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Mountain ecosystem services affected by land use changes and hydrological control works in Mediterranean catchments

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ABSTRACT

The use of check-dams in mountain environments to regulate fluxes of water and sediments is widely applied across Mediterranean mountains. Besides the use of “grey infrastructures” such as check-dams, other restoration and hydrological control measures rely more on the use of “green infrastructures” or “nature-based solutions” (e.g. reforestation, buffer lines) or a combination of both types of measures. It is widely accepted that both are complementary, and that prioritization should be based on economic, ecological and cultural criteria. This paper brings together all the knowledge generated during more than one decade concerning the impact of land use changes, reforestation, and hydrological control works on several ecosystem services in a representative Mediterranean catchment. The work evaluates different management scenarios aiming to optimize provision of ecosystem services in the area.

The study area is a medium-sized catchment (~300 km^2) in Southeast Spain, representative of Mediterranean mountains that experienced agricultural land abandonment, greening up, and restoration works in the second half of the twentieth century. The methods combined: (i) previous research results for the area that were organized in an ecosystem services framework, providing data for three representative scenarios of catchment management; (ii) the use of value content analysis of the existing management plans for the area to understand the view of the managers; and (iii) a multicriteria analysis of the management scenarios to determine the most sustainable scenario to optimize different ecosystem services. The results of the evaluation were later validated with the stakeholders (technicians and managers involved in the management plans) through interviews.

Our results show that solutions that respect landscape and ecological dynamics are more sustainable and cheaper in the medium and long term than scenarios based on “grey infrastructures”, although the latter could have more desirable short-term impacts. The value analysis reflects how there are some concepts, such as ecosystem services, that could easily be further incorporated into several management plans. When choosing a management scenario, this needs to be adapted to the local environmental conditions and to the specific objectives of the restoration works. Tailor-made management scenarios taking into account two factors (local conditions and specific management objectives) can optimize resources and achieve medium to long-term sustainability.

1. Introduction

1.1. Hydrological control works and historical changes of land use patterns.

Mediterranean landscapes have suffered important transformations in recent decades, affecting ecosystem services (ES) and human well-being (Martínez-Sastre et al., 2017). Medium altitude mountainous Mediterranean areas experienced such transformations because of socioeconomic changes and the introduction of large Forest Hydrological Restoration Projects in the second half of the XX century. These projects included the construction of check-dams and the reforestation of upper catchment areas, as in many other European countries (Piton et al., 2016). Consequently, many of these landscapes have experienced a greening-up process, recovering a high percentage of their vegetation cover in the last few decades. This trend has also been described worldwide (Zeng et al., 2016) and regionally for the North Mediterranean basin, with economies that are not further based on subsistence schemes (García-Ruizet al., 2011), meaning a less intensive use of forest.

The use of check-dams in mountain environments to control and

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regulate fluxes of water and sediment, has been widely applied across mountainous Mediterranean areas (Boix-Fayos et al., 2007; Castillo et al., 2007; Piton et al., 2016; Bombino et al., 2014; Fortugno et al., 2017). Check-dams are probably the most emblematic structure for torrent control. Piton et al. (2016) explained that many countries inherited a large number of these infrastructures and managers face decisions on whether to maintain them, destroy them, stop maintenance, or construct new ones. Decision makers must base their decisions on the risk of each alternative, taking into account existing structures and their effects. Determining the functions of check-dams and their impacts is key to the decision making process. However, it is not always easy to specify these functions because the watershed dynamics may have changed since the construction period, due to changes in land use patterns or variations in climatological conditions (Piton et al., 2016; Boix-Fayos et al., 2007; Nadeu et al., 2012; Fortugno et al., 2017; Eekhout et al., 2018).

Besides the use of "grey infrastructures" such as check-dams, there are other restoration and hydrological control measures that rely more on the use of "green infrastructures" or "nature-based solutions" (e.g. reforestations, buffer lines) or combinations of both types of measures. Although there is still discussion on when and where to use grey and/or green infrastructures, it is widely accepted that both are complementary (Piton et al., 2016) and that prioritization should be based on both economic and ecological criteria (Balmford et al., 2000; Izquierdo & Grau, 2009). The understanding of the multiple impacts, benefits, interactions and trade-offs of these different kinds of hydrological control works will help to define criteria for the decisions.

1.2. The combination of multicriteria analysis and ecosystem services for the evaluation of the impact of hydrological control works

Knowledge about the effect of greening-up of Mediterranean catchments on their hydrological response has advanced significantly in recent decades (Bosch and Hewlett, 1982; Gallart and Llorens, 2003; Buendia et al., 2016). Impacts of hydrological control works and reforestations on fluvial morphology and geomorphological dynamics (Boix-Fayos et al., 2008, 2007; Quiñonero-Rubio et al., 2016), and their effects on the carbon cycle (Boix-Fayos et al., 2009; Nadeu et al., 2013) were described. However, an integrated vision of how the changes in the landscape affect different ES and their trade-offs is lacking.

Semiarid and subhumid areas of the Mediterranean Basin host several hotspots of biodiversity and provide vital ES. Afforestation has been used extensively to restore these areas; however, integrated studies on the impact of afforestation on the provision of ES are scarce (Derak and Cortina, 2014). Recently, several studies have highlighted the possibility of evaluating the sustainability of management decisions, land use changes, and landscape evolution in terms of ES (Derak et al., 2017). Although, very often, policy makers and researchers recognize that the ability to integrate ES into decision making has advanced considerably over the last few years (Schaefer et al., 2015), there are still challenges to overcome. Inclusion of the ES concept would help to maximize social welfare and to overcome the use of a conventional economic evaluation as the sole criterion (Mavrommati et al., 2017).

Multicriteria analysis (MCA) can provide a suitable set of methods for sustainability evaluations, since it can combine and integrate non-marketable goods and services, it can incorporate a mixture of quantitative and qualitative information, and it allows the visualization of the opinions of different groups of stakeholders (Derak et al., 2017). In combination with the ES concept, it can provide a framework to evaluate how different kinds of management or land use perform over multiple ES (Blattert et al., 2017).

A significant amount of information is available on the effects of land use changes and hydrological control works on soil erosion, fluvial morphological and hydrological processes, sediment yield, and organic carbon dynamics in soils and sediments in Mediterranean catchments (Boix-Fayos et al., 2007, 2009; Eekhout and de Vente, 2019; Martínez-Mena et al., 2019; Nadeu et al., 2014; Piton et al., 2016; Cutillas et.al., 2018; García-Ruizet al., 2011). However, this available scientific information has not fully reached technicians and the managers dealing with catchments and forest management plans. Greater interaction between scientists and decision makers could benefit the planning of catchment and forest management. Some authors recommend the use of MCA techniques to analyze complex forest problems and for planning forest systems, taking into account stakeholder views (Diaz-Balteiro and Romero, 2008; Diaz-Balteiro et al., 2017)

To contribute to a more integrated analysis and support better informed decision making, this paper aims to (i) collect all the knowledge generated during fifteen years of studies of a representative Mediterranean catchment regarding the impacts of land use changes, forest and hydrological correction works on several ES, and (ii) evaluate different management scenarios at the catchment scale in relation to the optimization of ES.

This evaluation takes into account three official management plans of water and forest currently in force. All of these plans had specific objectives and used, at different degrees, hydrological control works and reforestation activities, to accomplish them. We related the objectives of the plans to the research results of the past decades in our study area, by using an ES framework and an MCA analysis technique. The results of the evaluation were validated with the stakeholders (technicians and managers of the management plans) through interviews. This analysis allowed the understanding of the performanceof different management scenarios.

2. Study area

2.1. Environmental conditions and representativeness of the area

The Upper Taibilla catchment (Fig. 1) is representative of many medium-altitude Mediterranean mountainous catchments in Spain because of its physical and socioeconomic characteristics and the catchment management measures that were carried out since the second half of the XX century. The area represents a medium size catchment that experienced in the last 60 years a "greening up" process (Pérez-Cutillas et al., 2018). This was the result of the convergence of (i) a large abandonment of agricultural land as a direct consequence of a rural exodus to the urban and coastal areas due to socioeconomic reasons. This is a general pattern observed for many mountain areas of the Northern Mediterranean region (García-Ruizet al., 2011). Furthermore, (ii) reforestation and hydrological control works were carried out in the

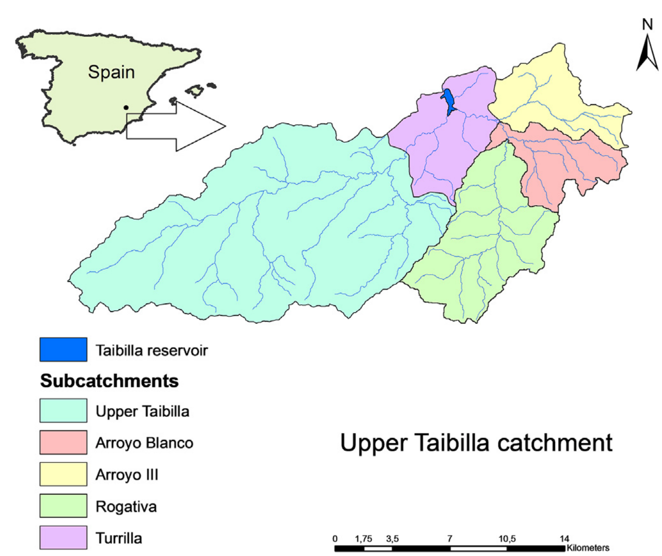

Fig. 1. Study area, Upper Taibilla catchment with subcatchments.

Fig. 2. Details of the study area. a) Mosaic landscape of the Upper Taibilla catchment, natural forest and reforested patches alternating with cereal fields; b) Forest recovery 40 years after reforestation activities and socioeconomic changes; c) Silted check-dam in good condition 30 years after construction; d) Erosion pool and incision downstream of a small check-dam; e) Alluvial wedge of very fine sediment behind a check-dam behaving as small aquifer; f) Downstream erosion of a check-dam affecting its own structure; g) Bank erosion processes affecting downstream areas of the subcatchments; h) outlet of the Rogativa subcatchment at the Taibilla reservoir.

catchment (Fig. 2). This type of hydrological control works were very common in Europe in the last five decades (Piton et al., 2016). The catchment is located at the boundary between the regions of Murcia and Albacete (UTM 4226930N 565029E, SE Spain) and is one of the most important tributaries of the Segura river. More specific information of the study area is given at Supplementary material (S1).

2.2. Management plans including reforestations and hydrological control works

Forest and hydrological control works have been performed for erosion control and flood regulation in Spain since 1901. Nowadays, they are carried out in the framework of agreements between the central administration and the regional administrations (Comunidades Autónomas) and are co-financed by European funds (Ministerio de Medio Ambiente, 2001). For this research we consulted three management plans which have a stake in the forest and hydrological control works in the Region of Murcia and the catchment of the Segura River. These three plans all focus on the use of reforestation and hydrological control works for the regulation of fluxes (water and sediment), acknowledging that their use has some other positive, collateral environmental effects. For more information on the management plans currently in force see Supplementary material (S2).

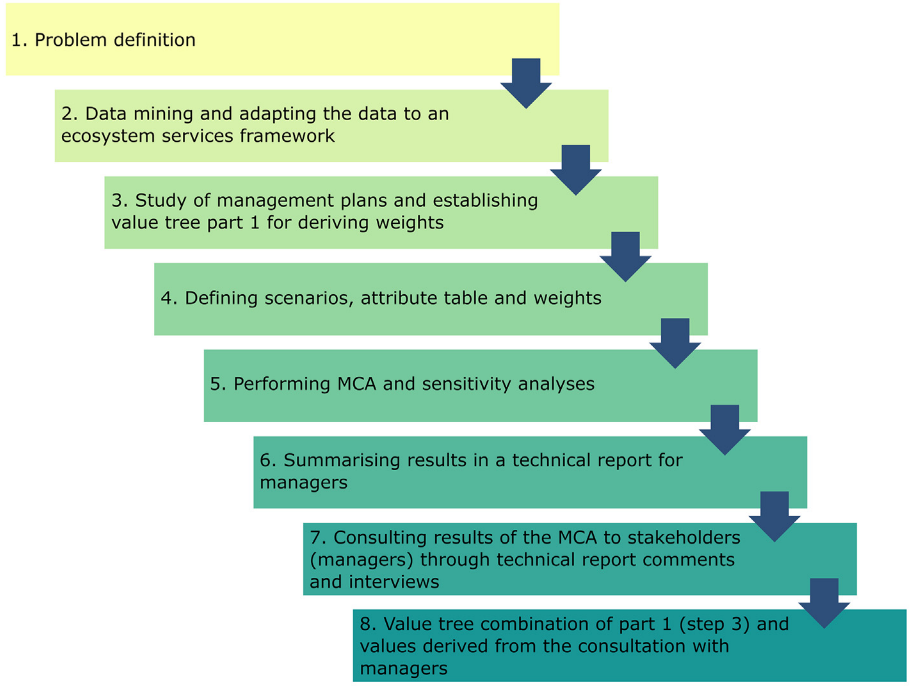

Fig. 3. Work flow chart.

3. Methods

This work is based on existing field and modelling data partially published (Boix-Fayos et al., 2007, 2008, 2009, Quiñonero-Rubio et al. 2016, Nadeu et al., 2012, 2015, Pérez-Cutillas et al., 2018, Halifa-Marín et al., 2019) from previous research in the area, obtained in different research projects along 15 years, for a mountainous catchment representative for the Northern Mediterranean Basin. Available data were re-organized to obtain ES indicators. Based on these, several catchment management scenarios (Section 3.2) were evaluated. A Multi Criteria Analysis, focusing on the intelligence phase (Zucca et al., 2008), was used to evaluate the scenarios. The focus was more on structuring the problem, gaining insight and learning from the problem dealt with (Myšiak, 2006). Fig. 3 presents an overview of the methodology and workflow involving eight steps.

3.1. Problem definition

Land use changes occurred on a wide scale in the Upper Taibilla catchment in the last 60 years. These changes were related to the abandonment of agricultural activities, due to a strong rural exodus, and the natural recovery of vegetation in abandoned fields, together with the reforestations and construction of check-dams as part of the hydrological control works carried out by the Spanish Government and Regional and Water Authorities.

During the last fifteen years several research projects were carried out in the area to understand how all the changes that took place in the catchment affected hydrological and sediment dynamics, erosion processes, and the organic carbon cycle of soils and sediments. We found many answers to some of our initial questions (Boix-Fayos et al., 2015, 2009, 2008, 2007; Nadeu et al., 2011, 2012), although some new questions emerged. In short, we found an important decrease in the sediments and water flow through the channel (Boix-Fayos et al., 2007, 2008; Quiñonero-Rubio et al., 2016) and an increase in the organic carbon stocks in soils and sediments (Boix-Fayos et al., 2009, Nadeu et al., 2012, 2014; Halifa-Marín et al., 2018). Fluvial geomorphological processes also changed in the area during the last few decades because of anthropic changes (land use and land cover) and slight climate changes (Boix-Fayos et al., 2007). Many of the changes were environmentally positive, but particular trade-offs were also identified (Step 1, Fig. 3).

As an example illustrating the ambivalence of the effects of the measures undertaken: the large erosion control and flood regulation resulted in a change in the hydrological and sediment dynamics causing a downstream sediment deficit in the channel. Most of the sediment was stabilized on the slopes and in the upstream channel area. This enhanced other downstream erosion processes (channel and bank erosion), but at the same time the stabilization of the sediment created sinks for carbon sequestration and biodiversity hotspots (Boix-Fayos et al., 2007, 2015; Nadeu et al. 2012; Halifa-Marín et al., 2018).

Some of the main questions that arose from these findings were:

Given the natural recovery of the vegetation in the area, to what extent did the construction of check-dams provide additional benefits?
How can we relate the hydrogeomorphological and ecological responses of the catchment to the natural and anthropogenic disturbances in terms of ES?
Can we make a specific assessment of management scenarios based on ES?

3.2. Scenarios, attributes table and data sources

Based on the above questions and the available knowledge, we constructed three management scenarios (steps 3 and 4, Fig. 3) combining different degrees of anthropogenic impacts (including natural recovery of vegetation and hydrological control works) and evaluated how they would affect a series of ES provided by the catchments. We first identified several ES (Table 1) in different categories provided by the medium-sized catchments for which we had information from previous research, to construct the indicators for the ES evaluation (Egoh et al., 2012; Martínez-Sastre et al., 2017; Derak and Cortina, 2014). The selected indicators could provide information on 3 of the common 4 groups of ES (Supporting, Regulating, Provisioning and Cultural; Costanza et al., 2017). From a large selection of the ES provided by these catchments, we focused only on the ES for which we

Table 1
ES indicators, and sources of data used to evaluate the management scenarios for the Upper Taibilla case study.

ES Groups	ES Subgroups	Indicators	Units	Description	Data sources[2]
Supporting	Soil condition	Soil organic carbon (OC) (stock to 10 cm depth)	tn[1]	Average of soil OC stocks based on sample collections for each land use type, results were extrapolated to each land use pattern	Halifa-Marín et al., 2019, Boix Fayos et al. (2009, 2015)
		% Forest (high and medium density)	Percentage	Percentage of forest area based on photointerpretation in different years	Pérez-Cutillas et al. (2018)
Regulating	Erosion prevention/ control	Sediment yield (erosion control)	tn	Modeled for each alternative	Boix-Fayos et al. (2008)
		Hillslope erosion	Percentage of forms and qualitative descriptions	Based on field geomorphological mapping and photointerpretation	Boix-Fayos et al. (2007, 2008), Nadeu et al. (2011, 2012)
		Bank erosion	Percentage of forms and qualitative descriptions	Based on field geomorphological mapping and photointerpretation	Boix-Fayos et al. (2007, 2008), Nadeu et al. (2011, 2012)
		Gully erosion	Percentage of forms and qualitative descriptions	Based on field geomorphological mapping and photointerpretation	Boix-Fayos et al. (2007, 2008), Nadeu et al. (2011, 2012)
		Channel erosion	Percentage of forms and qualitative descriptions	Based on field geomorphological mapping and photointerpretation	Boix-Fayos et al. (2007, 2008), Nadeu et al. (2011, 2012)
	Climate regulation	OC stored in channel sediments (stock)	tn	Total OC stored in channel estimated by sampling and extrapolated with geomorphological cartography	Halifa-Marín et al. (2019)
	Moderation of extreme events	Stability and connectivity of channels	-	Estimated with a sediment connectivity index developed for capturing different spatial scales and geomorphological elements	Quiñonero-Rubio et al. (2013)
		Check-dams	Number	Number of check-dams for each alternative	Quiñonero-Rubio et al. (2016)
		Vegetation in channel	Percentage of densely vegetated channel bars	Based on channel vegetation mapping from photointepretation	Halifa-Marín et al. (2019)
Provisioning	Water provisioning	Water discharge	m^3 Annual average 1933–1948; 1996–2012	Discharge measured in gauge stations at the Taibilla reservoir	Pérez-Cutillas et al. (2018); MAGRAMA, Anuario de Aforos
		Runoff coefficient	-	Estimated based on discharge data	Pérez-Cutillas et al. (2018)
Economic		Cost of restoration	€/ha	Average values from different restoration projects in the region	Quiñonero-Rubio et al. (2016)

1 Values in metric tonnes (tn) are referred to the whole catchment
2 All data used in the construction of the ES indicators and for evaluating the scenarios were generated within the Soil and Water Conservation Group of CEBAS-CSIC.

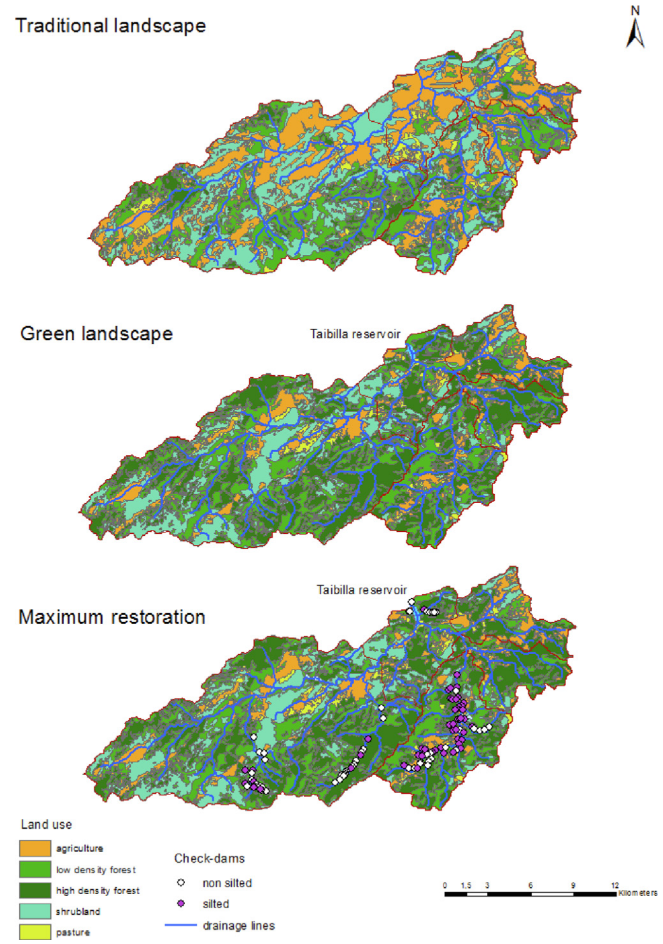

Fig. 4. Spatial representation of the management scenarios, including land use classes and silted and non-silted check-dams.

could provide first-hand research information and key information on erosion and flood control and carbon sequestration. Very often this information is not considered because latest scientific findings are not directly available to the responsible technicians. In addition, we included the cost of the restoration activities as an economic criterion in the MCA. It is beyond the objective of this paper to provide a complete view of all possible ES provided by the management scenarios analyzed. Especially some possible touristic and cultural services (i.e. increase of value of the areas as touristic and cultural destinations) and indirect economic impacts (i.e. employment force, new economic activities) were not considered and were not the object of this approach. However, the potential scenarios could affect those aspects and would be valuable to explore them in future studies.

The construction of the management scenarios to be evaluated was inspired by historical situations that we had previously studied in terms of land use and hydrogeomorphological processes (Boix-Fayos et al., 2009, 2007; Quiñonero-Rubio et al., 2016; Pérez-Cutillas et al., 2018). They included real historical and present-day situations and a virtual scenario (Step 4, Fig. 3).

The three management scenarios chosen were (Fig. 4):

1. Scenario 1:”Traditional landscape”. This represents a situation with no intervention in the traditional landscape as it was in the years 1950–60. It is based on a real historical landscape.
2. Scenario 2: “Green landscape”. This represents the natural recovery and reforestation landscape that developed from the 1960s until the present day. It is a scenario based on a virtual landscape, in which the green cover is the real present-day vegetation, but does not include the “grey infrastructure” of check-dams.
3. Scenario 3: “Maximum restoration”. This represents the real maximum intervention landscape that developed since the 1960s (Table 2). This scenario includes all check-dams constructed in the catchment since the 1970’s and the recovery of the vegetation through different reforestations and natural growth of vegetation.

3.3. Multicriteria analysis: Standardization and weights

To evaluate the scenarios, a MCA was carried out using the software Definite 3.1 (Janssen and Herwijnen, 2017). The MCA consists of a structured approach to address trade-offs among multiple, often competing, objectives (Beinat, 1997; Mavrommati et al., 2017). Through a MCA, it is possible to obtain a classification of a set of land use scenarios according to their contribution to the provision of vital ES (Koschkeet al., 2012; Fontana et al., 2013). However, like other models, MCA represents a simplification and an abstraction from the real system (Munda, 2004). The MCA method applied and presented here was “Weighted summation” because it is a reliable and straightforward method (Hajkowicz, 2007), methodologically sound, easy to explain and transparent (Janssen, 2001). Other MCA methods (Evamix, Electre II and Regime) were tested and the results were similar to the results obtained by the Weighted summation method. A sensitivity analysis to test the influence of the MCA method is presented in Supplementary material 4 (S4).

To feed the MCA we first built an “effects table” (step 2, Fig. 3) in which the impacts of each management scenario on the ES indicators of Table 1 were estimated. The ES indicators, or effects, used a ratio scale for quantitative data and a 0-Plus (0, +, ++, +++) scale for qualitative data. All effects were standardized using the maximum standardization method, except for “sediment yield” and “runoff coefficient” that were standardized using concave functions based on expert knowledge and scientific results of previous research on both issues.

The MCA included the perspective of managers and technicians, based on the management plans that included hydrological control works and reforestation in the area (step 3, Fig. 3). The idea was to evaluate how the management scenarios performed regarding the different objectives of the management plans and if they optimized additional ES. Three management plans were reviewed (Section 2.2 and Supplementary material S2):

(i) At the national level the *“National Plan of Priority Actions on hydrological and forestry Restoration, Erosion control and fight against desertification”* (NPPARE, Ministerio de Medio Ambiente, 2001).
(ii) At the regional level the “Action Plan of Forestry Policy of the Murcia Region 2016–2020” (APFMR) (Consejería de Agricultura,

Table 2
Combinations of weights used for each MCA analysis.

Groups of ES – or “main groups of effects” in each MCA	Regulating first, economy second, other third (MCA1)	Regulating and economy, equal, others second (MCA2)	All equal importance (MCA3)	All equal, but economy less important (MCA4)	Regulating most important, the rest equal (MCA5)
Supporting	0.104	0.104	0.250	0.313	0.160
Regulating	0.521	0.396	0.250	0.313	0.521
Provisioning	0.104	0.104	0.250	0.313	0.160
Economy	0.271	0.396	0.250	0.063	0.160

Agua y Medioambiente, 2016).
(iii) At the catchment level the catchment hydrological plan of the Segura River 2009–2021, 2021, carried out by the Confederación Hidrográfica del Segura and Ministerio de Agricultura, Alimentación y Medioambiente.

The plans were reviewed to identify their objectives in relation to the use of reforestation, hydrological control works, and the general economic resources allocated to them. A value tree was used to derive weights (Stillwell et al., 1987) in step 4 (Fig. 3 of the paper), by understanding the priorities of the decision makers as represented by the management plans. The three plans consulted use reforestation and hydrological control works as measures for erosion control and flood regulation. However, the distinct plans pay differing degrees of attention to the economic benefits and ES provided by the catchment areas, as explained in Section 2.2. Thus, several weight combinations were assigned (Table 2) to capture the slightly different value perspectives of the different management plans. More information on the value tree construction and the assignment of the different weights for the MCA is given in Supplementary material (S3).

3.4. Sensitivity analysis

Sensitivity of the first ranked scenario to changes in weights (step 5, Fig. 3) was analysed by estimating the smallest change in weight that results the first ranked scenario to lose its first position. The analyses were performed using the software Definite 3.1 (Janssen and Herwijnen, 2017). The difference between the original weight and the reversed weights were used to analyse the stability of the best performing scenario of each MCA and for each group of effects.

To test the sensitivity of the results to the type of MCA method used all the analyses were repeated using the Evamix, Electre II and Regime method. Using different MCA methods resulted in some changes in rankings between the first and second position. The results of this sensitivity analysis are presented in Supplementary material 4 (S4).

Finally, the sensitivity to a change in the score of the Economic criterion “Cost of restoration” was also tested to understand how first and second alternatives exchanged positions with a change on this criterion.

3.5. Validation of the results

To validate the results, a consultation was carried out with managers and technicians involved in the three management plans, belonging to different administrations with knowledge and expertise on reforestations and hydrological control works. A short technical report with the main results of the research and an interview with six technical questions were addressed to them (10 interviews) (steps 6 and 7, Fig. 3). Their answers were used to complete a second value tree and to identify barriers and opportunities in the management plans in relation to the optimization of reforestation and hydrological control works (step 8, Fig. 3).

4. Results

4.1. ES provided by the different management scenarios

The effects table (Table 3) was constructed by combining the concept of ES from Braat and Groot (2012) and the selection of indicators for ES from Brown et al. (2014), Egoh et al. (2012), and Derak and Cortina (2014). The data to produce the indicators were extracted from previous research in the area (Table 1). The list of selected indicators consisted of those that, in most of the cases, had different values for the three scenarios.

For the group of supporting ES, soil organic carbon was used as the main indicator. The soil organic carbon stock in the surface soil (10 cm) of the drainage area was larger in the second and third scenario (118582 tn) than in the first (96971 tn), because it is directly dependent on the land use pattern. The forest cover was much lower in the first scenario (36%), based on the land use map of 1956, and it was the same for the second and third scenarios (68%). The soil organic carbon stock and forest cover were based on the mapping of the land use pattern in 2012 and direct soil sampling (Boix-Fayos et al., 2015; Nadeu et al., 2015; Pérez-Cutillas et al., 2018; Halifa-Marín et al., 2019).

We considered three regulating ES: erosion control, climate regulation, and moderation of extreme events. For the first two, several indicators were available from earlier research in the area. Erosion control and moderation of extreme events converge with the main objectives of the management plans that include reforestation and hydrological control works in the area. For erosion control we had quantitative information on sediment yield for the three scenarios, obtained from the application of erosion models at the catchment scale, calibrated with sediment yields at the subcatchment scale obtained in the field (Boix-Fayos et al., 2008; Quiñonero-Rubio et al., 2016). Also, quantitative and qualitative information on different erosion processes at the catchment scale (bank, channel, and gully erosion) for the two extreme management scenarios (first and third) could be extrapolated to the second (Boix-Fayos et al., 2015; Halifa-Marín et al., 2019; Nadeu et al., 2012).

The simulated sediment yield at the outlet of the Rogativa subcatchment, was much larger in the first scenario and much lower in the third, due to the effect of check-dams. However, in the second scenario, which only included the soil conservation effect of the vegetation on the slopes, the reduction of the sediment yield was around 50% compared to the first (Boix-Fayos et al., 2008).

Besides the sediment yield, the bank, and channel erosion was controlled much more in the first scenario than in the third. Several studies in the area showed how a higher sediment input from the slopes to the channel results in less erosion in the channel, due to a reserve of sediment circulating in the channel. However, when sediments are retained behind check-dams and on the slopes, channel erosion (incision processes) and bank erosion take place more frequently (Simon and Darby, 2002; Boix-Fayos et al., 2007; Nadeu et al., 2012). All these effects are reflected on the 0/+ scale in the effects table (Table 2).

Regarding climate regulation, the stock of carbon in fluvial sediments was taken as a proxy for the potential of fluvial sediments as carbon sinks contributing to climate change mitigation. Quantitative information was available for the first (989.7 $g\,m^{-2}$, Halifa-Marín et al., 2019) and third (1211.1 $g\,m^{-2}$, Halifa-Marín et al., 2019) scenarios and it was extrapolated to the second.

For the ecosystem service “Moderation of extreme events” three proxies were used: the network of check-dams, the channel vegetation, and the connectivity index. The network of check dams is considered beneficial and refers to the number of check-dams present in the channel contributing to water and sediment retention, although their effectiveness depends on the trap efficiency of each dam (Boix-Fayos et al., 2008; Quiñonero-Rubio et al., 2016).

The channel vegetation is a benefit and indicates natural retention of sediment within the channel, trapped by the vegetation. The quantitative data on the vegetation patterns of the channel, available for the first and third scenarios, indicated a high increase in the percentage of vegetation cover in the fluvial bars of the channel between both scenarios. This information was extrapolated to the second scenario on a qualitative scale. For the vegetation in the channel and the organic carbon stock of the fluvial sediments, the second scenario was considered to have a value intermediate between those of the first and third scenarios. This is because of the absence of alluvial wedges behind the check-dams in the second scenario. These alluvial wedges behave as small wetlands with high vegetation covers and soil organic carbon stocks (Boix-Fayos et al., 2009).

The connectivity index used was developed by Quiñonero-Rubio et al. (2013) and gives an indication of the connectivity of the sediment

Table 3
Effects table.

Group of ES and other effects	ESs	Indicators/Effects	Cost (C) or Benefit (B)	Unit	Standardization method	Traditional landscape	Green landscape	Maximum restoration
Supporting	Soil conditions	Soil organic carbon	B	tn	maximum	96071.94	118,582	118,582
		Standardization				0.81	1	1
		Forest area	B	%	maximum	9.61	29.23	29.23
		Standardization				0.33	1	1
Regulating	Erosion control	Sediment yield	C	tn	concave	1123	632	137
		Standardization				0	0.93	1
		Gully erosion control	B	0/+ + +	maximum	+ + +	+ +/+ + +	+
		Standardization				1	0.83	0.33
		Bank erosion control	B	0/+ + +	maximum	+ + +	+ +/+ + +	+
		Standardization				1	0.83	0.33
		Channel erosion control	B	0/+ + +	maximum	+ + +	+ +/+ + +	+
		Standardization				1	0.83	0.33
	Climate regulation	Carbon storage in sediments	B	0/+ + +	maximum	+	+ +	+ + +
		Standardization				0.33	0.67	1
	Moderation of extreme events	Check-dams network	B	Number	maximum	0	0	120
		Standardization				0	0	1
		Channel vegetation	B	0/+ + +	maximum	+	+ +	+ + +
		Standardization				0.33	0.67	1
		Connectivity of channels	C	adimensional	maximum	0.12	0.031	0.029
		Standardization				0	0.74	0.76
Provisioning	Water provisioning	Water discharge	C	0/+ + +	maximum	+	+ +/+ + +	+ + +
		Standardization				0.33	0.83	1
		Runoff coefficient	C	adimensional	concave	0.14	0.08	0.08
		Standardization				0	0.92	0.92
Economic		Cost of restoration	C	€	maximum	0	80	135
		Standardization				1	0.41	0

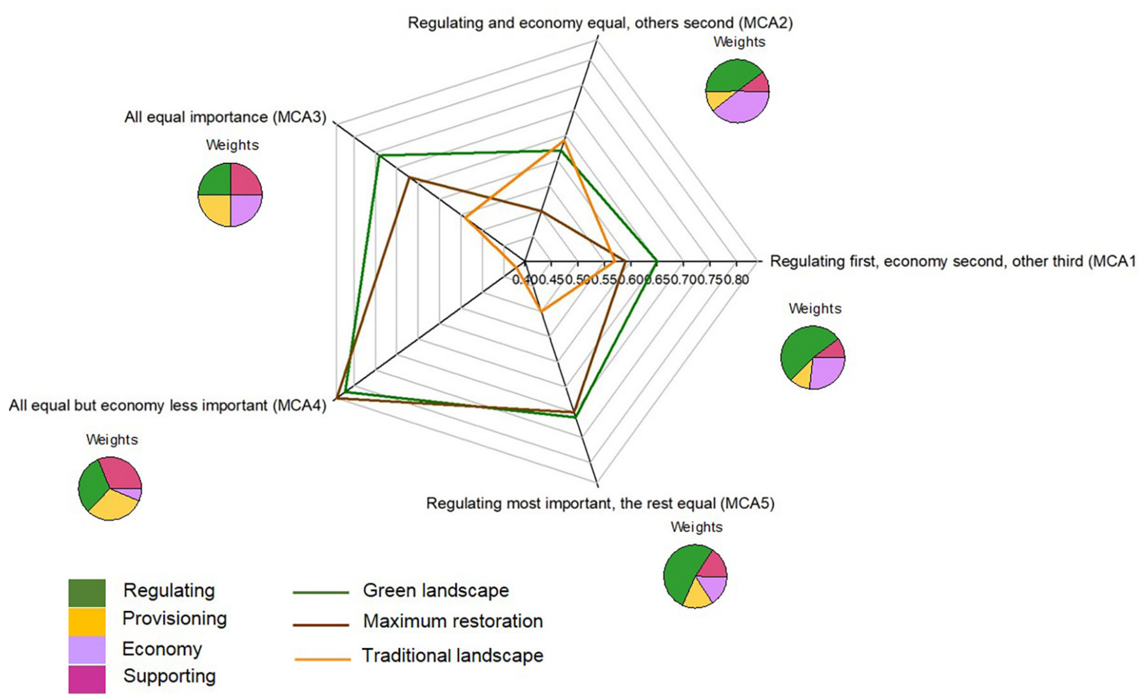

Fig. 5. Performance of the three management scenarios considering different distributions of weights.

flowing through the channel; the higher the index the higher the connectivity, which is considered a cost in relation to moderation of extreme events. This index takes into account fluvial hydrogeomorphological features and human impacts. Data on the connectivity index were available for the three proposed scenarios. The traditional scenario had the highest value and the third scenario, with check-dams, showed the lowest connectivity of sediments. Reservoir sediment yield may increase under high connectivity decreasing the capacity of the reservoir.

From the group of provisioning ES, water provisioning was characterized by water discharge and runoff coefficients as proxies, representing the water flow at the outlet of the catchment. Data were available for the first (69.16 ± 32.06 mm) and third scenarios (36.56 ± 10.62 mm; Pérez-Cutillas et al., 2018), and extrapolated with a 0/+ scale for the second scenario. Both proxies were considered as a cost in this case; lower runoff and discharge mean a higher infiltration capacity and higher recharge of the aquifers. In this case, this is favourable for local water provisioning, regulation of floods, and erosion control. For the third scenario, both the runoff on the slopes and the water discharge at the outlet are much lower, due to the higher infiltration capacities of the soils on the slopes that have a much more continuous vegetation cover. Also, in the channel, increases in the vegetation cover and in the number of check-dams favour infiltration and percolation.

Finally, an economic evaluation criterion was added. This included an estimate of the average costs of restoration per hectare, based on the values of several restoration projects, including reforestations and construction of check-dams, as analysed in Quiñonero-Rubio et al. (2016). The third scenario was 40% more expensive than the second, while the first scenario did not have restoration costs. No information related to the possible economic benefits (generation of temporal jobs) associated to the scenarios could be found. However it could be important to include it in future evaluations, together with the medium-long term positive economic impact of the restored landscapes (i.e. generation of tourist activities, natural protection figures).

4.2. General comparison of the scenarios

A general comparison of the management scenarios (Fig. 5) shows that the “Traditional landscape” was very different from the other two scenarios, having the lowest score for all the weight combinations – with one exception, when the economy and regulating ES had equal maximum weights relative to the other groups of ES (MCA2, Fig. 5). From the other combinations of weights (MCA1, MCA3 and MCA5, Fig. 5), “Green landscape” performed better than “Maximum restoration”. It was only in one weight combination with equal weights for all ES and a very low weight for economy (MCA4, Fig. 5) that “Maximum restoration” performed slightly better than “Green landscape”.

4.3. Detailed analysis of scenarios

Fig. 6 shows in detail the scores of the different scenarios for the different groups of ES and the final score taking into account the different weights. The scenarios “Maximum restoration” and “Green landscape” obtained the maximum scores for supporting ES (both 1). Those were very similar for regulating ES (0.74 and 0.66, respectively), and had a very similar performance also for provisioning ES (0.96 and 0.87, respectively). “Traditional landscape” performed much worse for supporting, regulating, and provisioning ES, but had the highest score for economy because it does not involve expenditure on reforestation and hydrological correction works. In economic terms, “Green landscape” was also a much better scenario than “Maximum restoration”.

When the largest weight was given to the regulating ES (MCA1, MCA5, Fig. 6), “Green landscape” was the best scenario, followed very closely by “Maximum restoration”. When the weights were balanced, distributed among all groups of ES (MCA3, Fig. 6), “Green landscape” was still the best scenario, closely followed by “Maximum restoration”. When economy was a priority at the same level as regulating ES (MCA2, Fig. 6), “Traditional landscape” was the best option, closely followed by “Green landscape”. When economy had a very low weight in the analysis, “Maximum restoration” (MCA4, Fig. 6) was the best option, almost at the same level as “Green landscape”.

4.4. Sensitivity analysis

The difference between the original weights of the effects and their reversal points indicates how stable each scenario is for that group of effects. When this difference is close to 0, it indicates instability, because a small change in the weight results in rank reversal of the scenarios. Fig. 7A shows the difference between original weights and reversal points for each MCA at which the first scenario losses its position. MCA3, with equal weights for all groups of effects, seems to represent the most stable first scenario because of the higher difference of weights for almost all the groups of effects. With MCA3 “Green Landscape” is the best scenario. MCA1 considering regulating first, economy second, seems also quite stable and identifies “Green landscape” as the best

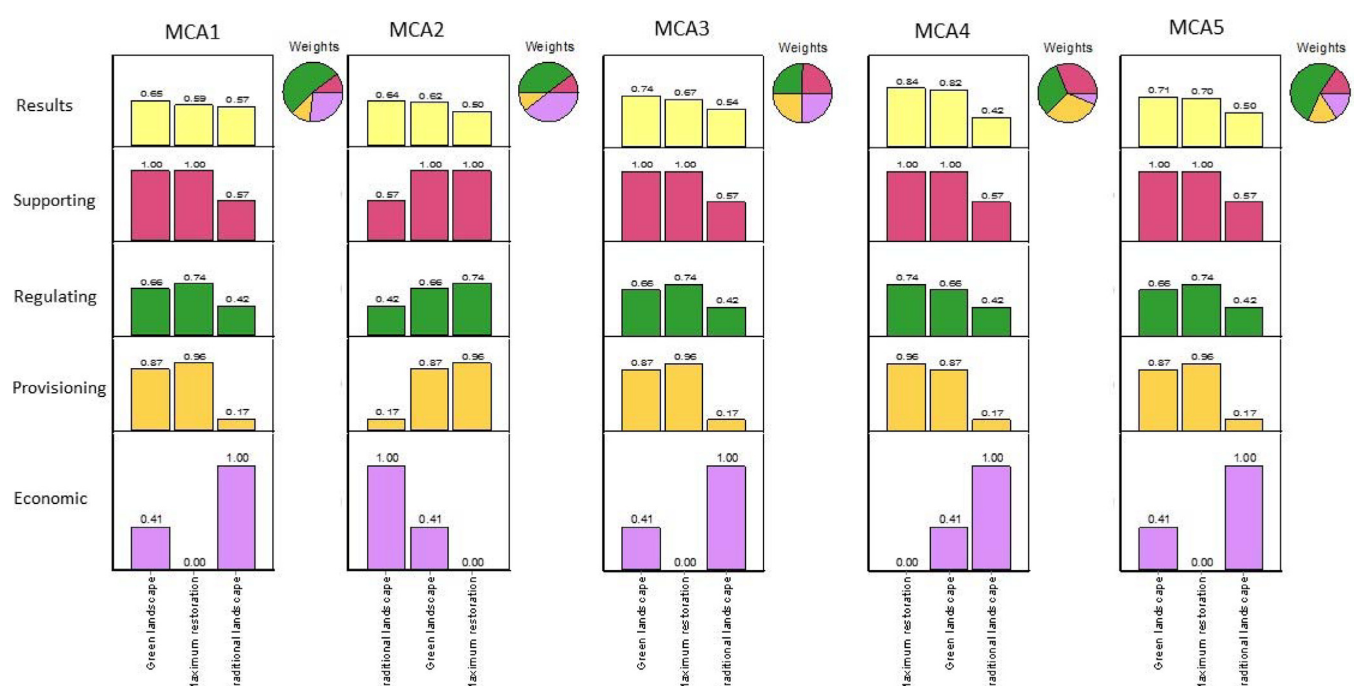

Fig. 6. Scores of the different scenarios with different weight combinations (Pink: supporting ES; Green: regulating ES; Yellow: provisioning ES; Purple Economic effects).

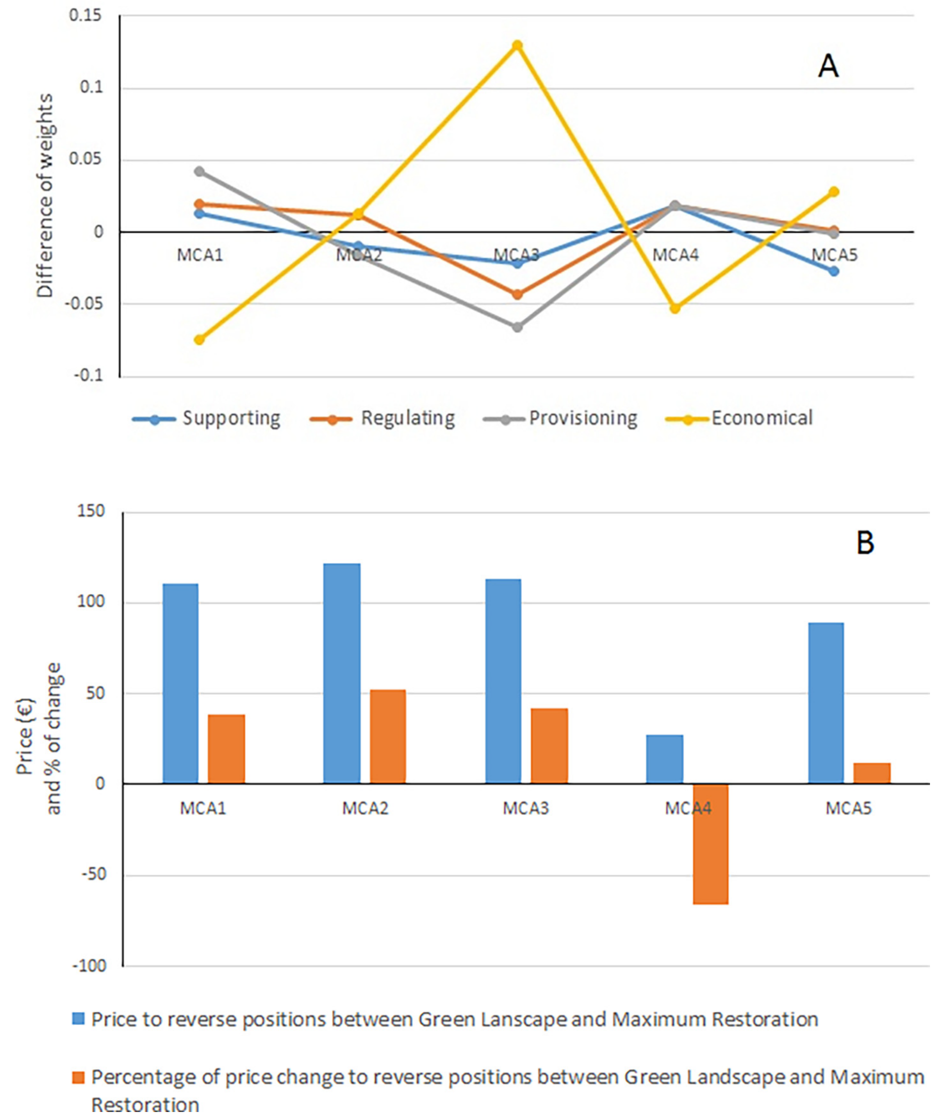

Fig. 7. A. Difference between the original weights for the main groups of ES and the reversal points of the weights at which the first scenario in each MCA loses its position B. Stability of the effect "cost of restoration" to reverse positions of Green landscape and Maximum restoration alternatives. At lower % of change of the price, lower stability.

scenario. MCA2 (Regulating and economy equal, others second, first scenario "Traditional landscape"), MCA4 (all equal but economy less important, first scenario "Maximum restoration") and MCA5 (regulating most important, the rest equal, first scenario "Green landscape") are less stable with differences between weights close to 0.

The scenarios "Green landscape" and "Maximum restoration" obtain equal scores for Supporting ES (Fig. 6) and almost the same scores for Provisioning and Regulating ES (Fig. 6). Thus, the economic criterion is key to take decisions. In this sense we tested the stability of the score of the economic criterion to reverse the position of both alternatives (Fig. 7B) in the ranking. The analysis shows that "Green landscape" is quite a stable scenario for MCA1, MCA2 and MCA3, because a quite important increase of the restoration price had to happen for "Maximum restoration" becoming a better scenario than "Green landscape" (increases from 80 €/ha to 111–122 €/ha; Fig. 7B). However for MCA4, the scenario "Green landscape" would have to lower its cost from 80 to 27 €/ha to be preferred to "Maximum restoration". Also with only an increase from 80 to 89.65 €/ha in MCA5, "Maximum restoration" becomes a better scenario than "Green landscape".

4.5. Value tree analysis of management plans and interviews with managers

Two value trees – of the analysis of the management plans (A) and the interviews with the managers (B), respectively – were combined in the common value tree presented in Fig. 8. The first value tree (Fig. 8A) was used to derive the weights for the MCA (Section 3.3). The second (Fig. 8B) was based on the analysis of the answers of the managers in the interviews, after reading the technical summary of the MCA results. The idea was to compare if there was an evolution from the values of the management plans to the actual views, expressed by the managers and technicians based on their experiences and after reading the technical report. From this information, we identified barriers and opportunities for the optimization of the use of reforestation and hydrological control works, those are integrated in the common value tree (Fig. 8).

The managers and the management plans shared similar values regarding the protection of infrastructures and hydrological and erosion control. In addition, the managers expressed high interest in the evaluation of the impacts of hydrological control works and in the use of green infrastructure. For the optimization of the use of reforestation and hydrological control works the main barriers identified were in relation to the specific focus of each management plan. The

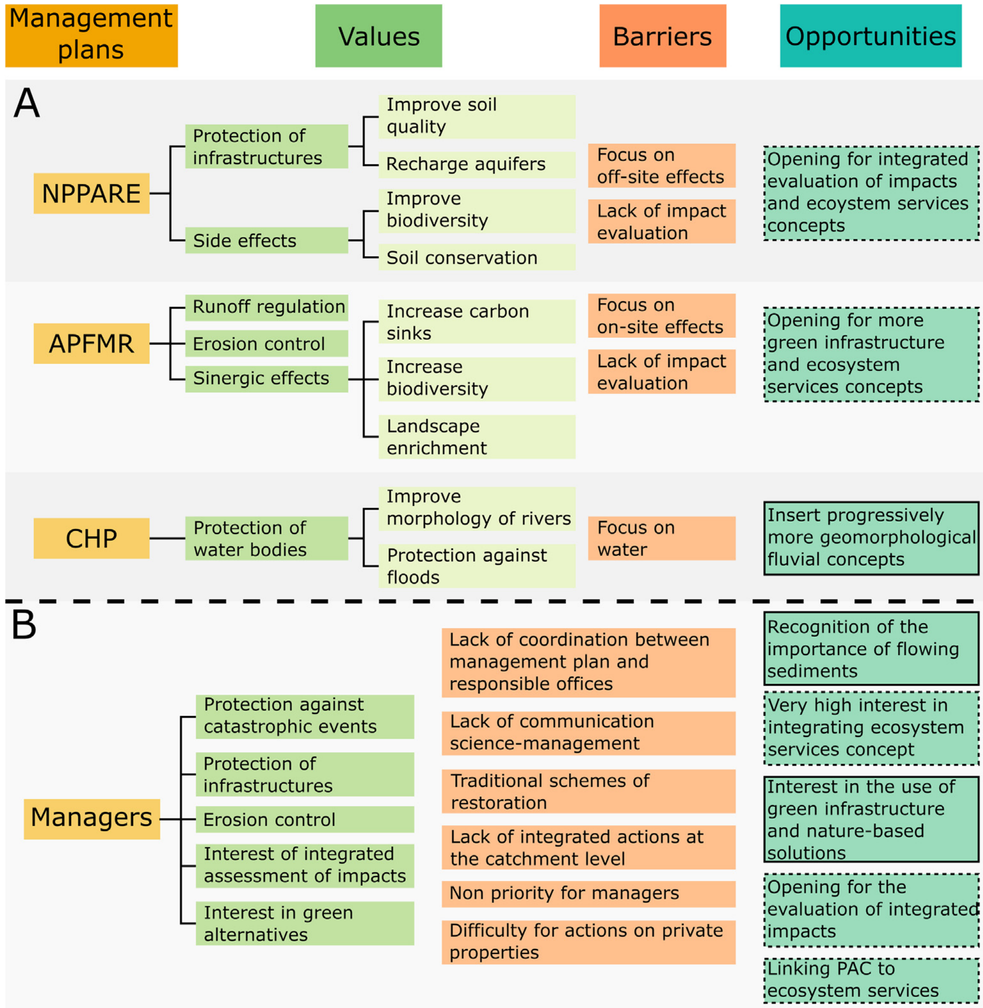

Fig. 8. Value tree and identification of barriers and opportunities related to the use of reforestation and hydrological control works. The value tree is a combination of two value trees: (i) one based on the analysis of the management plans for the area as explained in Section 2.2 (A), and (ii) one based on the interviews with managers (B). The boxes with a dashed border identify opportunities in relation to better integration of the ES concept. The boxes with a continuous border identify opportunities for the introduction of geomorphological concepts and impacts with the use of reforestation and hydrological control works.

management plans constrained the use of those measures for sediment control, disregarding benefits for additional ES, and all of them lacked an evaluation of the impacts.

The interviews with the managers revealed many more barriers to the optimization of reforestation and hydrological control works: a lack of coordination of administration offices at the different political levels, a low priority for such measures in the agenda of managers, a lack of integrated actions at the catchment level, partially due to difficulties in undertaking actions on private properties, and a lack of communication between scientists and managers regarding the use of traditional restoration schemes.

The value tree analysis and the identification of barriers allowed us to distinguish common grounds for opportunities. These were mentioned in different ways during the interviews and were also identified in the management plans. There is a convergence on two subjects: (i) integration of the ES concept in relation to the reforestation and hydrological control works (grey boxes in Fig. 8) and (ii) the introduction of geomorphological impacts and concepts with the use of these measures (white boxes in Fig. 8).

5. Discussion

5.1. The importance of impact assessments for evaluation and design of new management plans

The management plans analysed in this study and the interviews with the stakeholders revealed that:

(i) The ES concept (mentioned in different ways as synergies or side effects) underlies the management plans. However, it is not yet fully incorporated regarding the planning and implementation of hydrological control works and reforestations.
(ii) The scientific state of the art in relation to the ecological and geomorphological impacts of hydrological control works and reforestation is not fully known among managers and is not incorporated into the new plans.
(iii) There is a clear demand for more scientific support to “decision makers”, managers, and technicians regarding the optimization of hydrological control and reforestation plans.

Decision science can help to fill the gap between science and decision makers, detecting how to incorporate scientific results into the decision making process (von Winterfeldt, 2013). This author postulates that the decision making process is based on ‘beliefs’ and ‘values’.

Beliefs are understood as perceptions of reality, facts, and opinions that should be informed by science. Values are understood as the sense of what needs to be achieved, goals, objectives, and associated trade-offs (von Winterfeldt, 2013). So, it is a challenge for the scientific community to influence the decision making process by influencing the beliefs of decision makers (von Winterfeldt, 2013).

In this process of bridging the gap between science and decision makers, MCA techniques could help the incorporation of stakeholder perspectives at different stages during the process. In this case study, the managerś perspective was incorporated first during the definition of the MCA, adopting different weights, and secondly in the results validation phase. MCA techniques have been widely applied in diverse forest problems (Diaz-Balteiro and Romero, 2008). Some authors have even combined MCA decision making and group decision making (GDM) to resolve complex forestry problems in which different social groups or stakeholders perceived the relative importance of the criteria used in different ways. Hence, the joint use of approaches and techniques has turned out to be an important tool for a variety of forestry problems (Diaz-Balteiro and Romero, 2008). The application of MCA techniques for ES is being incorporated progressively at the scientific level (Eggers et al., 2017; Blattert et al., 2017; Derak et al., 2017; Diaz-Balteiro et al., 2017), although ES approaches have not been incorporated fully at the management level.

MCA has been used already to obtain a classification of a set of land uses according to their contribution to the provision of vital ES (Koschkeet al., 2012; Fontana et al., 2013). However, like other models, MCA represents a simplification and an abstraction from the real system (Munda, 2004), and operational validity is needed to check the agreement between MCA outputs and the real system (Dodgson et al., 2001). Here, validation was performed by consulting the stakeholders involved. This validation confirmed the coherence of the results, but also pointed out the complexity of the management situations and the difficulties in capturing all the angles of this complexity in a MCA. It helped also to identify the barriers to and the opportunities for the optimization of the use of hydrological control works to regulate water and sediment fluxes, and value the benefits and tradeoffs for other ES.

5.2. Assessing multiple impacts of hydrological control works and reforestations

Reforestations and hydrological control works are carried out by public institutions to regulate fluxes of water and sediments, achieve soil and water conservation, and protect downstream infrastructures. Both have many additional impacts on the landscape, on fluvial geomorphological processes (Boix-Fayos et al., 2007; Fortugno et al., 2017; Quiñonero-Rubio et al., 2016; Simon and Darby, 2002), and on the ecology of catchments (Bombino et al., 2014). Many managers are not aware of the multiple impacts of such measures on the fluvial system and on the landscape, as was perceived in the interviews carried out. Therefore, the benefits and the tradeoffs of the impacts are not taken into account during planning activities. This lack of awareness and knowledge regarding multiple impacts explains why, in forestry and agricultural planning interventions, those related to carbon cycles, aesthetics, and biodiversity are very often not considered (Cortina et al., 2011).

Two examples of the impacts of hydrological control works included in our MCA, one positive (i) and one negative (ii, trade-offs), are:

(i) One of the main problems of intensive interventions in the landscape is the drastic alteration of the water and sediment dynamics, in some cases involving the change from one specific fluvial dynamics to another. For instance, excessive control of sediment fluxes can lead to sediment and water deficit in fluvial channels, triggering, in the medium term, other erosion processes such as bank erosion and channel erosion. These massive erosion processes introduce large amounts of sediments into the channel and change the channel morphology (Simon and Darby, 2002; Kondolf et al., 2002; Stott and Mount, 2004). Several examples can be seen around Europe (Keesstra et al., 2005; Boix-Fayos et al., 2007; Beck et al., 2009; Quiñonero-Rubio et al., 2016) and in China, where the success of the ecological restoration of the Yellow river resulted in a severe deficit of water and sediment (Fu et al., 2017). Such effects could be taken into account and prevented in specific cases, by adapting the type and quantity of the restoration or hydrological control works.

(ii) Sediments deposited within fluvial channel areas, in particular the sediments trapped by check-dams, are able to induce carbon sequestration if climatic conditions are favorable. The channel deposits can have organic carbon concentrations similar to those of forest or shrubland soils, and large organic carbon stocks due to the accumulation in deep sediment layers. The sediments trapped by the check-dams are not very far from their original sources, have not travelled long distances, and are not excessively selected; this means that they preserve some aggregate structures able to protect the organic carbon bound to the mineral fraction (Boix-Fayos et al., 2015; Martínez-Mena et al., 2019). Upon their deposition and the stabilization of the fluvial dynamics, due to sediment reduction in the fluvial network, vegetation colonizes the deposited sediments. Fresh organic carbon inputs from plant litter, roots and exudates enter the sediments, inducing processes of pedogenesis – which are able, in the medium to long term, to convert sediments into early stage-soils, while enhancing carbon sequestration processes and stabilising the sediments (Boix-Fayos et al., 2015; Martínez-Mena et al., 2019; Arce et al., 2019).

5.3. Use of grey and green infrastructures for several ES, depending on the local conditions

In this study we have compared two historical scenarios ("Traditional landscape" and "Maximum restoration") with a virtual one, "Green landscape", as an exercise to understand the benefits and tradeoffs of past or potential decisions with regard to ES. The objective was to evaluate and learn from past situations. It was an attempt to understand the multiple impacts of management scenarios on ES, as a concept to consider it in real decision processes.

The "Maximum restoration" and "Green landscape" scenarios had very similar performances – specifically for "regulating ES", but also obtained not very different scores for Provisioning and Supporting ES. Although in five of the analysis, "Green landscape" obtains a better position in the ranking than "Maximum restoration". This could be seen also from the results of the sensitivity analysis carried out, where in some cases just small changes in the weights can result in an exchange of the positions in the ranking of the alternatives. As well as the use of different MCA methods (Supplementary material 4) can result in slightly different rankings. However, when taking into account economy, "Green landscape" was a better scenario than "Maximum restoration". In general, "Green landscape" could achieve almost the same regulating objectives as "Maximum restoration" but at a lower cost. This supports the idea that vegetation restoration and nature based solutions are more sustainable economically and as long term solutions. Hydrological control works serve better for specific problems and as short-term solutions, but often at a higher economic cost.

Very often, when on-site evaluations of check-dams are carried out they focus on their condition (scour, undercut, fractures and displacement, risk of destruction in case of extreme events) (Romang et al., 2003). In the case of restoration programs including check-dams and reforestation, the evaluations refer to the success of the establishment of the vegetation and to the control of the sediments flowing in the channels. For example, in the Carrión river, located in a badland landscape in Spain, a great success of the restoration works was reported eight decades later (Hevia et al., 2014). The vegetation cover was more than 90%, there were 100 check-dams, and the sediment concentration in the river had decreased by three orders of magnitude. Such on-site specific evaluations are necessary and relevant but also perspective-limited. They can be the starting point for evaluations of multiple impacts, including off-site effects, impacts on other ES and economic impacts, to aid future management.

Recently, some authors underlined the importance of looking for a balance between the cost and effectiveness of restoration methods, taking into account side-effects (Piton et al., 2016; Quiñonero-Rubio et al., 2016). In many mountain areas hundreds of check-dams have been inherited, as emblematic structures aiming to control geomorphological forces. To decide how such structures need to be managed in the future, we need to know their impacts and if the circumstances have changed. Therefore, Piton et al. (2016) proposed a revision of the function of the check-dams. They explained that decision makers must base their decisions on the risk of each scenario, taking into account existing structures and their effects. In some cases, the risk of check-dams collapse, causing massive introduction of sediments into the catchments, needs to be included. This is relevant because of the catastrophic situations that the redistribution of such sediments could cause (Alcoverro et al., 1999; Boardman and Foster, 2011).

Determining the functions of check-dams is key to the decision process. It is not always easy to specify these functions because the watershed dynamics may have changed since the construction period, as in our case study in the Upper Taibilla catchment. In addition to changes in the landscape and fluvial dynamics in a decadal time frame, the importance of the sediment cascade (Boix-Fayos et al., 2015; Fortugno et al., 2017) and continuity within the river system is better understood now (Piton et al., 2016).

Very often, low cost restoration methods can result in high effectiveness. Wang et al. (2016) found that the disparity of the conservation costs was much larger than that of the ecological benefits when comparing four conservation methods in China. They concluded that closing hillsides for afforestation was the most cost-effective scheme. Over decades and as a result of political, management, and socio-economic decisions or climate change, landscapes can change, as in our example, and thus the objectives of regulating water and sediment flows must change also (Piton et al., 2016).

Wang et al. (2016) explained how conservation does not need to be enforced at all costs. They even postulated that a certain level of environmental degradation is permissible, and even necessary, because there are many objectives including economic development, social welfare, and equity, that may conflict and trade-offs have to be made. This stresses the need for integrated landscape planning considering multiple landscape functions. With this pilot study, we aim to put some of the newly identified ES functions into perspective to help the decision making process and support integrated landscape planning.

6. Conclusions

The effects of hydrological control works go beyond the specific functions that they were designed for. The incorporation of multiple impacts of hydrological control works into the evaluation of various management scenarios allowed us to obtain an insight into their performance regarding various ES and to compare their stability. The results helped us to understand different dimensions regarding the benefits and trade-offs of the use of check-dams and reforestations in catchment management. This type of analysis can help more robust decision making regarding the selection of management scenarios and integrated landuse planning, by incorporating scientific knowledge as well as stakeholder preferences. Our results illustrate for example, how the incorporation of geomorphological concepts and organic carbon dynamics of soils and sediments are crucial and need to be taken into account when analyzing the multiple impacts of hydrological control works on ES.

Our results show that solutions that respect the landscape and ecological dynamics are equally effective but more sustainable at a lower cost in the medium and long term than solutions including large-scale grey infrastructures based on check dams. Each management scenario has to be adapted to the local environmental conditions and the specific objectives of the restoration or hydrological control works. Tailor-made management scenarios, taking into account local environmental and socioeconomic conditions and specific management objectives can optimize resources and achieve medium to long term sustainability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2020.101136.

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