a low erosion value. By increasing the resolution from the first level to the second level, we are able to differentiate three erosion thresholds in the northern region (Fig. 2 b, c). Furthermore, some areas identified at level one as showing low erosion were re-identified as presenting both medium and high erosion regions when examined at the finer detail of level 3, facilitating more precise identification and location of areas for restoration. The mean erosion rates (and the calculated standard deviations) exhibit similar values within single watersheds (Fig. 2a, b, c) and a direct relationship was observed between the mean erosion rates and the calculated standard deviations. Subwatershed erosion rates that exceed the highest erosion threshold, indicating areas subjected to a high erosion risk, can be easily identified (Fig. 2a,b,c). This pattern is repeated across different scales. However, the data dispersion increases as the detail of the analysis increases through the three levels of data aggregation. At the third level, some subwatersheds with high standard deviations and mean erosion values in the low-to-medium erosion threshold range are identifiable (Fig. 2 c).

3.2. Ecosystem service patterns across subwatershed levels.

There is a clear distinction in the ecosystem service supply across the study area (Fig. 3). The northern, lower, reaches of the watershed showed the lowest values, which increased toward the south of the basin. However, at the third level, the ecosystem service supply was highly differentiated (Fig. 3 c). Increasing the scale of analysis by decreasing the pixel aggregation up to the third level revealed previously masked ecosystem service values (Fig. 3). At the first level, the maximum number of services that overlap at the basin scale was five, but it increased to six as the resolution increased. Our method of calculation also influenced this trend. Here, we used the majority rule, which, when equal numbers of cells within a subwatershed received the highest and the second highest value, assigns the lower value to the subwatershed. In any case, at the lowest scale of pixel aggregation (higher detail), it is at the third level of analysis, the most detailed segregation of ecosystem services related to erosion is observed.

3.3. Hierarchy maps and patterns across subwatershed levels

In searching for a scale of analysis that offers adequate spatial differentiation of the relationship between the state factor and the degradation factor, we plotted ecosystem service bundle overlaps against the average erosion rates for the three aggregation levels analyzed (Fig. 4). The first level of analysis did not highlight any subwatersheds with high erosion rates and either high or low ecosystem service values (Fig. 4 a). In contrast, at the third level of analysis, the combination of ecosystem services and erosion for these thresholds was clear, highlighting the problem of generalization at the first and second levels (Fig. 4 c).

3.4. Hierarchical map of management units at the second and third subwatershed levels

The two case study subwatersheds, 4 and 63, provide contrasting examples that demonstrate the differences that are detectable across scales (Fig. 5). At the second level, the same spatial heterogeneity is observed for ecosystem service delivery and the associated erosion (Fig. 5 a, b). Our two selected subwatersheds show marked differences in the number of services delivered, with 0-1-2 ecosystem services being observed for subwatershed 4 associated with an erosion rate of <12 t $ha^{-1}yr^{-1}$ (Fig. 5 a) and 3-4-6 services being obtained in subwatershed 63 with an erosion rate > 17 t $ha^{-1}yr^{-1}$ (Fig. 5 b). In subwatershed 63 the priority restoration area is represented by 3 and 4 services (at levels one and two) and an erosion rate > 17 t ha^{-1} yr^{-1}, corresponding to the greater part of the subwatershed (Figure 5 b). Moving from level one to level three, diversification increases (Fig. 4 c, d) and for subwatershed 4, the number of services now ranges from 0 to 3, but they are all associated with low erosion thresholds (Fig. 4 c). In subwatershed 63, at level three, the number of services per subwatershed ranged from 3 to 6 and most of the subwatersheds appear to present high erosion thresholds (Fig. 4 d).

4. Discussion

4.1. Restoration implications from multi-scale analyses

Landscapes are complex systems that require multi-scale analyses if they are to be appropriately managed and if the outcomes of interventions are to be anticipated (Hay et al. 2001). Basin-scale analyses (such as that performed in our case study area, the Martín Basin) appear to represent an appropriate extent scale for evaluating our methodology. In fact the basin is considered the optimal functional ecological unit of management or, at least, that where more intensive interactions occur between human use of the resources and ecological processes (Golley 1994), both of which determine ecosystem services. Exploring a variety of spatial scales has been recognized as necessary for understanding resource distribution (Lewis et al. 1996; White and Walker 1997). In our case, different spatial scales (levels of analysis) were used to investigate the spatial locations of possible restoration actions and the dynamics of ecosystem services associated with erosion. The type of multiscale spatial analysis performed in the Martín Basin to assess ecosystem services, which has frequently been suggested (Kremen and Ostfeld 2005; Hein et al. 2006; de Groot et al. 2010), proved useful for identifying sites to be targeted for restoration (to ameliorate erosion) that simultaneously increase the provision of a selected bundle of ecosystem services.

An initial top-down assessment of the Martín region was able to provide a general understanding of this area and to identify broad areas that required restoration action (Trabucchi et al. 2012a). Chu et al. (2003) described this need for obtaining a broad-scale understanding related to system dynamics so that it will be possible to explain cause-effect relationships in detail. The introduction of additional hierarchies or levels facilitates the integration of more detailed information. Our third level of analysis was found to be key in determining watershed processes and the mechanism of ecosystem degradation (Nakamura et al. 2005). As expected, reducing pixel aggregation increased spatial differentiation and detail and facilitated the location of areas for the prioritization of restoration and management actions. The second and especially, the third level of analysis followed a bottom-up approach. This approach increased the accuracy of the identification of site-scale areas to be targeted for action and provides a defensible basis for hypothesis testing in field experiments. We explored the third level scale (highest resolution) in detail, as this scale was regarded as the most economically suitable for directing restoration actions. In our case study area, this level of analysis corresponded closely to the scale of opencast mine areas, which present a mean average area of 1.5 km^2.

The fine-scale analysis highlighted subwatersheds or geographical areas in the basin where restoration actions to control erosion should be prioritized hierarchically to maintain or increase the provision of ecosystem services. This would not have been possible identified if we had only undertaken a single broad level (first level) of analysis.

4.2. Developed approach for including priority restoration areas

As a first step in restoration planning, a regional analysis aims at constructing an overview of ecosystem conditions to identify altered areas in need of management action (Nakamura et al. 2005). To manage a river basin efficiently, objectives must be established and restoration priorities identified (Kondolf and Micheli 1995). This understanding is essential to achieve the optimal and efficient allocation of limited resources (Palik et al. 2000; Suding 2011), especially at a broad scale, where costs can grow exponentially. In the Martín Basin, areas presenting few services and low erosion rates were found to be predominant in the flat northern areas, which have historically delivered provisioning services related to food production. In this homogeneous landscape with an oligotrophic environment (low precipitation, low soil organic matter content), restoration actions would be disproportionately expensive compared with the benefits that would be derived from such actions.

We have adapted a simple risk decision support matrix previously used in watershed risk analysis (Milne and Lewis 2011) to facilitate the selection of priority areas for restoration (Fig. 6). Here, we have aligned three erosion thresholds with high and low ecosystem service supplies, developing priority cases, or scenarios. Cases 3, 4, 5 and 6 present a lower risk of losing services through erosion, and strategies aimed at improving land-use practices should be targeted to these areas. Areas classified as high priority, cases 1 and 2 here, should be considered for restoration action so that ecosystem services vital for the entire basin will be reestablished and maintained. This decision support tool was derived from a data dispersion plot of erosion vs. ecosystem services (Fig. 4, right). Identifying goals for restoration and prioritizing restoration efforts are subjective processes to some extent (Palik et al. 2000) and this approach can easily be modified to achieve different restoration targets.

A hierarchical mapping approach could be used for a variety of purposes, particularly in exercises related to site location (Palik et al. 2000; Palik et al. 2003). Area selection can be further refined by coupling the generation of hierarchy maps for prioritizing subwatersheds with desired biological or physical ecological indicators (e.g., water quality, land use, erosion) (Niemi and McDonald 2004), combinations of which can be chosen to infer cause and effect relationships (such as explanatory environmental variables and responses manifested as changes in ecosystem services) (Nakamura et al. 2005). Furthermore, alternative state models, emphasizing internally reinforced states and recovery thresholds, can help in guiding restoration efforts (Suding et al. 2004). These thresholds could include types of pollution (e.g., nutrients, suspended soil, gas emissions) and general environmental disturbance thresholds (e.g., fires, floods, drought) (Groffman et al. 2006).

Ecological problems often require the extrapolation of fine-scale measurements for the analysis of broad-scale phenomena (Turner et al. 1994). The generation of hierarchical maps that allow the evaluation of restoration activity across a hierarchy of scales, ranging from a broad region to an individual site (Ziemer 1999), appears to be a logical and efficient way of locating key potential restoration areas. It is well recognized that restoration and landscape ecology exhibit an unexplored mutualistic relationship (Bell et al. 1997; Li et al. 2003). Our proposed framework integrates multi-scale studies, representing a key interest in landscape ecology (Turner et al. 1994; Hay et al. 2001; Brandt 2003; Burnett and Blaschke 2003; Wu 2004), with the type of hierarchical prioritization used in restoration ecology (Lee and Grant 1995; Palik et al. 2000; Cipollini et al. 2005; Nakamura et al. 2005; Comín et al. 2009) and the growing field of ecosystem service research (Fisher et al. 2009; Reyers et al. 2009; De Groot et al. 2010; Su et al. 2012). Such a multidisciplinary approach has been recommended to make restoration plans more cost efficient (Rey Benayas et al. 2009; Bullock et al. 2011; Trabucchi, et al. 2012b) and to enhance research and the application of the three disciplines. Here, the focus of ecological restoration shifts from the site-scale studies adopted in the past aimed at the reestablishment of historical abiotic conditions to promote the natural return of the vegetation (Dobson et al. 1997; Bell 1998; Prach et al. 2001) or the reestablishment and improvement of animal habitat (Huxel and Hastings 1999; Bond and Lake 2003) to broad analyses of environmental conditions at regional scales. This vision is supported by modern restoration practices, which acknowledge the importance of ecosystem patterns and processes occurring at landscape scales (Nakamura et al. 2005). During the nested analysis, various spatial and field assessment data (fire, drought, flood) can be added as 20 m grid or layers to complement and enrich the analyses and improve the precision of prioritization according to the proposed objectives making our methodology extremely adaptable at each single case of research purpose.

4.3. Investigation of possible trade-offs in restoration prioritization

Ecosystem service trade-offs are defined as situations in which the provision of one service is reduced as a consequence of increased use of another ecosystem service (Bennett et al. 2009) and can arise from the differing interests of social agents (Martín-López et al. 2012). Analyzing the spatial patterns of ecosystem service bundles allows us to understand how services are distributed across a landscape, how the distributions of different services compare and where trade-offs and synergies among ecosystem services might occur (Raudsepp-Hearne et al. 2010). The presented approach highlights where potential ecosystem service improvement can be achieved through restoration and consequently, which trade-offs can be established between the services evaluated here (carbon storage, soil formation and retention, water flow regulation, surface water provisioning, eco-tourism), which contribute positively to natural resource enhancement and those that contribute negatively to natural resource conservation, which are typically provisioning services based on human extractive activities as intensive agriculture and mining. Conventional agricultural practices degrade the soil structure and soil microbial communities due to mechanical activities such as plowing, but management practices can also protect the soil and reduce erosion and runoff (Lupwayi et al. 1998; Holland 2004). The Martín Basin, especially its northern region, displays clear evidence of trade-offs between regulatory and provisioning services, which is an issue that has been noted in many other regions of the world (Rodríguez et al. 2006; Power 2010). Management decisions often focus on the immediate provisioning of a commodity or service at the expense of this service or another ecosystem service at a distant location or in the future (Power 2010). However, win-win scenarios are possible when appropriate land-use practices, such as conservation tillage, crop diversification and legume intensification, are applied (López et al. 1998; Prosperi et al. 2006; Trabucchi et al. 2012a). The potential success of integrating these approaches depends on the maintenance of ecological integrity and cohesion (Gómez-Sal and González-García 2007). Therefore, it may be possible to manage agro-ecosystems to support a diversity of ecosystem services while still maintaining or even enhancing certain provisioning services (Power 2010; Nainggolan et al. 2011). Understanding the benefits and costs of different types of management practices is necessary to allow the establishment and maintenance of sustainable agro-ecosystems (Dale and Polasky 2007).

Due to the predominant natural land cover in the southern part of the Martín Basin, the trade-offs among ecosystem services in this region are of another type and are more difficult to identify because they also exhibit many synergies and dependent ecological processes. For example, most of the ecosystem services produced in perennial vegetation areas, such as under forest cover, are related to water (e.g., purification, regulation) and these, in turn, are linked to soil (e.g., accumulation, retention) (Klijn et al. 1996; Milne and Lewis 2011; Powlson et al. 2011). While there are clear synergies, there are also potential trade-offs. For example, increasing carbon storage through the planting of fast-growing trees for CO_2 accumulation (a carbon storage service linked to climate regulation) or cellulose production (a provisioning service) may reduce the surface water supply and could also result in the salinization and/or acidification of soils, with consequent decreases in ecosystem services associated with grasslands and reduced resilience of such systems (Bot and Benites 2005; Cespedes-Payret et al. 2009).

Identifying trade-offs is an important step that allows policy makers to understand the long-term effects of preferring one ecosystem service over another and the consequences of focusing only on the present provision of a service, rather than the future (Rodríguez et al. 2006).

4.4. Possible methodological limitations and future research needs

4.4.1 Data management

Spatial analysis typically involves GIS overlay analysis and geoprocessing to combine diverse sources of input layers to derive a desired map. This analysis is often complicated by differences in parent scales, years of creation, accuracy levels, modeled data and minimum mapping units for each input layer (Troy and Wilson 2006). There is no single “correct” or “optimal” scale for characterizing spatial heterogeneity, but comparisons between landscapes using pattern indices must be based on the same spatial resolution and extent. Indeed, a comprehensive empirical database containing pattern metric “scalograms” and other forms of multiple-scale information on diverse landscapes is crucial for achieving a general understanding of landscape patterns and developing spatial scaling rules (Wu 2004). The relationship between ecosystem service delivery and the regulation of environmental factors, such as erosion, may also change according to the spatial scale of analysis (Jackway and Deriche 1996). An analyst's job will often include assembling many layers with different resolutions to obtain a final map that is suitable for management purposes. Ecosystem services, such as the ecological functions and processes from which they are derived, may change in relation to the spatial pattern of observation (Hein et al. 2006, Hurteau et al. 2009), posing a major challenge for mapping these services. It is difficult to define the most appropriate scale of a study, as the resolution at which the phenomena of interest operate and are operated upon may not be immediately apparent (Rutchey and Godin 2009). Thus, in most cases, the best practice may be to adopt the highest resolution affordable (Haines-Young and Chopping 1996) but there must be a threshold for increasing the resolution (decreasing the grain size) of the analysis which once surpassed provides not so useful information as it is not related to functional aspects of the ecosystem (basin in our approach) or could result on excess of resources used in the analysis versus value of the information obtained. Furthermore, high-quality databases and new sampling approaches that support research at broader spatial and temporal scales are critical for enhancing ecological understanding and supporting further development of restoration ecology as a scientific discipline (Michener 1997).

4.4.2. Statistical analysis

Selecting appropriate statistical procedures and asking the right questions is vital for meeting targets (Marcot 1998). This study employed one of several available methods for aggregating spatial data to analyze ecosystem service bundles. We used the majority rule method because of our interest in identifying the major number of services present at each spatial level (Trabucchi, submitted). Although this is probably the most commonly used rule in ecological and remote sensing applications (Wu 2004), it would be interesting to compare how other different aggregation methods affect the characteristics of ecosystem service bundles. The use of rules, such as maximum, minimum and average rules and others available in GIS zonal statistical tools can have a marked effect on the obtained results (Smith et al. 2007).

4.4.3. Validation of the framework

In the Martín Basin, some subwatersheds at the third level, classified as being of high priority for restoration (presenting erosion of > 17 t ha^{-1} yr^{-1} and >3 ecosystem services), coincide with closed mines. This finding confirmed both the appropriateness of the size of the subwatersheds generated at this level as well as the erosion and ecosystem service categorization applied for prioritizing restoration. However, future studies are needed to investigate the application of hierarchical maps at a mine scale, where these data are available, to further validate the approach presented here.

5. Conclusion

A sequence of multiple-scale analyses is essential and strongly recommended for ecosystem assessment in restoration planning and spatial ecology studies (Wu et al. 2000; Nakamura et al. 2005). Ecosystem services are supplied at various spatial and temporal scales. Soil erosion is a threat to the continued productivity and flow of terrestrial and hydrological ecosystem services. The growing field of ecosystem service research must be integrated into restoration ecology, enriching prioritization exercises. The identification and classification of ecosystem services is the key objective of the regional-scale analysis presented here, in which limited resources were identified and located in a semiarid environment.

Our multiple spatial-scale framework, including three levels of subwatershed analysis, allows us to identify priority areas in terms of erosion risk and ecosystem services. The fact that various spatial and field assessment data can be added as layers to complement and enrich the analyses and improve the precision of prioritization make our methodology extremely adaptable at each single case of research purpose. This framework provides a logical approach for restoration site selection as well as planning restoration activities at a basin scale, which features currently are being called for by the scientific community.

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Figure caption:

Fig. 1 Maps of the Martín River basin showing its hydrological network, the upper (South) part and the lower (North) part of the basin and coal mine areas

Fig. 2 Erosion map at first (A), second (B) and third (C) level scales. On the right of each map are plotted the relationship between mean erosion and standard deviation

Fig. 3 Ecosystem services bundle map at first (A), second (B) and third (C) level scale. Figure A show subwatershed number 4(North) and 63 (South) which are highlighted by the blue circle

Fig. 4 Hierarchy map at first (A), second (B) and third level scale. On the right of each map are plotted the erosion mean values against numbers of ecosystem service corresponding at each subwatershed for each level scale

Fig. 5 Hierarchy map for subwatershed 4(A) and 63(B) at second level scale and for subwatershed 4(C) and 63 (D) at third level scale. On the right of each map are plotted the erosion mean values against numbers of ecosystem service corresponding at each subwatershed for each level scale