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Original Article

Development of a spatially explicit approach for mapping ecosystem services in the Brazilian Savanna – *MapES*

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A R T I C L E I N F O

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Land management
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A B S T R A C T

The objective of the presented study is the development of a spatially explicit approach for mapping ecosystem services (*MapES*) by using specific knowledge about the Cerrado biome (Brazilian Savanna). This biome covers an area of about 2 million km^2, i.e. nearly 24% of the total area of Brazil, and has come under substantial pressure during the last 50 years caused by strong land-use/land-cover change, mostly due to agricultural expansion and urbanization. Because of its fast transformation rate, there is an enormous demand for knowledge, and its application, about the effects of land-use/land-cover on the capacity of providing or maintaining ecosystem services. The *MapES* approach was developed using a vast existing knowledge base. After analyzing and structuring this knowledge the relationships between land-use/land-cover and the potential to provide or maintain eight ecosystem services (Erosion Control, Runoff Control, Water Supply, Water Quality Maintenance, Soil Quality Maintenance, Biodiversity Maintenance, Food Production and Energy Production) were parametrized. In addition, the approach was developed as spatially explicit by including landscape properties (soil, slope and distance to river network) in the cell based system. A reference map of potential natural vegetation and a land use map for 2013 for a meso-scale experimental catchment (32.7 km^2) were produced. The catchment was used as an example to apply the approach, i.e. assessing and visualizing changes from before human interference to the current land use situation. Finally, a procedure for assessing the potential impacts of land-use/land-cover on ecosystem services considering the methodological limitations of the respective monitoring. The presented approach is easy to understand, to modify and to adapt to other situations and might be therefore used in other context of decision support. It might also help to fill the gap between land use planning and numeric modeling using very complex tools.

1. Introduction

The Brazilian savanna (Cerrado biome) covers about 204 million hectares, i.e. ca. 24% of Brazil (Instituto Brasileiro de Geografia e Estatística, 2004). It constitutes the second largest biome of Brazil after the Amazon rainforest. The Cerrado encompasses the region of the Brazilian Central Plateau (*planalto*) with average altitudes between 1000 and 1300 m above sea level. The population of Cerrado is currently around 30 million, i.e. 15% of the total population of Brazil.

The region provides a wide range of ecosystem services. It plays a crucial role for the water cycle and water resources of eight of the twelve major Brazilian river basins, e.g. Paraná, São Francisco, Tocantins, Paraguai, and Parnaíba. Therefore, the Cerrado has been also called "the cradle of the Brazilian waters" (*berço das águas do Brasil*). The importance of the water resources of the Cerrado for Brazil's hydroelectric power plants has been shown by Lima et al. (2011). In addition, the waters of the Cerrado feed other regions such as the Pantanal biome, one of the largest wetlands of the world (Lima et al., 2011). In context with biodiversity, the Cerrado biome has been described as the savanna with one of the highest biodiversity worldwide (Ribeiro and Walter, 2008), with more than 11,000 native plant species (Mendonça et al., 2008), of which 4400 are endemic (Myers et al., 2000). The agronomic value of the Cerrado biome and its spatial variability has been recognized early (Waibel, 1948). Despite its late exploitation starting only in the 1960s, today it contributes substantially to the agricultural production of Brazil. For 2006, the shares of the Cerrado for the total national production were 89% for cotton, 69% for sorghum, 55% for beef, 53% for soybean, 48% for coffee, 37%

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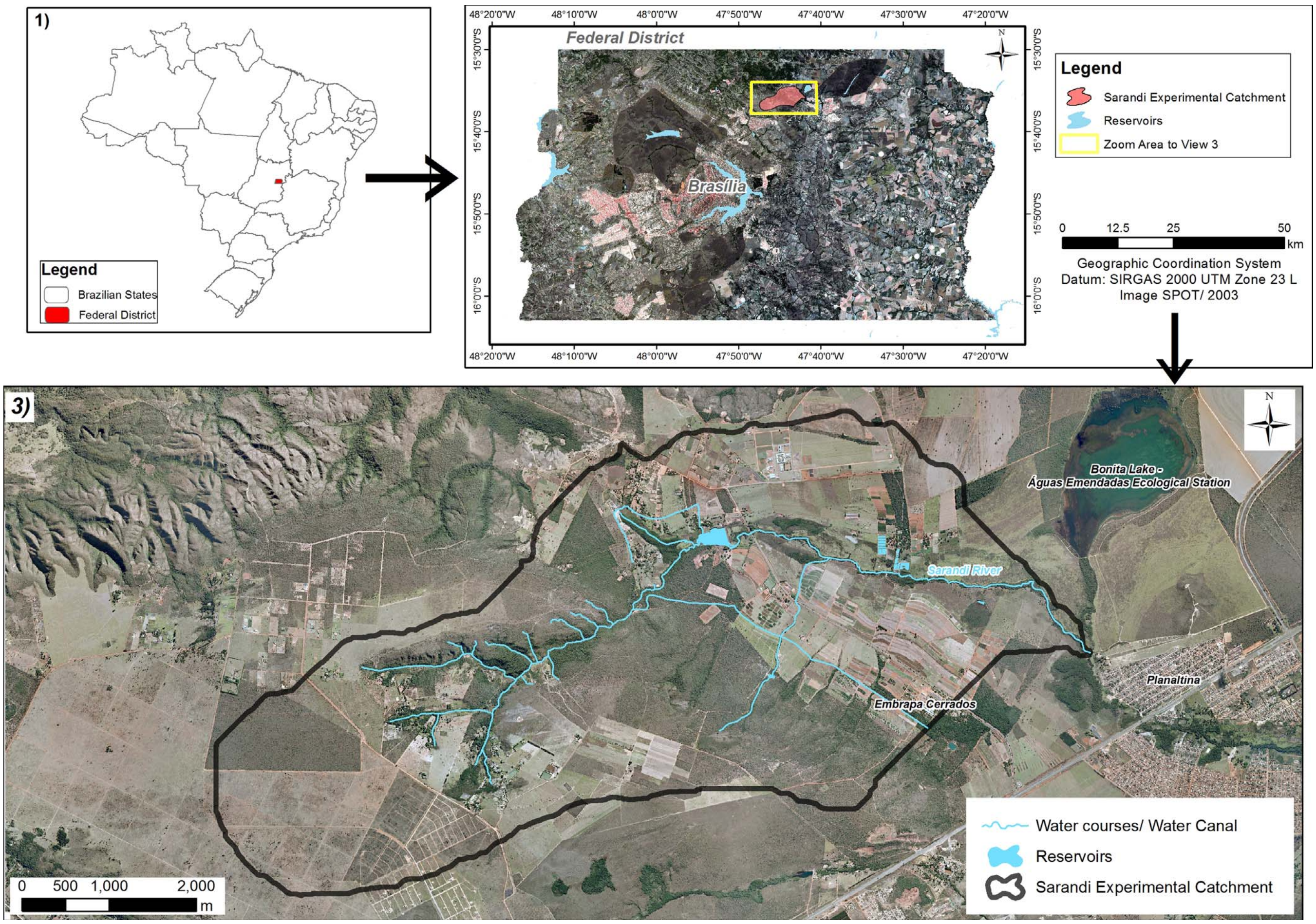

Fig. 1. Location of the Sarandi Experimental Catchment (SEC) in Brazil.

for rice, 30% for corn, 25% of beans and 13% for sugarcane (Lopes and Daher, 2008).

The Cerrado has come under substantial pressure during the last 50 years caused by strong land-use/land-cover change (LULCC), mostly due to agricultural expansion and urbanization (Lorz et al., 2012). The latest estimates showed that about 40% of the natural vegetation of Cerrado has been already converted into agricultural land (Sano et al., 2010). The deforestation rate of the Cerrado in 2010 was even higher than this of the Amazonas biome (Ministério do Meio Ambiente, 2014).

Given the enormous socio-economic and environmental importance on the one hand, and the fast transformation rate of the Cerrado biome on the other hand, there is an urgent need for knowledge about the effects of land-use/land-cover (LULC) on the capacity of providing or maintaining ecosystem services (ES), such as provision of water, biodiversity, food, energy etc. (Millennium Ecosystem Assessment, 2005; The Economics of ecosystems and biodiversity, 2010; de Groot et al., 2012; Costanza et al., 2014; Costanza, 2016). The mapping of ecosystem services of the Cerrado is a crucial step to understand and communicate how the natural environment (i) contributes to human well-being, (ii) might be affected by land use and (iii) might be used in a sustainable way.

Several approaches have been developed for mapping environmental processes related to ecosystem services (Egoh et al., 2008; Ditt et al., 2010; Vigerstol and Aukema 2011; Fuerst et al., 2012; Martínez-Harms and Balvanera, 2012; Lorz et al., 2012; Koschke et al., 2014; Lima et al., 2014a; Potschin and Haines-Young, 2016; Maes et al., 2016). However, the major challenges for applying these approaches are the wide range of landscapes, the complexity of natural systems, and the other uncertainties involving the impact assessment of different human activities on ecological processes (Hou et al., 2013). Therefore there is an evident need to consider regional particularities, especially for the development, the adaptation, and the parameterization of approaches to the specific regional frame conditions. Our study aimed at developing a spatially explicit approach for mapping ecosystem services (*MapES*) by using specific knowledge of the Cerrado biome as a reference. The outstanding data situation and the representativity of the study area for the Cerrado biome are an excellent base for this purpose. A major element is the vast knowledge base created during around four decades of research by the Brazilian Corporation for Agricultural Research (Embrapa), focusing on natural and agricultural characteristics and potentials of the Cerrado biome.

Our contribution might be of wider interest to the scientific community and land managers because (i) the problem of mapping and assessing ecosystem services is frequent and urgent (Maes et al., 2016), especially for the Cerrado, (ii) the developed approach might be easily modified if newer/improved data is available, and (iii) the *MapES* approach might be used for land management and landscape planning within the Cerrado biome and other regions to use the potential of the ecosystem service approach (Opdam 2016).

2. Material and methods

2.1. Study area

The Sarandi Experimental Catchment (SEC; Fig. 1), with a total area of 32.7 km^2, is located in the northern region of the Federal District, Brazil, which is part of the Cerrado biome.

The SEC is located in the center of the Brazilian central Plateau

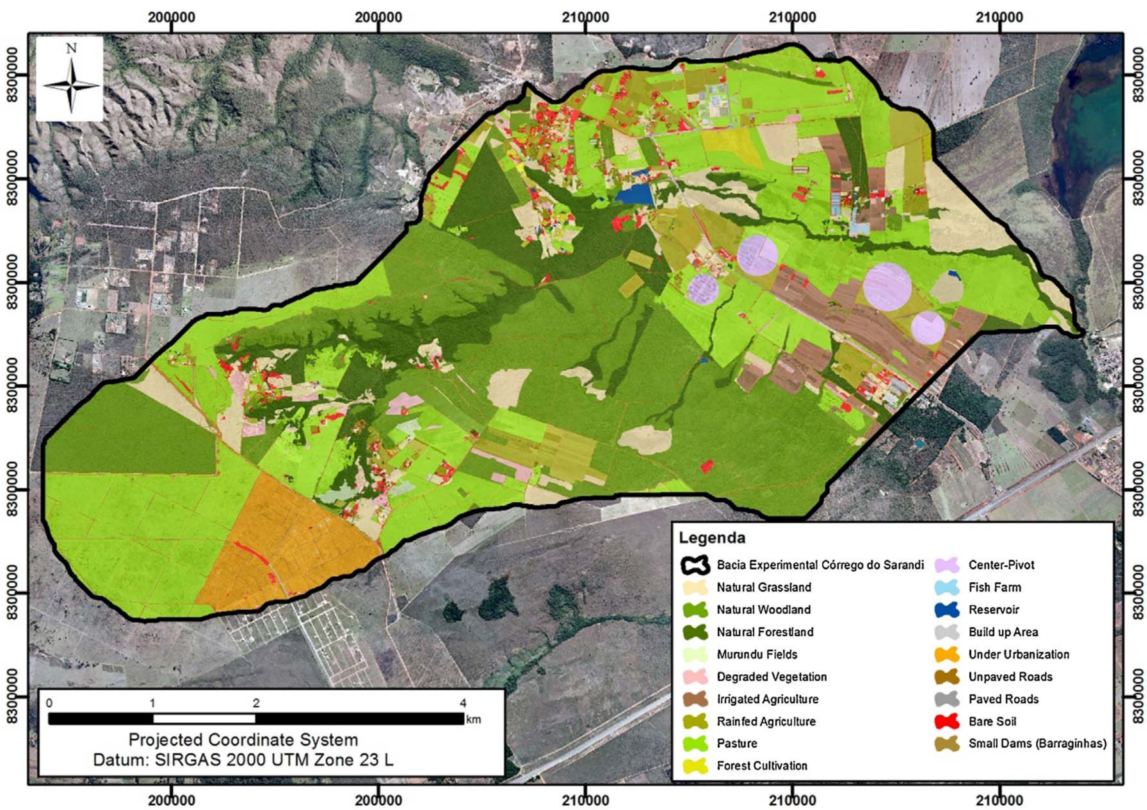

Fig. 2. Land-use/land-cover in the Sarandi Experimental Catchment for 2013 (Chaves et al., 2014).

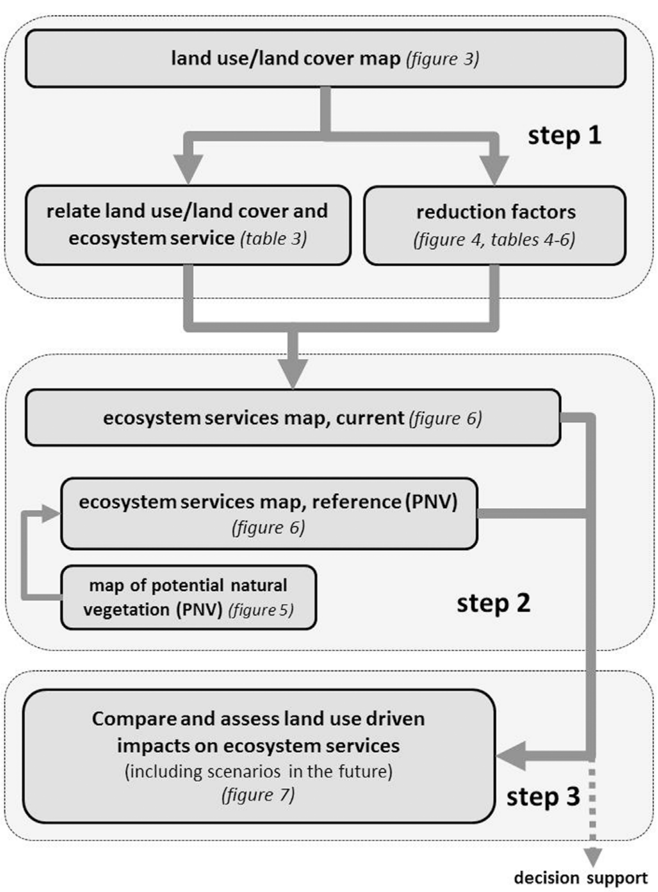

Fig. 3. Flowchart of the study.

Table 1
Relation of soil type and potential natural vegetation adapted from Spera et al. (2005).

Soil type[a]	Potential Natural Vegetation
Cambisols	Tree Savanna
Cambissolos (CX 1–4)	*Cerrado Tipico, Cerrado Ralo*[b]
Ferralsols	Tree Savanna
Latossolos Amarelos (LA)	*Cerrado Típico*
Ferralsols	Tree Savanna
Latossolos Vermelhos (LV 2–3)	*Cerrado Típico*
Ferralsols	Forest
Latossolos Vermelho-Amarelos (LVA 1)	*Cerradão*
Ferralsols	Tree Savanna
Latossolos Vermelho-Amarelos (LVA 2–4)	*Cerrado Típico*
Gleysols	Grass Savanna
Gleissolos (GX 1–2)	*Campo Limpo Úmido*[c]
Arenosols	Tree Savanna
Neossolos Quartzarênicos (RQ)	*Cerrado Ralo*[b]

[a] Soil types according to Reference Soil Group (WRB 2015) and according to Brazilian Soil Classification System (Anjos et al., 2012). Note the generalized representation of soil units in the soil map (Fig. 4a).
[b] Subtype of Cerrado with sparse tree cover and low trees on outcrops.
[c] Subtype of Cerrado, wet grass savanna with single trees, including Murundu fields (grass savanna on waterlogged soils).

(*planalto*) and is representative for climate, soil types, relief, vegetation, and land-use of this region. Characterized by a semi-humid tropical climate, rainfall is unevenly distributed throughout the year. Nearly 85% of the region's mean annual rainfall (1350 mm) occurs in the rainy season from November to April. The terrain is gently undulating with predominantly nutrient-poor but well-drained Latossolos (Empresa Brasileira de Pesquisa Agropecuária, 1978), i.e. Ferralsols (Food and Agriculture Organisation, 2015).

Due to the proximity to Brasília, the Capital of Brazil, and the high economic value of land in the region, the basin is subject to strong pressure due to urbanization and agricultural expansion. This makes

Table 2
Ecosystem services used for the approach with criteria/indicator and reference.

Ecosystem service	Criteria	References
Erosion control	Vegetation coverage Vegetation stratification Litter Runoff/Infiltration USLE[a] parameters Land-use intensity Soil disturbance Soil compaction	Wischmeier and Smith (1978); Adámoli et al. (1985); Dedecek et al. (1986); Resck (1998); Bertoni and Lombardi Neto (1999); Resck et al. (2000); Beutler et al. (2001); Brunet et al. (2002); D'Andréa et al. (2002); Neufeldt et al. (2002); Klein and Libardi (2002); Oliveira et al. (2005); Sartori et al. (2005); Leão et al. (2006); Araújo et al. (2007); Lima et al. (2007); Marchão et al. (2007); Ribeiro and Walter (2008); Borges et al. (2009); Giambelluca et al. (2009); Carneiro et al. (2009); Lima and Lopes (2009); Lima et al. (2013); Lorz et al. (2012); Lima et al. (2014a).
Runoff control	Vegetation coverage Vegetation stratification Litter Runoff/Infiltration Land-use intensity Soil disturbance Soil compaction	Adámoli et al. (1985); Dedecek et al. (1986); Resck (1998); Silva and Oliveira (1999); Resck et al. (2000); Beutler et al. (2001); Lima et al. (2001); Brunet et al. (2002); D'Andréa et al. (2002); Neufeldt et al. (2002); Klein and Libardi (2002); Balbino et al. (2004); Sartori et al. (2005); Oliveira et al. (2005); Leão et al. (2006); Araújo et al. (2007); Lima et al. (2007); Marchão et al. (2007); Ribeiro and Walter (2008); Borges et al. (2009); Giambelluca et al. (2009); Carneiro et al. (2009); Lima (2010); Lima et al. (2013).
Water supply	Aquifer recharge Baseflow Minimum streamflow Soil depth Infiltration Water use	Matson et al. (1997); Adámoli et al. (1985); Tucci (2000); Smakhtin (2001); Lima et al. (2001); Sartori et al. (2005); Sano et al. (2005); Silva et al. (2008); Lima (2010); Pinto et al. (2010); Santos (2012); Vasconcelos et al. (2012); Lima et al. (2013); Strauch et al. (2013); Watanabe and Ortega (2014).
Water quality maintenance	Agrochemicals use Sediment yield Runoff/Infiltration Natural conditions Monitoring data	Matson et al. (1997); Oliveira-Filho and Lima (2002); Sousa and Lobato (2004); Silva et al. (2007); Carneiro et al. (2009); Parron et al. (2009); Rabelo et al. (2009); Muniz et al. (2011).
Soil quality maintenance	Physical characteristics Chemical characteristics Biological characteristics Natural conditions Agrochemicals use Biomass	Adámoli et al. (1985); Matson et al. (1997); Resck (1998); Marchiori-Junior and Melo (1999); Alvarenga et al. (1999); Resck et al. (2000); Melloni et al. (2001); Lilienfein et al. (2003); Mendes et al. (2003); Matsuoka et al. (2003); Oliveira et al. (2004); Sousa and Lobato (2004); Araújo et al. (2007); Jakelaitis et al. (2008); Silva et al. (2009); Hungria et al. (2009); Kaschuk et al. (2010); Peixoto et al. (2010); Kaschuk et al. (2011); Mendes et al. (2012); Lorz et al. (2012); Egoh et al. (2016).
Biodiversity maintenance	Vegetation coverage Vegetation stratification Land-use intensity Natural conditions Habitat maintenance	Almeida (1995); Matson et al. (1997); Ratter et al. (1997); Bagno (1998); Parron et al. (1998); Ribeiro et al. (2001); Bridgewater et al. (2004); Ribeiro et al. (2008); Sano et al. (2008); Ribeiro and Walter (2008); Aquino et al. (2009); Kaschuk et al. (2010); Aquino et al. (2014); Balvanera et al. (2014); Oliveira and Frizzas (2014).
Food production	Native fruits Native seeds Cattle Agriculture Fish	Matson et al. (1997); Almeida et al. (1998); Aquino et al. (2008); Lopes and Daher (2008); Ribeiro et al. (2008); Vieira et al. (2010); Pereira et al. (2012); Martha-Junior and Ferreira Filho (2012); Rocha et al. (2013); Egoh et al. (2016).
Energy production	Wood Biofuel Coal Sugar cane Hydroelectricity	McKendry (2002); Vale and Felfili (2005); Cavalcante et al. (2009); Vale et al. (2010); Chaves et al. (2013); Lima et al. (2014).

[a] USLE: Universal Soil Loss Equation.

the study area an interesting object for analyzing the effects of LULC/LULCC on ecosystem services.

The LULC mapping of the SEC (Fig. 2) was conducted based on (i) the interpretation of aerial orthophotos, with a spatial resolution of 1 m, using tone, color, structure and other visible features which gives indication to land use and ii) field validation (ground truth) (Chaves et al., 2014).

As shown in Fig. 2, the 18 LULC types of the SEC cover a representative range of land uses of the region, justifying the use of this catchment as an experimental area for this study. LULC types for the SEC were taken from Chaves et al. (2014), who also showed that currently nearly 50 % of the catchment has already been covered by anthropic land use, mainly by pasture (30%), agriculture (7% rainfed and 6% irrigated), and urbanized areas (4%).

2.2. Development of the MapES approach

2.2.1. General

The *MapES* approach is basically a framework for identifying and assessing ecosystem services of different land-use and landscape properties based on a set of criteria (indicators after Müller et al., 2016) taken mostly from literature and expert knowledge. However, it has to be noted that the complexity of environmental processes and the difficulties of measuring environmental impacts at some scales make expert knowledge frequently the only option for assessing ecosystem services (Vieira 2005). Within the step of assessing land use effects a crucial procedure was the (re)organization of knowledge for analyzing the cause-effect relationships between land-use, land-cover, relief, soil types, geographical position, and the provision of ecosystem services. The following ecosystem services were assessed, (1) Erosion Control, (2) Runoff Control, (3) Water Supply, (4) Water Quality Maintenance, (5) Soil Quality Maintenance, (6) Biodiversity Maintenance, (7) Food

Table 3
Assignment of LULC type and ecosystem services.

LULC Class	Ecosystem Services							
	Erosion Control	Runoff Control	Water Supply	Water Quality Maintenance	Soil Quality Maintenance	Biodiversity Maintenance	Food Production	Energy Production
Natural woodland[a]	80	80	80	100	100	100	20	40
Rainfed agriculture	50	60	70	30	50	20	80	70
Pasture	60	60	80	50	60	30	70	20
Reservoir	100	100	100	50	0	30	10	100
Irrigated agriculture	60	50	20	20	40	10	100	100
Natural grassland[b]	80	80	90	100	100	100	30	10
Built up area[c]	20	0	10	0	0	0	0	0
Forest cultivation	70	70	50	60	50	30	0	100
Degraded vegetation	30	40	40	80	30	30	5	10
Bare soil	10	20	10	60	0	0	0	0
Natural forestland[d]	80	80	70	100	100	100	20	60
Fish farming	100	100	50	20	0	10	100	0
Small dams	100	100	90	90	0	10	0	0
Center-pivot[e]	60	50	20	20	40	10	100	100
Unpaved roads	0	10	10	0	0	0	0	0
Paved roads	0	0	10	0	0	0	0	0
Murundu fields	80	80	80	100	100	100	5	5
Urbanization[f]	0	30	30	10	0	10	0	5

[a] Tree savanna in Table 1.
[b] Grass savanna in Table 1.
[c] Buildings.
[d] Forest in Table 1.
[e] Circle irrigation system.
[f] Areas under the process of urbanization.

Table 4
Reduction factors for soil properties.

Soil class	Erosion Control	Runoff Control	Water Supply	Water Quality Maintenance	Soil Quality Maintenance	Biodiversity Maintenance	Food Production	Energy Production
Gleysols (GX 1–2)	0.80	0.60	0.60	0.80	1.00	1.00	0.40	0.40
Arenosols (RQ)	0.60	0.90	0.90	0.60	1.00	1.00	0.80	0.80
Cambisols (CX 1–4)	0.70	0.80	0.80	0.70	1.00	1.00	0.60	0.60
Ferralsols (LV 2–3)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ferralsols (LA)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ferralsols (LVA 1–4)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 5
Reduction factors for slope.

Slope (%)	Erosion Control	Runoff Control	Water Supply	Water Quality Maintenance	Soil Quality Maintenance	Biodiversity Maintenance	Food Production	Energy Production
< 1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1–5	0.95	0.90	0.90	0.95	1.00	1.00	1.00	1.00
5–10	0.90	0.80	0.80	0.90	0.95	1.00	0.80	0.85
10–20	0.80	0.60	0.60	0.80	0.90	1.00	0.60	0.70
20–45	0.60	0.50	0.50	0.60	0.85	1.00	0.40	0.50

Table 6
Reduction factors for distance from river network.

Distance (m)	Water Quality Maintenance
< 30	0.50
30–50	0.70
50–100	0.80
100–200	0.90
> 200	1.00

Production and (8) Energy Production. The procedure encompasses three major steps (Fig. 3).

step 1: Assessment of the effects of LULC on ecosystem services by creating (i) a scale from 0 to 100 that relates LULC with each of the studied ecosystem services, and (ii) a reduction factor (0–1) relating landscape properties (soil type, slope, and distance to river network) with each of the studied ecosystem services. A value of 1 means no reduction on the provision of the corresponding service, and value of < 1 indicates that a landscape property impedes the provision of an ecosystem service;

step 2: creating maps of ecosystem services for current LULC and a

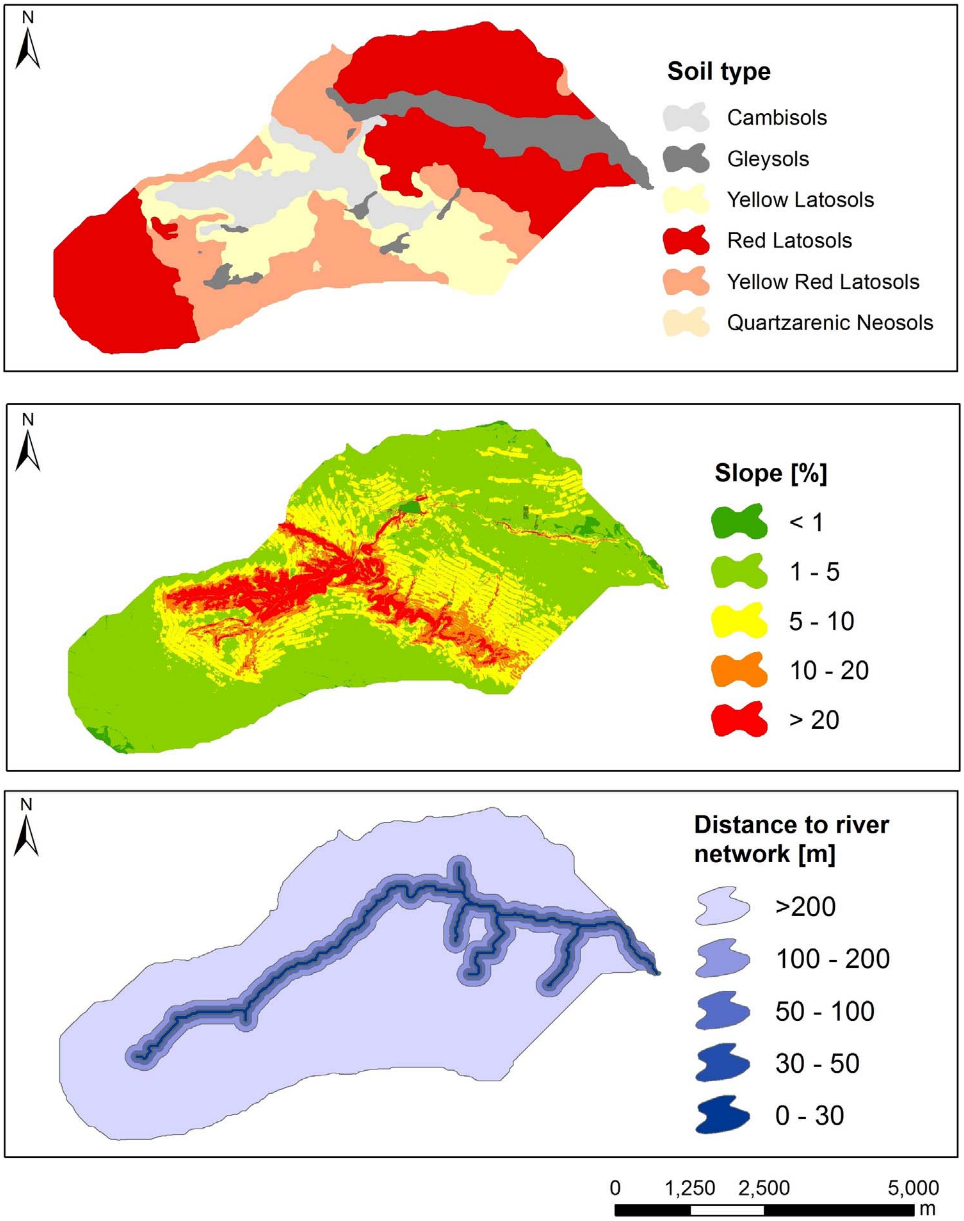

Fig. 4. Landscape properties for the Sarandi Experimental Catchment [scale 1:30,000], (a) generalized soil map (Lima et al., 2014b), note the representation is generalized, (b) map of slope derived from data of SRTM 90 (Chaves et al., 2014), (c) map of distance to river network based on buffers of the main drainage lines.

map of potential natural vegetation (PNV) as reference, by (i) converting vector into raster (maps of LULC, reference, and landscape properties), and (ii) performing calculations (multiplications) to create maps of ecosystem services for the current LULC and for the reference (PNV);

step 3: (i) compare both results, considering current and reference LULC, and (ii) establish, for each ecosystem service, a maximum variation limit that indicates if the differences between the results obtained under current and reference conditions should be identified considering the uncertainties of the respective methods used to measure the ecosystem service indicators.

This approach might also be used to run and to analyze LULC scenarios to support decision making.

2.2.2. Map of potential natural vegetation

A map of the potential natural vegetation (PNV) was produced as reference for an assumed pristine situation before human intervention. Assumptions of Spera et al. (2005) on the association of soil class, soil texture, volume of micropores and drainage with PNV for a study area in the Brazilian Cerrado were used (Table 1). However, Spera et al. (2005) point out soil type and vegetation type are only in some cases associated. In case of the widely distributed Ferralsols other physical parameters such as soil depth, fertility, drainage and position in the landscape are crucial. Nevertheless, for the Jardim river basin, in the immediate vicinity of the study area, Spera et al. (2005) were able to establish a relation between soil properties and vegetation type.

2.2.3. Relating ecosystem services with LULC and landscape properties

The core of the study is the assessment of LULC effects – also considering landscape properties – on ecosystem services. We chose criteria/indicators following the recommendations ideas of the ecosystem service indicator system by Müller et al. (2016) for assessing and defining these relationships for the Cerrado biome for each ecosystem service (Table 2) using mostly the knowledge base of Embrapa Cerrados (Center for Agricultural Research on the Savannas).

The most important ecosystems services for the Cerrado were chosen based on discussions with experts in different fields (soil, water etc.), land-use managers, and researchers working in the Cerrado. In a second step we selected criteria to relate land-use, landscape properties and ecosystem services based mostly on reference, e.g. publications,

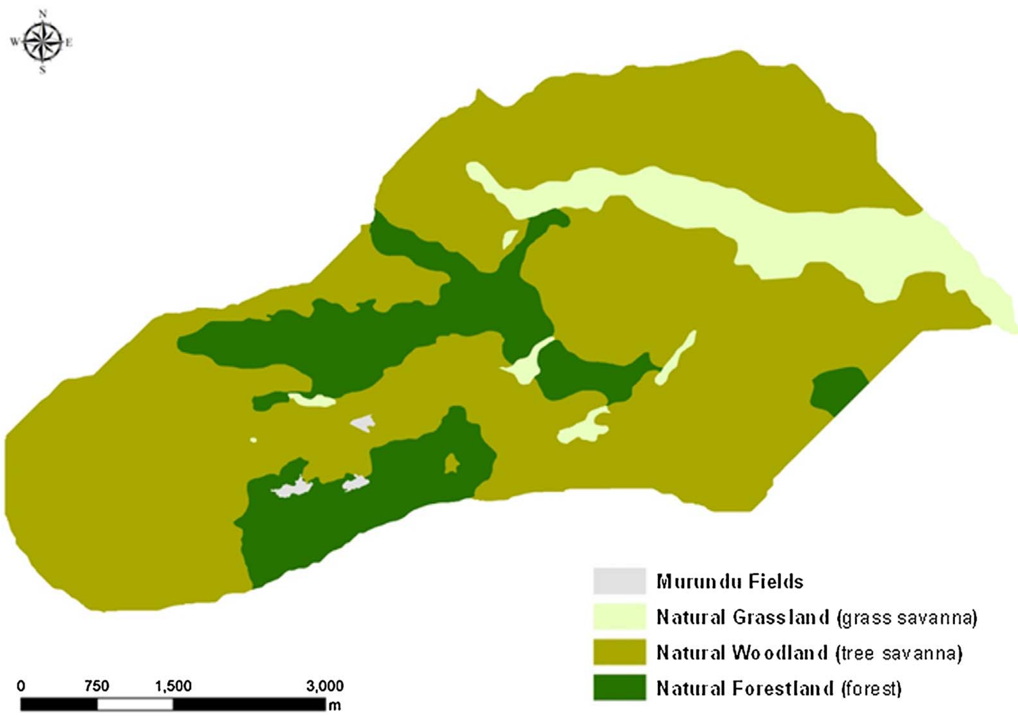

Fig. 5. Potential natural vegetation (PNV) of the Sarandi Experimental Catchment based on the relationship between soil properties and vegetation type according to Spera et al. (2005).

technical papers or reports, or, if not available, on expert knowledge (Vieira 2005). Each LULC class was related to ecosystem services and rated on scale from 0 to 100. Where 0 means no provision and 100 means full provision of the respective ecosystem service (Koschke et al., 2014).

2.2.4. Defining the thresholds of uncertainty

Uncertainty in ecosystem service indication has many sources (Müller et al., 2016). The thresholds of uncertainty in this study are defined as the limits of uncertainty due to respective methods used to measure ecosystem service indicators.

The thresholds are crucial for assessing the area, the location, and/or the intensity of LULC that is needed to show an impact on ecosystem service outside the range of methodological uncertainty. This is for example essential in assessing the success of payment for environmental services (PES) programs. The lower and upper thresholds were obtained by combining the ecosystem service values of the reference (PNV) and range factors (Rg factors) defined based on the errors given by monitoring methods of the ecosystem service indicators, and expert knowledge (Vieira 2005).

For example, the Rg factor defined for Water Supply will be lower than for Runoff Control, because it is based on baseflow that could be measured with higher accuracy than storm runoff that is frequently estimated by extrapolation of the rating-curve (Fill 1987; Santos et al., 2001). Considering sediment flow as indicator to evaluate Erosion Control, the Rg factor might be much higher due to the increased complexity and the cumulative uncertainty involved in the generation of this data (Walling 1977). Biodiversity is a highly complex parameter for almost all regions with limited knowledge about processes and dynamics (Ministério do Meio Ambiente, 2003; Lewinsohn and Prado 2005). Therefore uncertainty in measuring biodiversity is rather high, i.e. resulting in high Rg factors. The same is true for soil quality maintenance because it includes soil information that is based mostly on point data, which means additional uncertainty by transferring this into spatial data.

3. Results

3.1. Relations between LULC and ecosystem services

The core of *MapES* is the linkage between LULC and the potential to provide an ecosystem service (Table 3).

It should be noted that the resulting values are attributed based on reference and expert knowledge. The attribution of values presented for ecosystem services (Table 3) is based on the criteria listed in Table 2. Since the character of the MapES approach is rather open it would be also possible to obtain values from other sources, e.g. experiments or mathematical procedures (e.g. Koschke et al., 2014).

For better understanding of the results presented in Table 3, examples of the analyses with a more detailed explanation are shown in the following.

For Erosion Control three groups of LULC classes with similar values were identified depending mostly on the density of vegetation cover. The first group compromises LULC classes with rather dense vegetation cover, e.g. natural woodland, pasture etc. Within this group a further differentiation between natural and agricultural land cover was made because of the temporary lack of vegetation in agricultural sites. The second group consists of LULC classes without or only with a scarce vegetation cover, e.g. roads, settlements etc. Areas without Erosion Control (value = 0) are roads, which usually act as pathways for sediments, and areas under urbanization, where construction sites are major sources for sediment flow into the river network. The third group compromises fish farms, small dams and reservoirs, which act as sediment sinks.

There is a strong relation between values for Erosion and Runoff Control (Table 3), because both depend on the same physical conditions. This is not always the case, like for built-up areas, where large portions of the surface are sealed and will provide nearly no Runoff Control (value = 0). However, it will provide at least a minimum of Erosion Control (value = 20), because of the higher share of sealed surfaces which are less prone to soil erosion. The inverse pattern exists for example for areas under urbanization, where construction sites will act as major sediment sources and provide nearly no Erosion Control (value = 0), but, because of infiltration, at least some Runoff Control

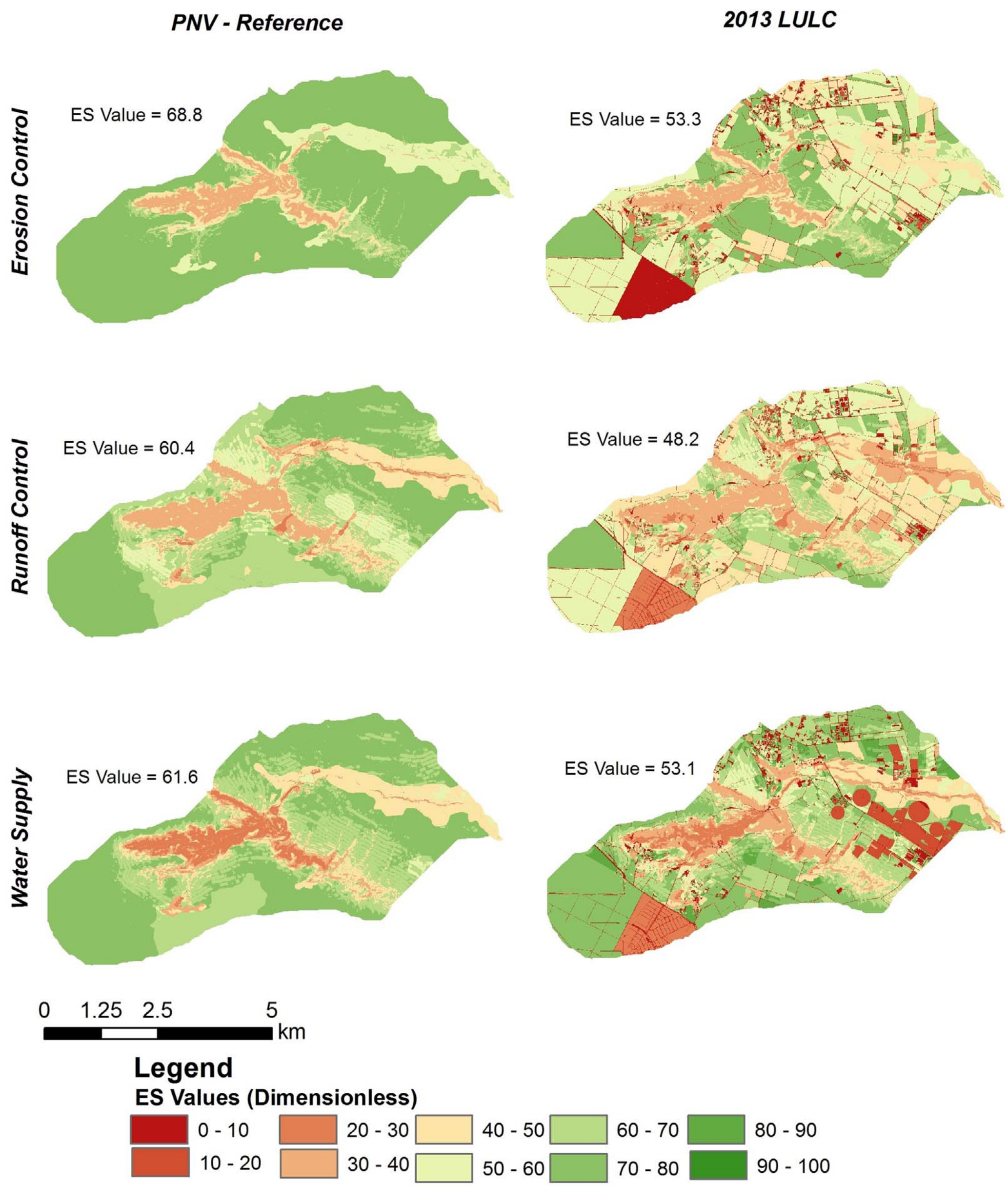

Fig. 6. Ecosystem Service Erosion Control, Runoff Control, and Water Supply for the Sarandi Experimental Catchment for PNV as reference (left) and LULC in 2013 (right).

(value = 30). Values for Runoff Control and Water Supply are corresponding, but Water Supply takes also groundwater recharge, baseflow and water use, mostly by irrigation, into account.

The Maintenance of Water Quality, Soil Quality and Biodiversity are closely connected to natural vegetation, because of the assumed dynamic equilibrium between vegetation, soil and water for the reference (PNV). Areas with human interference show frequently values of "0" for Soil Quality Maintenance, because soils are destroyed or buried by infrastructure, e.g. roads, built up areas, reservoirs, and small dams. For Biodiversity Maintenance low and very low values are attributed to man-made LULC classes.

The most productive areas in terms of Food Production are the intense agricultural areas, e.g. irrigated areas and fish farming (value = 100), followed by rainfed agriculture and pasture, with slightly lower values (80 and 70 respectively). Natural areas perform rather low in Food Production (values ≤ 30).

Energy Production is mostly a matter of hydropower (reservoirs) or usable biomass provision by natural systems (natural areas) and by man-made systems (plantations, biofuel crops).

3.2. Reduction factors

In a second step landscape properties were included in the assessment to make the *MapES* approach spatially explicit. For three landscape properties, i.e. soil, slope and distance to river network, reduction factors were estimated (Tables 4–6). Reduction factors are based on landscape properties (Fig. 4) most relevant for the considered ecosystem services.

The procedure is based on the idea a certain location in the landscape will support fully an ecosystem service, then a reduction factor of 1 is assigned, or only with limitations, then a reduction factor of < 1 is assigned (Tables 4–6).

Examples for the definition of the reduction factors are given as follows.

- Example 1, soils with high groundwater table, i.e. Gleysols, will not support Energy or Food Production to full extent (reduction factor 0.4), but will not limit Biodiversity Maintenance (reduction factor 1; Table 4).
- Example 2, slope with inclinations of 25–45% will not provide Erosion Control to full extent (reduction factor 0.6) but will not limit

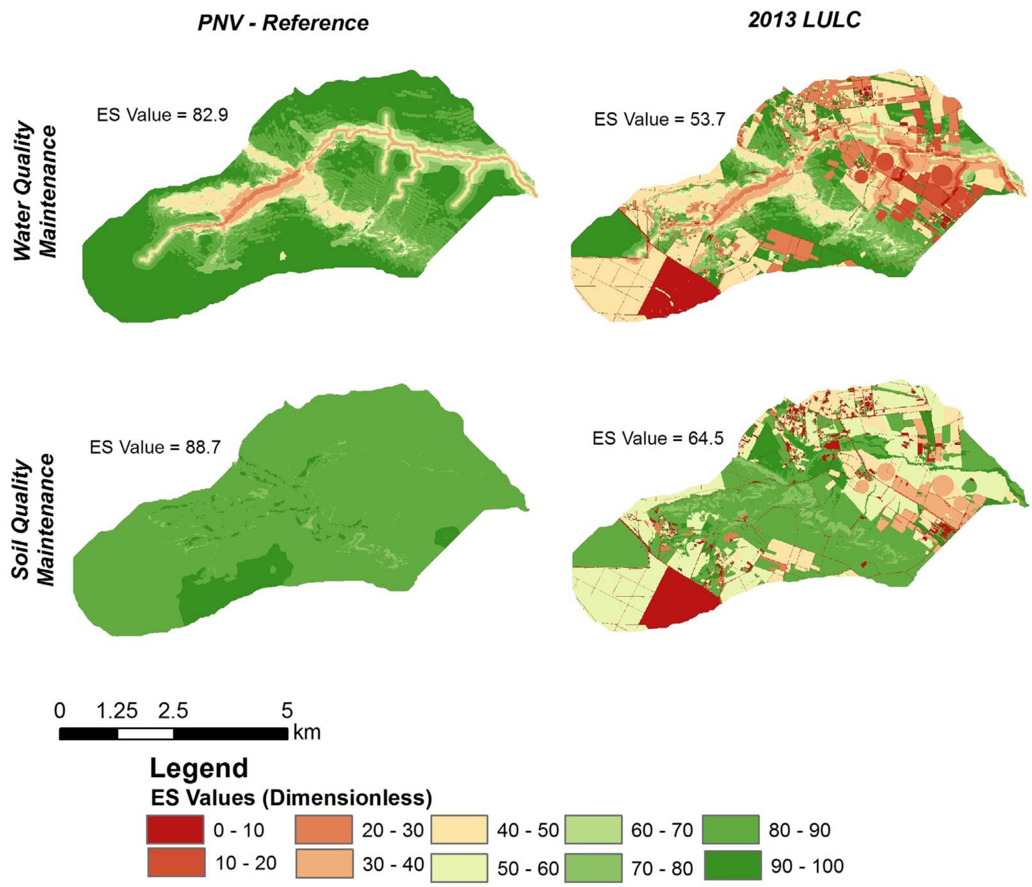

Fig. 7. Ecosystem Service Water Quality Maintenance and Soil Quality Maintenance for the Sarandi Experimental Catchment for PNV as reference (left) and LULC in 2013 (right).

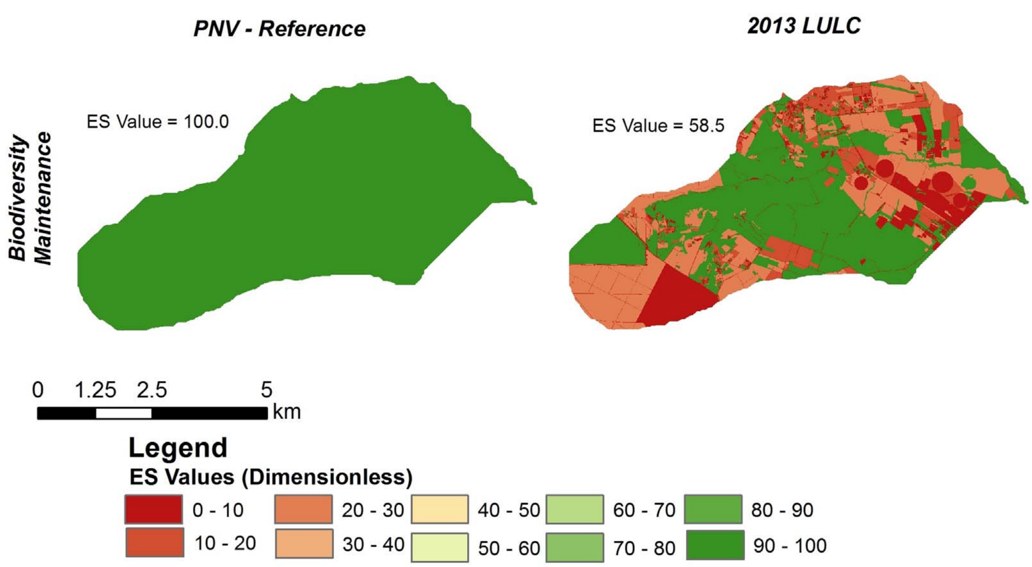

Fig. 8. Ecosystem Service Biodiversity Maintenance for the Sarandi Experimental Catchment for PNV as reference (left) and LULC in 2013 (right).

Biodiversity Maintenance (reduction factor 1; Table 5).

- Example 3, the distance from the river network is decisive only for supporting Water Quality Maintenance and was not considered for other ecosystem services within this approach (Table 6).

3.3. Map of potential natural vegetation – the reference

The Potential Natural Vegetation (PNV) is dominated by tree savanna (*Cerrado Típico, Cerrado Ralo*). Forest (*Cerradão*) and grass savanna (*Campo Limpo Úmido*), both situated in alluvial areas along the Sarandi river, covered only smaller parts of the study area (Fig. 5). The map was validated by using the natural vegetation units of the current LULC map of the Sarandi Experimental Catchment (Fig. 1). In total, the assumed PNV is in accordance with descriptions of the vegetation cover of the Cerrado biome by other authors (e.g. Oliveira-Filho and Ratter, 2002; Ribeiro and Walter, 2008).

3.3.1. Maps of ecosystem services

Ecosystem services maps are shown in Figs. 6–9.

The comparison of reference and current situation shows a loss of erosion control, i.e. decrease of the total ecosystem service value from 68.8 to 53.3, because of land use change. This is mostly caused by built-

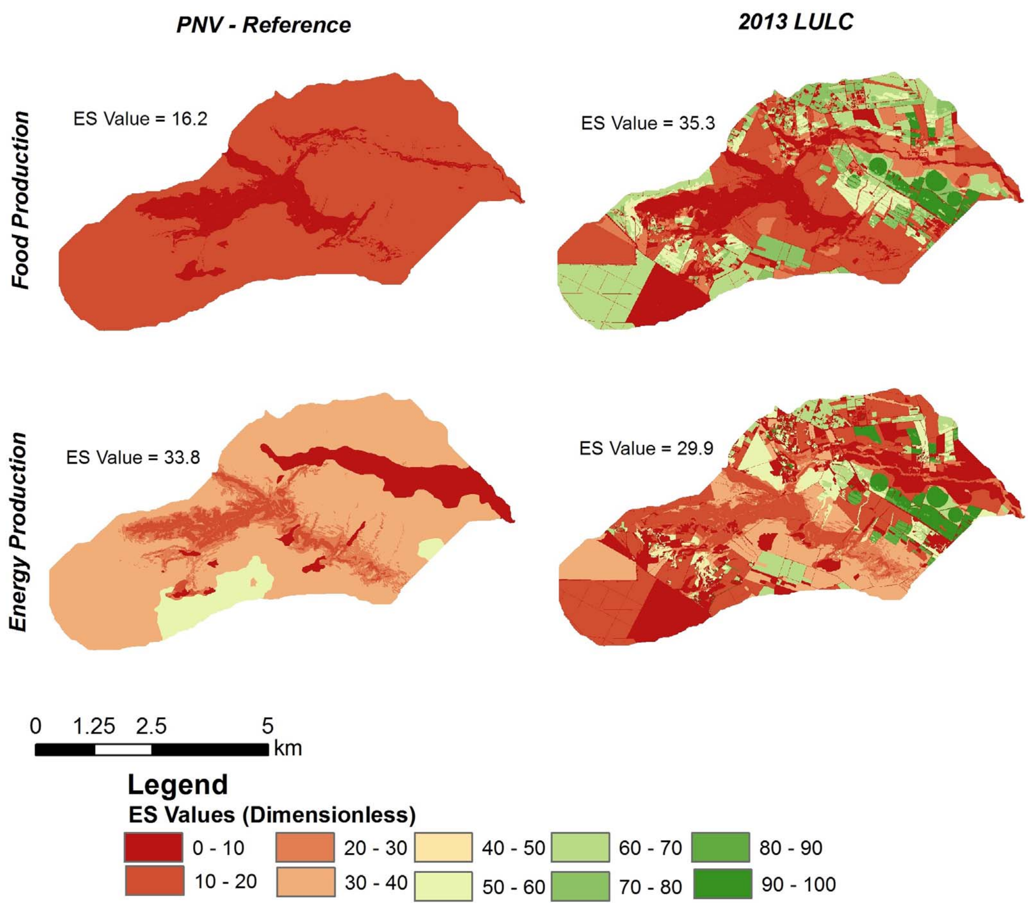

Fig. 9. Ecosystem Service Food Production and Energy Production for the Sarandi Experimental Catchment for PNV as reference (left) and LULC in 2013 (right).

Table 7
Total ecosystem service values, Rg factors and calculated thresholds of uncertainty for the ecosystem services.

Ecosystem Services	Total ecosystem service values		Rg factor	Thresholds of ecosystem service values	
	LULC 2013	Reference		Lower	Upper
Erosion Control	53.25	68.78	0.30	48.15	89.41
Runnof Control	48.23	60.41	0.10	54.37	66.45
Water Supply	53.09	61.60	0.05	58.52	64.68
Water Quality Maintenance	53.74	82.91	0.30	58.04	100.00
Soil Quality Maintenance	64.46	88.67	0.40	53.20	100.00
Biodiversity Maintenance	58.54	100.00	0.40	60.00	100.00
Food Production	35.29	16.25	0.30	11.38	21.13
Energy Production	29.91	33.76	0.30	23.63	43.89

up areas, i.e. to a large extent one settlement in the upper part of SEC, which have only a very limited erosion control (ES value = 20; see Table 3) compared to the reference (ES value = 80). In addition, the scattered built-up areas and sites with bare soil (ES values = 20 and 10, respectively) in the northern part contribute to the decrease. The contribution of agriculture to the losses due to pasture in the west and a mixture of pasture and arable land (mostly irrigated) in the eastern part of SEC is rather moderate. The impact is mostly caused by the total area of these land use classes, because ecosystem service values (pasture = 60, rainfed agriculture = 50, irrigated agriculture = 60) are only slightly lower compared to the reference ecosystem service values. Forest areas without land use change in the northern center of the SEC have a limited value of Erosion Control (= 30–40), because the rather high initial ecosystem service value of forests (=80, Table 3) is substantially reduced due to Cambisols (reduction factor = 0.7) and slopes of 20–45% (reduction factor = 0.6). However, until now the changes in Erosion Control are moderate compared to the reference. The situation might change negatively if the physical limitations of the landscape are not taken into account, e.g. urbanization or agricultural expansion in steep areas.

The pattern of Runoff Control for the reference and the land use in 2013 is as expected very similar to Erosion Control and Water Supply (see Table 3). However, the effects of land use change on runoff control are stronger, since the efficiency of vegetation to retain sediment is higher than for Runoff Control. For Water Supply a major difference is the impact of irrigated agriculture (ES value = 20) as especially visible in the eastern part of SEC.

The reference situation for water quality maintenance shows a lower contribution of the areas closer to the river network, because of the potential of riparian zones (simplified as buffer zones) to interact with water quality (Table 6). However, all human interference may have negative impacts on Water Quality Maintenance, especially settlements and agriculture with high intensity, e.g. horticulture, irrigated farmland.

The Soil Quality Maintenance is considered very high for the reference because of the dynamic equilibrium of vegetation type and soil properties. The small differences within the map and the difference to 100 of the total value are caused by the reduction factors (Tables 4 and 5). The loss of soil quality maintenance is mostly caused by imbalance and subsequent need of repeated fertilizing due to agriculture with high intensity, built-up areas and bare soil sites.

The values of biodiversity are falling in two groups, which have either ecosystem service values of 100 or ecosystem service values ≤30 (Table 3). For the reference it was assumed that all natural land cover classes provide maximum potential for biodiversity maintenance. For

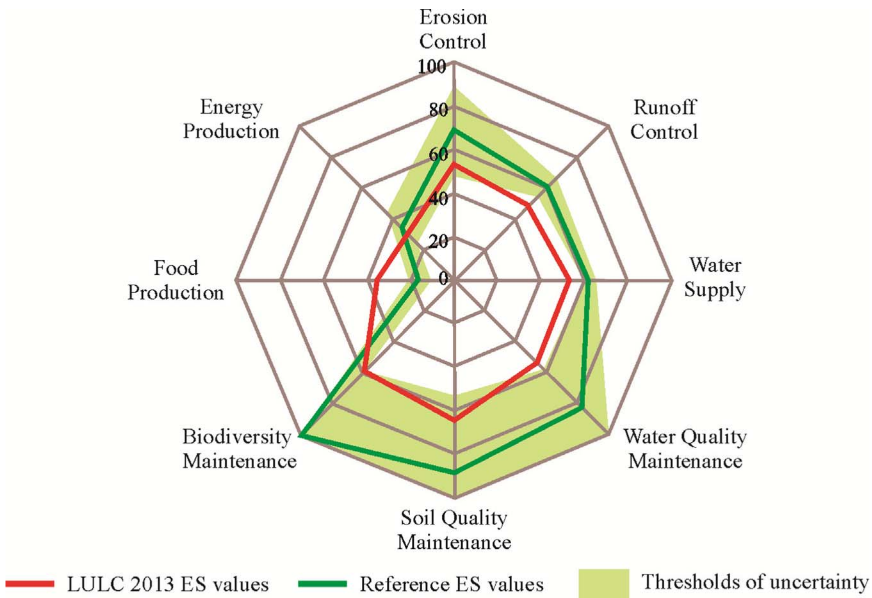

Fig. 10. Visualization of the integrated assessment of total ecosystem service values for Sarandi Experimental Catchment, reference and LULC 2013, and the respective thresholds of uncertainty.

the LULC in 2013 there is distinct split into natural land cover, the PNV, and built-up, agricultural areas and other areas with rather low ecosystem service values. This is mostly due to the removal or the change of natural vegetation cover, i.e. total or partial loss of habitats.

The low total ecosystem service values for Food Production are caused by the low provision potential of the Cerrado biome compared to agricultural areas. The rather low value for the LULC in 2013 is mostly because of the limited extent of agricultural areas (43%) due to the environmental limitations of the basin, e.g. steep slopes with shallow soils. The reference situation for Energy Production is different because of the potential to provide fuel wood, mostly as charcoal. Despite the increase of this potential due to irrigated agricultural, forest plantation and reservoirs (ES values = 100), there is a total net loss due to the expansion of pasture, urbanization and infrastructure (ES values ≤20).

3.4. Integrated assessment of ecosystem service maps

The integrated assessment of ecosystem service maps is done in two steps, first to analyze the threshold of uncertainty using range factors (Rg) and second to assess the interrelated effects of LULC changes. The Rg factors were used to define the upper and lower thresholds, i.e. ranges, of uncertainty as shown in Table 7.

High values of uncertainty and very wide ranges were used for example for biodiversity maintenance (Rg factor 0.4, range 60–100) or soil quality maintenance (Rg factor 0.4, range 53–100). This is due to the uncertainty in the measurements of the relevant criteria (see chapter 2.5). Low values of uncertainty were assumed for water supply (Rg factor 0.05, range 59–65) due to the high accuracy of measurements (see chapter 2.5).

The areas outside the uncertainty range (shaded areas in Fig. 10) are considered as areas where changes are beyond the methodological error of measuring the ecosystem service. Changes that fall inside this range might have an impact, but it can be also attributed to methodological inaccuracies. For the SEC the change from reference to LULC 2013 show for food production a positive effect, i.e. gain of ecosystem service, and for runoff control, water supply and water quality maintenance are net losses are to observe. For the other ecosystem services the simulated changes have a very high uncertainty, i.e. the change is within the shaded area. In consequence one cannot be sure about the actual effect of land use changes on the respective ecosystem service.

4. Conclusions

The developed approach is open to changes and improvements on all levels, i.e. ecosystem service values, reduction factors, Rg factors, number of ecosystem services etc. It is not a specific tool behind the procedure, but any GIS or even simple manual application is possible. Because of the empirical character of the presented approach there are also limitations. These are mostly due to the limited knowledge of the users about status and processes in the complex interaction of LULC and ecosystem services in a landscape unit. However, the approach is easy to understand, to modify and to adapt to other situations and might be therefore used in decision support in context of future land use scenarios. It might also help to integrate ecosystem services in landscape planning (Opdam 2016) and fill the gap between land use planning and numeric modeling using very complex tools. An additional benefit of this approach is the opportunity of compiling and analyzing existing knowledge on status, processes and impacts of human activities on ecosystem services in a certain landscape, as we could show for the Cerrado biome.

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