Ferrari, M., et al., 2016, "Analysis of Bundles and Drivers of Change of Multiple Ecosystem Services in an Alpine Region", *Journal of Environmental Assessment Policy and Management,* vol. 18, no. 04, pp. 1650026.

Available at http://dx.doi.org/10.1142/S1464333216500265

(Article begins on next page)

Journal of Environmental Assessment Policy and Management

Analysis of bundles and drivers of change of multiple ecosystem services in an Alpine region

--Manuscript Draft--

Manuscript Number:	JEAPM-D-16-00061R1
Full Title:	Analysis of bundles and drivers of change of multiple ecosystem services in an Alpine region
Article Type:	Research Paper
Keywords:	Ecosystem services; bundles; drivers of change; principal components; cluster analysis; Alpine region
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Abstract:	Approaches based on the concept of the ecosystem services need analyses of the sets of spatially correlated services (i.e. bundles) and of the external factors that modify the ecosystem service supply (i.e. drivers of change). At present, appropriate methods to analyze bundles and drivers of change are still under development. This study proposes a method based on a combination of spatial and statistical analyses to define bundles and to explain the drivers of change of 24 ecosystem services in Trentino, an Alpine region of Italy. Results show that multiple services can be grouped in a few number of bundles with a complex shape. When mapping multiple services across the territory, the spatial units of representation are a combination of the intrinsic units of representation of single ecosystem services and land use classes. Land use management was found as the external factor that causes the greatest variability of the ecosystem services distribution across the region.
Response to Reviewers:	 MANUSCRIPT From line 100 to line 110: I inserted the explanation for PCA as requested In inserted the minor edits: *Abstract: When mapping multiple services......a combination the metric units.....- change to a combination "of" metric units *line 18 First there is not general agreement.... - change "not" to "no" *line 34 Maes et al (2011b) considered the supply of 13 sevices for all Europe ...- change "all" Europe to "the whole of" Europe *line 36 bundles definition - change "bundles" to "bundles'" *line 46 the region .....above "sea level" - change to "above sea level (a.s.l)" *line 84 Principal component - change to small "p"

	*line 86 According to Pheniger et al (2013), in clusters are..... - remove "in" *line 171 the theoretical rational of "PCA" - change to "Principal Component Analysis (PCA)" since this is the first time the abbreviation PCA is used, so the full wording should be stated *line 203 Table 3, first "raw" - change to "row" *line 205 Table 3, second "raw" - change to "row" *line 216 ...bundles, "expect" - change to "except" *line 218 ....bundles, "expect" - change to "except" *290 Such results confirm "what found by"..... - change to "what was found by" TABLES I adjusted the order of the tables: Table 2 becomes Table 3; Table 3 becomes Table 4; old Table 4 becomes Table 2 Table 4 (before 3): I added a note to define the meaning of the bolded text. FIGURE Figure 2 – I removed the reference to the 'red arrow' and I used greyscale

1 Introduction

Understanding the interaction among multiple ecosystem services in a landscape provides key information to guide land use planning and management decisions (Daily & Matson 2008; Bennet et al. 2009). While the science of single ecosystem services assessment is improving (Martínez-Harmsa and Balvanera P. 2012), and interactions among ecosystem services are being increasingly explored (e.g. Raudsepp-Hearne et al. 2009; Maes et al. 2011b; Qiu and Turner 2013), appropriate methods to analyze bundles and drivers of change of ecosystem services are still under development (Anton et al. 2010).

Bundles of ecosystem services are sets of spatially correlated services (Bennet et al. 2009; Raudsepp-Hearne et al. 2009), which have been mainly identified by clustering the ecosystem services, and analysing the spatial distribution of clusters and the distribution of the ecosystem services across clusters (Raudsepp-Hearne et al. 2009; Plieninger et al. 2013). Drivers of change are defined as the external factors that directly or indirectly modify ecosystems and their capacity to provide services (MA 2005, Hodder et al. 2014). Spatial and statistical techniques are often employed to analyse bundles and drivers of change (Plieninger et al. 2013). However, similar approaches have two main limitations. First, there is no general agreement about what specific aspects must be investigated through these techniques. For example, in order to demonstrate that drivers causing the variance of ecosystem services across the region are of social and ecological type, Raudsepp-Hearne et al. (2009) and Maskel et al. (2013) looked at correlated ecosystem services in their principal components, while Maes et al. (2012a) looked at the correlations of the first three principal components with land use classes. Both analyses should be considered together when studying the drivers of change. Second, simplifications are introduced on the analysis of the ecosystem services, for example by limiting the number of services and assessing them by mapping information over the same spatial units (e.g. administrative areas), without considering the spatial heterogeneity of the ecosystem services distribution (like the distribution of water supply services over basins and of the agricultural services over agricultural areas). For example, Raudsepp-Hearne et al. (2009) considered the supply of 12 services, whose assessment indicators were mapped over administrative areas. Plieninger et al. (2013) considered the demand for 13 cultural services, whose indicators were mapped over land use classes. Maes et al. (2011b) considered the supply of 13 services for the whole of Europe, mapping them over territorial units for the European countries. According to Carpenter et al. (2006), such simplifications may strongly affect the bundles' definition and the identification of drivers of change.

The objective of this paper is to present a method to analyze bundles and drivers of change of multiple ecosystem services, by considering the spatial heterogeneity in the services distribution. In particular, two research questions are addressed:

- How are the ecosystem services distributed across bundles?
- What are the drivers of change that may influence the distribution of the ecosystem services across the region?

2 Study area

The study area is the Trentino region, located in the Italian Alps (see Figure 1). Across the region the elevation ranges from 62 to 3,343m above sea level (a.s.l.), with about 30% of the area under 1000m, 50% between 1,000 and 2,000m and 20% over 2000 m. Areas over 2000m are covered by glaciers, bare rocks, natural grasslands and pastures. Forests cover about 56% of Trentino and are found up to about 1800 m a.s.l.. Agricultural areas cover 5.8% of the whole region, while artificial surfaces (i.e. urban settlements and roads) cover 3.1% of the region. Urban settlements are located along the main valley floors and host about 500,000 people. For each valley there is a major urban settlement but several small villages and scattered houses are found across the entire region. The area occupies 14 catchments, and the lateral major rivers follow east-west or west-east directions to the major river, Adige. More than 300 lakes are found including the northern part of Lake Garda, the largest lake of Italy.

Such variety of the territory ensures the provision of several ecosystem services. Based on the list provided in Maes et al. (2011b), 24 ecosystem services were identified as the most important in the region, according to an expert survey described in Ferrari (2014). Each ecosystem service was assessed through an indicator (see Table 1). Indicators were identified through the same expert’s survey by considering two criteria: indicators must measure the actual biophysical value of the ecosystem service (as proposed in Plieninger et al. 2013), and must take into account the spatial heterogeneity of the service distribution. Hence, different indicators were mapped over different specific spatial units, such as cadastral parcels and forest types (Table 1).

For example, the e provisioning service "Agriculture production" was assessed through the indicator "Quantity of agricultural products", that measures the amount of the annual agricultural production (in quintals) for each agriculture type per hectare. It was mapped over cadastral parcels. The regulating service "Macro-Climate regulation" was assessed through the "Carbon stock" indicator, which measures the carbon (in tons and per hectare) stored annually by forests, grass/grasslands and tree cultivations. It was mapped over agricultural areas and forests. Finally, the cultural service "Scenic beauty" was assessed through the indicator "Landscape visibility", which measures the visibility of sites of particular landscape interest up to 10 km of distance.

3 Method

Bundles are firstly identified according to Plieninger et al. (2013) through a cluster analyses on ecosystem services (see Section 3.1). Then, the distribution of the bundles across the region and of ecosystem services across the bundles are investigated by analysing shape, correlation, spatial and aggregation pattern analyses (Section 3.2). The way drivers of change influence the distribution of ecosystem services are assessed by correlation analyses (Section 3.3).

3.1 Identification of ecosystem services bundles

A hierarchical cluster analysis (Kaufman & Rousseeuw 1990) is performed on the principal components (Pearson, 1901) of the ecosystem services indicators, coupled with an ANalysis Of SIMilarity (ANOSIM, Clarke 1993), in order to identify the proper number of clusters. According to Plieninger et al. (2013), clusters are the representation of the ecosystem services bundles.

The hierarchical cluster analysis is a technique to assign statistical units to one of multiple classes (i.e. clusters), based on the values of those units for different variables. In this way, the units of the same class are more similar to each other than units in any other class. Similarity is measured by Euclidean distance and clusters are compacted by Ward's method (Ward 1963). In clustering, significant principal components may be used instead of original variables (i.e. ecosystem services indicators) in order to avoid computational problems that may arise from a high number of input variables (in accordance with Plieninger et al. 2013). The principal components of ecosystem service indicators are independent variables which can measure the extent to which the values of ecosystem services change over their specific spatial units (i.e. the variance of the ecosystem services across the region). Principal components are obtained by a Principal Component Analysis (PCA, Pearson, 1901). PCA is a multivariate ordination technique that linearly combines input variables to generate new independent variables, i.e. the principal components. Each principal component measures a part of the variance of the original dataset. To be significant, the principal components must be able to measure at least the variance of one single input variable. From the mathematical point of view, this means that the variance of the new variables (the so called "*eigenvalue*" of the principal component) must be greater than 1. PCA guarantees that the number of principal components with variance greater than 1 is always smaller than the number of original variables and just a narrow set of principal components is enough to explain the most of the variance. The weights by which each original variable must be multiplied to get the principal components are called *loadings*.

The proper number of clusters is identified through the ANOSIM analysis. This technique considers the similarity of the samples among and within classes: the measure of similarity (R) is the difference of mean ranks of statistical units between and within clusters. R ranges from -1 to 1; 0 means no similarity and completely random clustering, while 1 means that all pairs of samples within clusters are more similar than to any pair from different clusters. The choice of the proper number of clusters is made looking at clustering that maximizes R.

This cluster analysis produces a map of ecosystem services bundles.

3.2 Explanation of ecosystem services bundles

Firstly, an analysis of the spatial distribution of bundles is conducted. The analysis aims at explaining the shape of bundles (dimension and degree of fragmentation of bundle patches), and the spatial correlation of bundles with three driving variables: elevation, catchments shape and land use.

Shape analysis. It consists in the computation of the area, of the total number of bundle patches, of the minimum, maximum and mean patch area, and of the fragmentation index for each bundle.

Correlation analysis between bundles and driving variables. Spearman statistical correlations between the bundles and the driving variables are computed in order to verify whether the bundle distribution follows the distribution of altitude, catchments shape, or land use classes. Following the method proposed in Maes et al. (2012a), we firstly calculate the Spearman statistical correlation between the clusters and the explanatory variables. Spearman correlation measures the degree of dependence between two variables. The output of the Spearman correlation analysis is a correlation coefficient (ρ) ranging between -1 and 1. High absolute values correspond to high dependence between bundles and the mentioned variables, while low absolute values correspond to low dependence. We considered significant correlations when $|\rho| >= 0.3$. In order to verify whether bundles and variables are correlated also in space, the maps of bundles and explanatory variables are crossed and the percentage of each variable in bundles is calculated. It is assumed that a bundle follows the distribution of variables when the percentage is above 90%.

Secondly, the distribution of ecosystem services across bundles is analysed to explain where (i.e. in what bundle) the provision of each ecosystem services is maximum, minimum or absent, and the richness, intensity and diversity of multiple ecosystem services in single bundles.

Analysis of the distribution of bundles across ecosystem services. This analysis allows to understand how single ecosystem services are supplied over bundles, and in particular in which bundles the supply is maximum, minimum or absent. For every ecosystem service indicator we calculate the normalized value (to maximum value). In every bundle we show the distribution of the normalized value by radar charts.

Aggregation patterns analysis. It is carried out in order to understand how multiple ecosystem services are supplied over bundles, and in particular in which bundle the richness, intensity and diversity of multiple ecosystem services are maximum, minimum or absent. We compute and map indices of richness, intensity and diversity (Shannon index), as proposed by Plieninger et al. (2013). Richness counts the number of ecosystem services that are present in each cluster (values of the service supply greater than zero); intensity sums the normalized values of the ecosystem services supply in every cluster.

3.3 Explanation of drivers of change

Drivers of change are characterized by means of a set of analyses aiming at the investigation of the distribution of ecosystem services across principal components (through the analysis of loadings), the distribution of principal components across bundles (through the correlation analysis between clusters the principal components) and the spatial distribution of principal components (through the correlation analysis between principal components and driving variables). The results of the analyses are then merged to explain ecosystem services changes in the territory and the drivers of such changes.

Analysis of loadings. The ecosystem services with the greatest variance are those correlated to the first principal component (PC1). The second principal component (PC2) measures the second highest variance of the ecosystem service indicators. Correlations between the ecosystem services and the principal components is proportional to the loadings of the first two principal components (Pearson, 1901). The graphical representation of ecosystem services in terms of the loadings of PC1 and PC2 is a vector, defined by a modulus and a direction (angle). We assume that the correlation between any ecosystem service and any principal component is significant when the vector modulus is greater than 0.1 and the angle between the vectors and PC1 and PC2 axes is lower than 30°.

Correlation analysis between bundles and principal components. Spearman statistical correlations between the principal components and the bundles are computed in order to identify the bundles where the greatest variance is present.

Correlation analysis between bundles and driving variables. As previously mentioned, principal components explain the variance of the ecosystem services, i.e. their variability across the region. The theoretical rationale of Principal Component Analysis (PCA) ensures that the first principal components explain most of the variance. The changes in the ecosystem services supply is assumed to be driven by external factors, the so called "drivers of change". According to existing studies (Raudsepp-Hearne et al. 2009; Maes et al. 2011a; Maskel et al. 2013), land use is the external factor driving main changes in ecosystem services values. In order to explore the influence of land use on the ecosystem services variability, we consider the Spearman correlations of the first two principal components with land use classes.

4 Results

4.1 Identification and explanation of ecosystem services bundles

First five principal components of 24 ecosystem services indicators have variance greater than 1 and they have been clustered. The hierarchies have been defined for 2 to 19 clusters (i.e. large clusters grouping samples with more dissimilar values vs. small clusters grouping samples with very similar values). According to ANOSIM, the Euclidean distance between the hierarchical classes is maximized with 11 clusters (see Figure 2). The map of ecosystem services clusters is in Figure 3. The explanation of each bundle is detailed in Table 2, according to the spatial distribution and types/values of ecosystem services. Information come from the analysis of the spatial distribution of bundles and of the distribution of ecosystem services across bundles. They are reported below.

Analysis of the spatial distribution of bundles

Shape analysis of bundles. Bundles are mapped over Trentino in Figure 3, which shows that Bundles 1 covers the majority of the forested area, while Bundles 2 corresponds to rocks and urban settlements, Bundles 3 is mainly present in the upper-eastern part, while Bundles 7 occupies preferentially the central part. Fragmentation indices highlight that Bundles 1 and Bundles 2 are the largest in area (occupying more than 40% of the region) and that the smallest are 8, 10 and 11 (occupying less than 0.1%). Bundles 2 has the highest number of patches, followed by Bundles 4. The most fragmented one is Bundles 8, while the most compact ones are 1 and 9. For details see Table 3.

Correlations with altitude. Bundles 2 shows a significant correlation (ρ = |0.4|) with altitude (96% of its area lies above 2800 m a.s.l.) as well as and Bundles 11 (all the area lies below 1000 m a.s.l.). Other bundles are homogeneously distributed across altitude (Table 4, first row).

Correlations with catchments. Catchments are not significantly correlated to clusters. However, small basins often lie in only one or two bundles (Table 4, second row). Only the Adige catchment, that occupies the central part of Trentino, includes all bundles, while Bundle 11 is only found in Adige catchment and in an eastern tributary.

Correlations with land use. Bundles 1 and 2 are correlated to land use (Table 4, third row): Bundle 1 contains more than 90% of the whole forested area and Bundle 2 contains more than 90% of glaciers and bare rocks. Furthermore, forests contain more than 90% of Bundles 3 and 11.

Analysis of the distribution of ecosystem services across bundles

Analysis of the distribution of bundles across ecosystem services. The contribution of the ecosystem services in each bundle is shown in 11 radar charts (Figure 7). For example, Agriculture production is supplied in 5 bundles (2, 4, 7, 9 and 10); the maximum provision is in Bundle 4, the minimum in Bundle 2. In all bundles, except Bundle 2, there is at least one ecosystem service with maximum provision, and in all bundles, except Bundle 3 and 8, there is at least one ecosystem service with minimum provision. Three couples of bundles have very similar types of ecosystem services:

(6,8), (1,3) and (9,10). The number of provisioning services per bundle ranges from 3 to 9 (out of 10); the number of regulating services ranges from 4 to 7 (out of 7); the number of cultural services ranges from 4 to 7 (out of 8).

Aggregation patterns analysis. Aggregation patterns show that Bundle 9 has the highest number of ecosystem services (i.e. 23 out of 25, cf. Figure 4 and Figure 5), while Bundle 8 has the lowest one (i.e. 11 out of 25). Despite that, intensity of cluster 9 is lower than the intensity of Bundle 8 (6.75 against 8.6). Highest intensity and diversity are in Bundle 3 (10.07 and 0.49 respectively, Figure 5 and Figure 6), while lowest intensity and diversity are Bundle 2 (3.49 and 0.49 respectively).

4.2 Characterization of principal components

Distribution of ecosystem services across principal components

The loadings of Figure 8 show that PC1 is highly correlated to nine ecosystem services (five provisioning, three regulating and one cultural service), while PC2 is highly correlated to four ecosystem services (two regulating and two cultural services). PC1 and PC2 are therefore able to explain 13 ecosystem services (out of 25).

Distribution of principal components across bundles

Correlations between PC1 and bundles (Table 4) are significant for Bundles 1, 2, 3, 4 and 5, while correlations between PC2 and bundles are significant for Bundles 4, 5 and 8. The ecosystem services with highest variability are in 6 bundles.

Spatial distribution of principal components

The map in Figure 9 shows that low values of PC1 correspond to forest areas, while high values to bare rocks, glaciers and urban settlements. Actually, the correlation of PC1 with land use is high ($|\rho| = 0.7$), while with altitude or catchments is not significant. PC2 does not have any significant correlation. The analysis of correlations with forest density showed that PC1 decreases for increasing values of forest density.

According to the characterization of principal components, two drivers of change affect three bundles and seven ecosystem services in Trentino. Drivers are forest management and land use management. The first driver affect bundle 1 (bundle of most common ecosystem services in forests) and bundle 3 (bundle of forest areas of high-intensity and high-diversity ecosystem services). Within the bundles, the ecosystem service affected are Honey production, Mushroom production (and collection), Fuel wood production and Macro-Climate regulation. The second driver affect bundle 4 (bundle of agricultural areas of high-intensity ecosystem services) and Agriculture production and Cultural heritage services.

5 Discussion

To date only few studies have dealt with the definition of ecosystem services bundles by means of analytical tools (e.g. Raudsepp-Hearne et al. 2009 and Plieninger et al. 2013) and even less studies have dealt with an analytical explanation of the ecosystem services variability and of the drivers causing such variability (e.g. Raudsepp-Hearne et al. 2009). Most of the available literature has formulated hypotheses on the theoretical framework of the ecosystem services bundles distribution and of drivers of change, and these topics are still an open field of research (Anton et al. 2010). The analyses proposed here allow the identification of the bundles to which each ecosystem services belongs, and of the values of such ecosystem services in the bundles. Moreover, they allow the identification of the factors that cause the main variability of ecosystem services (i.e. land use and forest management) and the specific ecosystem services on which they have great effect.

Principal components have been used here in order to avoid an a-priori selection of indicators, and a statistical criterion (ANOSIM) has been used in order to optimize the clustering. The characterization of the ecosystem services distribution across principal components by means of *loadings* is a novel application in the definition of drivers of change, as well as the computation of fragmentation indices to investigate the bundles shape. The main merit of the proposed methodology is that of having organized the analyses in a structured process where they are independent one from another. For instance, a wider set of variables (not only altitude, land use distribution, etc.) may be used to improve the knowledge about the spatial distribution of bundles.

In the present work, clusters of ecosystem services have been identified by means of a limited number of principal components and bundles have been defined through a narrow set of explanatory variables. However, the characterization of clusters is able to provide a reasonable explanation for bundles. Trentino region is characterized by a homogeneous distribution of ecosystem services, both in terms of type and value. In fact, only five bundles (i.e. less than half the number of identified bundles) are enough to represent 98% of the territory. Four of them represent forest areas, corresponding to 56% of the whole region. The fifth bundle represents poor-value ecosystem services areas, covering about 40% of the territory, and consisting in urbanized areas, bare rocks and other natural areas with low values of ecosystem services. On the other hand, small bundles correspond to areas where the supply of a single service, or of a narrow set of services, is very high with respect to other services. For instance, bundle 3 (that covers 7% of total forest areas) discriminates forests with high supply of fine-quality timber from the areas supplying the most common forest services. Such results confirm what was found by Raudsepp-Hearne et al. (2009) and by Haines-Young et al. (2012): the ecosystem services of a region group on a few number of bundles; this number is smaller than the number of spatial units on which they are mapped (municipalities in the case of Raudsepp-Hearne et al. 2009). In addition, bundles are geographically clustered and little fragmentized across the territory. Finally, poor ecosystem services areas group in one single bundle.

Drivers of change of ecosystem services have been investigated only for the first two principal components, and by means of a narrow set of explanatory variables. It was found that the supply of ecosystem services significantly changes across some forest areas due to land use management activities (and especially due to the activities involving forest loss). In particular, the highest supply variability is displayed by nine typical forest ecosystem services, which are distributed over five bundles. This is in accordance with findings of Steffan-Dewenter et al. (2007) and Haines-Young & Potschin (2010b), who demonstrated that the greatest loss of ecosystem services is associated with the initial or the complete conversion of the forest to a different ecosystem. Therefore, the study provides a solution to the problem of explaining the factors that cause the main variability of ecosystem services.

According to Dale and Polasky (2007) ecosystem services are provided within process-related landscape units such as watersheds, specific habitats, or natural units (i.e. intrinsic spatial units), and within such units, the ecosystem services values may be heterogeneous. Anderson et al. (2009) pointed out that there are few studies on which to base conclusions about the spatial relationships between habitats for different ecosystem services and benefits for biodiversity, because such studies disregard spatial heterogeneity. Syrbe and Walz (2012) stressed that this is a strong limitation for the analyses that require a spatial representation of ecosystem services. The present study attempts to consider intrinsic spatial heterogeneity for multiple ecosystem services together. The cluster analysis showed that 25 ecosystem services are represented together by 11 spatial units. It demonstrates that the intrinsic spatial heterogeneity of sets of correlated ecosystem services (they are 11 bundles) is lower than the intrinsic spatial heterogeneity of single ecosystem services (they were 20 spatial units of representation for 25 ecosystem services). According to the results, bundles are also different from the spatial units of single ecosystem services: the shape of bundles is not only a combination of spatial units, but they are also dependent on the values of single services in such units. Therefore, the number of clusters is lower than the spatial units of single ecosystem services, but their shape is more complex.

A moderate degree of correlation was found between forest bundles and land use: the only land use class that can be spatially recognized in bundles is that of forest. It demonstrates that spatial units of land use are not sufficient to represent the spatial heterogeneity of single ecosystem services, but one single spatial unit of land use (i.e. forest) is sufficient to represent the spatial heterogeneity of multiple ecosystem services.

6 Conclusions

The method proposed in this study allows the mapping of a relevant number of ecosystem services to be advanced, while accounting for the spatial heterogeneity of the ecosystem services distribution and of their values. In particular, the study provides a solution to the issue of defining the areas where sets of ecosystem services appear together, i.e. bundles, and to the issue of explaining the factors that cause the main variability of ecosystem services across the study region.

Management implications are to inform conservation efforts in the future, when there is spatial heterogeneity of the ecosystem services provision. Considering that bundles are sets of ecosystem services, their spatial representation depict areas that provide a considerable amount of ecosystem services to humans. Hence, no matter their biodiversity values, these areas could be given a protection status due to their contribution to the wellbeing of the local population.

Future research could be devoted to the identification of areas offering an optimum provision of ecosystem services and biodiversity value. In the same way, we expect that additional social and ecological conditions may affect the ecosystem services supply. For instance, demographic dynamics may influence the distribution of ecosystem services supply, as well as be oriented by it. Understanding which factors may have an actual influence requires the development of methods able to rank ecosystem services and to explain the relations between these services and the social and ecological conditions.

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TABLES

Table 1. 24 ecosystem services (ES, 2nd column) are grouped in three themes (1st column) and assessed by 24 indicators. Indicators are mapped over different spatial units (4th column).

ES theme	**ES**	**ES assessment Indicators**		
		Name (acronym)	**Unit of measurement**	**Spatial unit of representation**
Provisioning	Agriculture production	Amount of agricultural products	q ha^{-1} $year^{-1}$	Cadastral parcels
	Hunting production	Amount of hunting products	kg ha^{-1} $year^{-1}$	Game reserves
	Fishing production	Amount of fishing products	kg ha^{-1} $year^{-1}$	Fishing zones
	Mushroom production	Intensity of mushroom production	Dimensionless	Forest types
	Honey production	Intensity of honey production	Dimensionless	Areas of forest types 500 m close to forest ways
	Timber production	Amount of timber harvested	m^3 ha^{-1} $year^{-1}$	Forest lots
	Fuel wood production	Amount of fuel wood harvested	m^3 ha^{-1} $year^{-1}$	Forest lots
	Water supply from surface water network	Water consumption from surface water network	m^3 ha^{-1} $year^{-1}$	Sub-Catchments
	Water supply from groundwater	Water consumption from groundwater	m^3 ha^{-1} $year^{-1}$	Buffer of 200m around springs and wells
Regulating	Water quality regulation	Capacity of water ecosystems to reduce pollutants	Dimensionless	Buffer of 30 m around water network
	Water flow regulation	Specific discharge coefficient	m^3 s^{-1} ha^{-1}	Sub-Catchments
	Air quality regulation	Roughness of land surfaces adjacent to roads	Dimensionless	Buffer of 30 m around main roads
	Micro-Climate regulation	Ability of forests in mitigating temperature based on shape	Dimensionless	Forest patches
	Macro-Climate regulation	Carbon Stock	t ha^{-1}	Forest types and cadastral parcels of pastures, grasslands and orchards
	Hazards protection capacity	Forest watershed protection factor	Dimensionless	Grid cells
	Flood prevention capacity	Curve number	Dimensionless	Grid cells
Cultural	Cultural heritage	Proximity of cultural heritage sites to road network	Dimensionless	Grid cells
	Scenic beauty	Landscape visibility	(no. of visible points) ha^{-1}	Grid cells

Hunting	Density of hunters	(no. of hunters) ha^{-1} year^{-1}	Game reserves
Fishing	Fishing intensity	(no. of fishing activities) ha^{-1} year^{-1}	Fishing zones
Mushroom collection	Availability of mushrooms of good quality	Dimensionless	Forest types
Honey collection	Availability of honey of good quality	Dimensionless	Areas of forest types 150 m close to forest ways
Outdoor recreation	Intensity of sporting activities	(no. of sport activities) ha^{-1}	Patches of lakes, forest roads and ski slopes
Leisure	Density of recreational activities	Dimensionless	Patches of lakes and forest types

Table 2. 11 bundles are the sets of spatially correlated ecosystem services in Trentino. They are explained according to the spatial distribution and to the number, types and values of ecosystem services.

Bundles of	Spatial distribution of bundles	Number, types and values of ecosystem services in the bundles
1 **Most common ecosystem services in forests**	The bundle corresponds to 90% of forest areas of Trentino up to 2800 m a.s.l.. It is composed of few, large and little fragmented patches.	18 ecosystem services are supplied: four provisioning, seven regulating and seven cultural. They are typically of forest ecosystems. The provision is maximum for Honey production and Micro-Climate regulation services.
2 **Low-intensity and low-diversity ecosystem services**	The bundle includes 90% of the areas above 2800m a.s.l., which are essentially glaciers and bare rocks. It is composed of few, large and little fragmented patches.	The bundle covers the areas where the supply of ecosystem services is the lowest in terms of intensity and diversity. 17 services are supplied: three provisioning, seven regulating and seven cultural. With respect to other bundles, the supply is not maximum for any ecosystem service. It is minimum for five ecosystem services: Agriculture production, Micro-Climate regulation, Mushroom and Honey collection and Leisure.
3 **High-intensity and high-diversity ecosystem services in forests**	The bundle is covered for 90% by forest areas, corresponding to the forest areas of Val di Fiemme, where the use of forest services, like timber production, is very high.	18 services are supplied: five provisioning, six regulating and seven cultural. The supply is maximum for six services: Hunting, Mushroom, Honey and Timber production, Micro-Climate regulation and Hunting activity. With respect to other bundles, the supply of forest ecosystem services is the highest in terms of intensity and diversity.
4 **High-intensity ecosystem services in agriculture areas**	The bundle covers the agricultural areas up to 1000m a.s.l..	13 ecosystem services are supplied: three provisioning, six regulating and four cultural. With respect to other bundles, the supply of Agriculture production and Cultural heritage is maximum, while the supply of water regulation services (i.e. Water quality and Water flow regulation) is minimum.
5 **High-intensity recreation services in forests and over water network**	This bundle covers forest areas and fishing zones up to 2800m a.s.l..	17 ecosystem services are supplied: four provisioning, six regulating and seven cultural. With respect to other bundles, he supply of Leisure and Outdoor activities is maximum.
6 **High capacity in water regulation**	It is a small bundle composed of fragmented patches, homogeneously distributed over catchments up to 2800 m a.s.l.. It is typical of minor tributaries in the lateral valleys.	13 ecosystem services are supplied: three provisioning, five regulating and five cultural. The supply is maximum for two services: Water quality regulation and Flood prevention capacity.
7 **High-intensity human activities in semi-urbanized areas**	The bundle covers the central areas of the region, up to 1000m a.s.l.,	23 ecosystem services are supplied: eight provisioning, seven regulating and seven cultural. The supply is maximum for Hunting and Scenic beauty.
8 **Lowest number of ecosystem services and high-intensity values**	It is a small bundle composed of fragmented patches, homogeneously distributed over catchments up to 1000m a.s.l..	11 ecosystem services are supplied: three provisioning, four regulating and four cultural. With respect to other bundles, it is the less rich of ecosystem services. The supply is maximum for six ecosystem services: Hunting production, Fishing production and activity, Water supply from groundwater, Hazard protection capacity and Outdoor recreation.
9 **Highest number of ecosystem services and low-intensity values**	The bundle is composed of few, large and little fragmented patches. It is homogeneously distributed over altitude, catchments and it covers all land uses.	23 services ecosystem services are supplied: 10 provisioning, seven regulating and seven cultural. With respect to other bundles, it is the richest of ecosystem services. The supply is not maximum for any service. Instead. It is minimum for: Water supply from surface water network, Cultural heritage and Outdoor recreation.
10 **High-intensity regulating services**	The bundle is homogeneously distributed over altitude up to 1000m a.s.l..	21 ecosystem services are supplied: eight provisioning, seven regulating and six cultural. The supply is maximum for two regulating services: Water flow regulation and Air quality regulation.
11	It is the smallest bundle with	16 ecosystem services are supplied: seven provisioning, four

Ecosystem services in low-elevation forests	only 3 patches. All areas are below 1000m a.s.l. and they correspond to forests for more than 90%.	regulating and five cultural. The supply is maximum for two ecosystem services: Water supply from surface water network and Honey collection.

Table 3. Shape analysis of bundles

Bundles	**Area** [%]	**Number of patches** [No.]	**Min patch area** [ha]	**Max patch area** [ha]	**Mean patch area** [ha]	**Fragmentation index** [Dimensionless]
1	45.773	6767	1	96555	41.6	0.0
2	40.133	17362	1	54225	14.2	0.1
3	3.465	2642	1	653	8.1	0.1
4	4.901	7882	1	935	3.8	0.3
5	0.599	1655	1	326	2.2	0.4
6	0.166	530	1	85	1.9	0.5
7	4.106	1831	1	4546	13.8	0.1
8	0.016	69	1	6	1	0.7
9	0.816	20	1	2030	250.6	0.0
10	0.024	8	1	69	18.75	0.1
11	0.002	3	1	10	4	0.3

Table 4. Spearman correlation coefficients of bundles and principal components with altitude, catchments and land use. We consider significant correlations (bolded text) when correlation coefficients are greater than or equal to 0.3.

	Bundles											Principal components	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**PC1**	**PC2**
Altitude	0.2	**0.4**	0.0	0.2	0.1	0.0	0.2	0.0	0.0	0.0	**0.9**	0.2	0.2
Catchments	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Land use	**0.6**	**0.6**	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.7**	0.0
PC1	**0.6**	**0.7**	**0.7**	**0.3**	**0.3**	0.1	0.1	0.1	0.0	0.0	0.0	1	0.0
PC2	0.1	0.1	0.0	**0.3**	**0.3**	0.1	0.1	**0.3**	0.0	0.0	0.0	0.0	1

FIGURES

Figure 1. Trentino region within the Alps in Italy

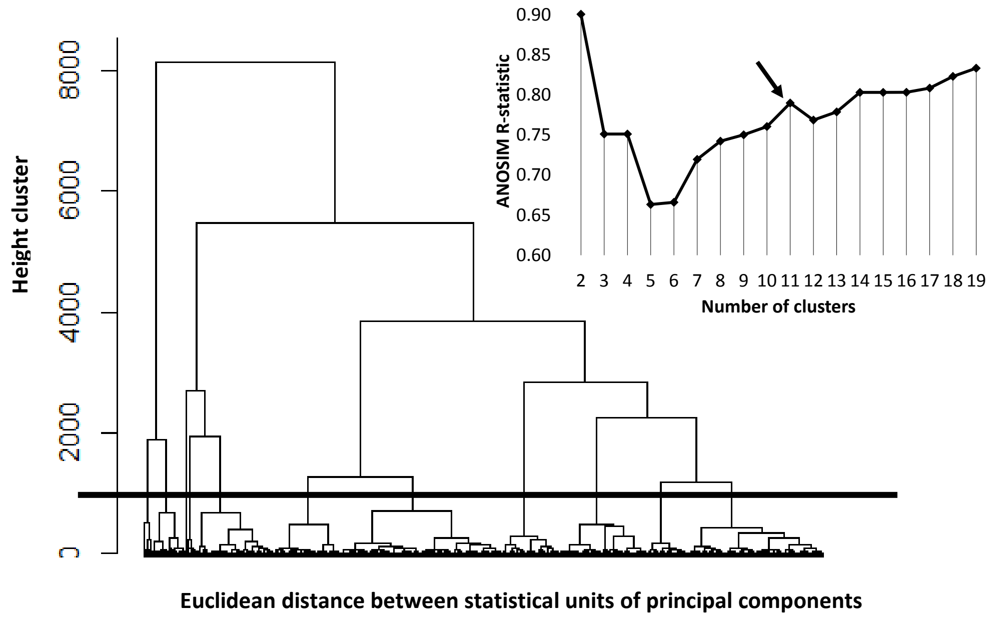


Figure 2. In clustering the most significant difference between the groups is realized for 11 clusters (local maximum of the ANOSIM, arrow), which corresponds to about 1000 of height in the dendogram (horizontal line).

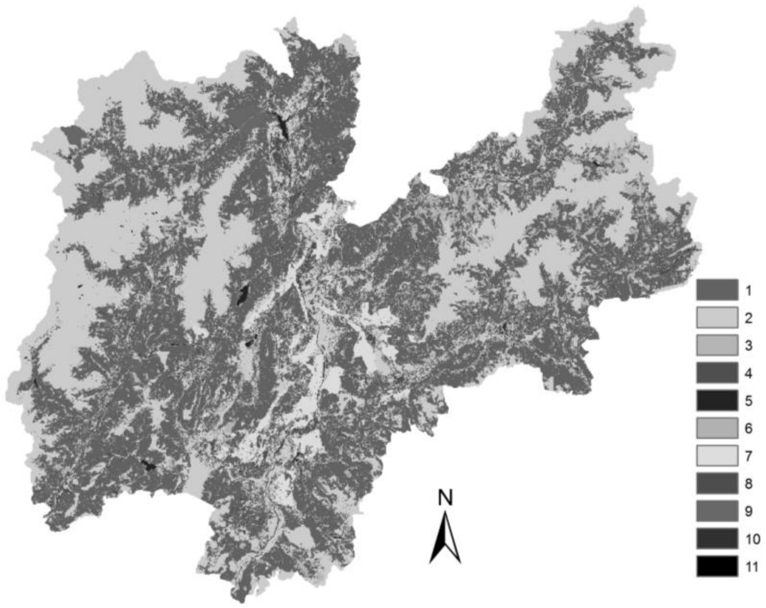


Figure 3. Map of 11 clusters, i.e. bundles of ecosystem services

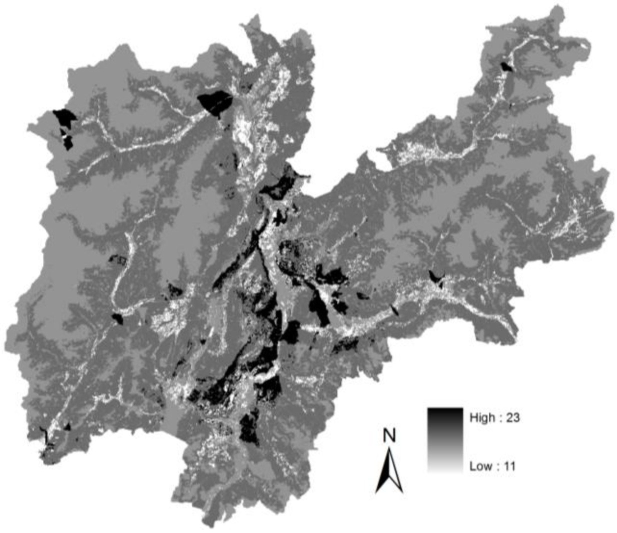


Figure 4. Richness index

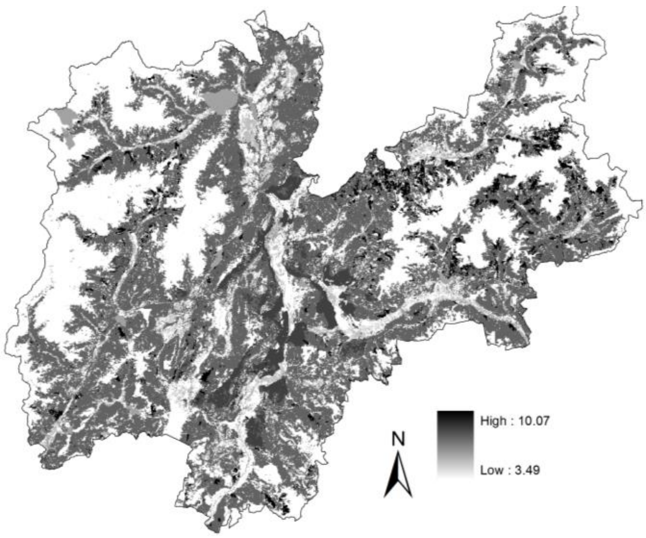


Figure 5. Intensity index

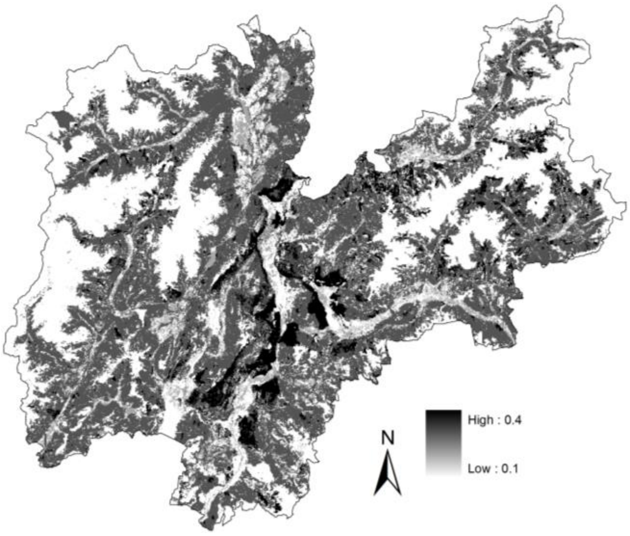
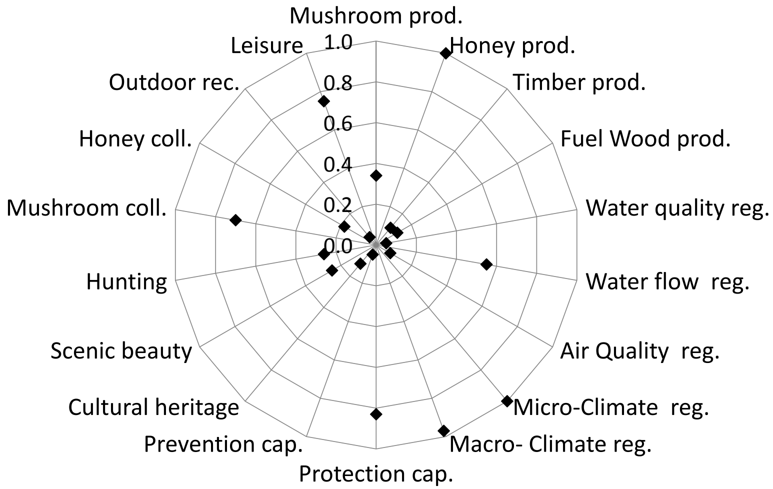
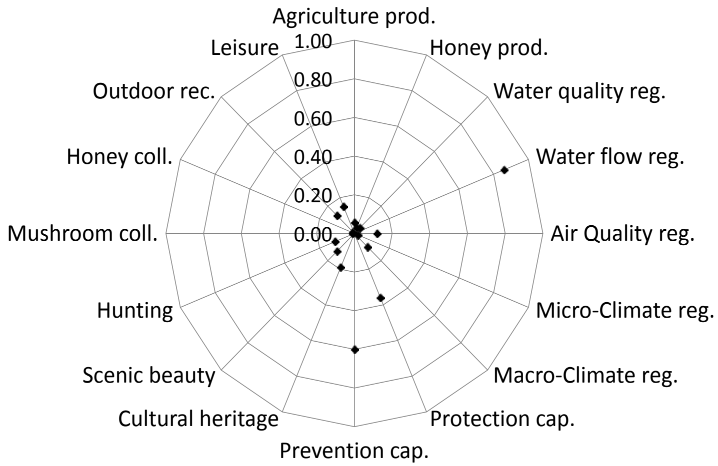


Figure 6. Diversity index

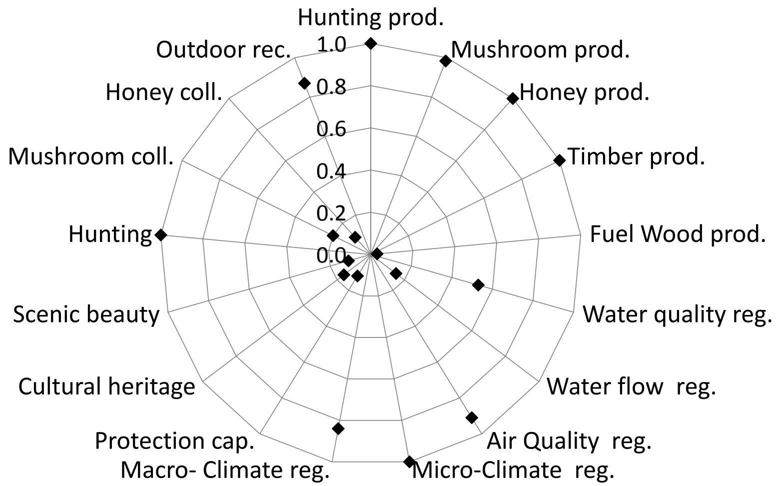
Cluster 1



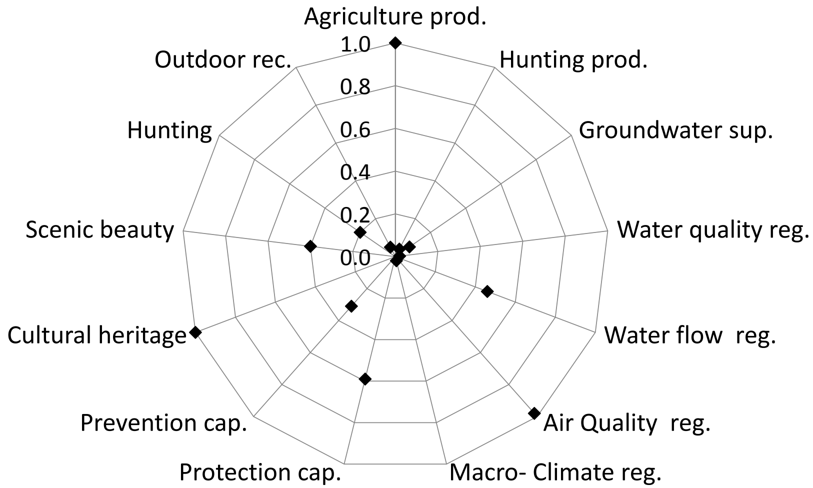
Cluster 2



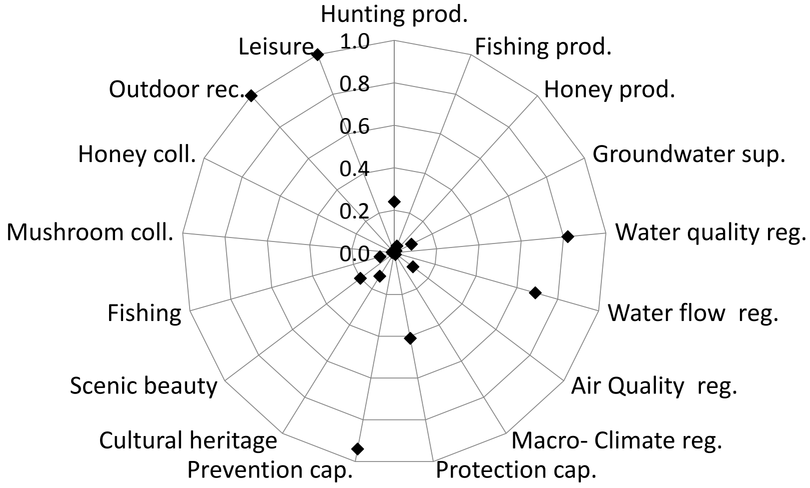
Cluster 3



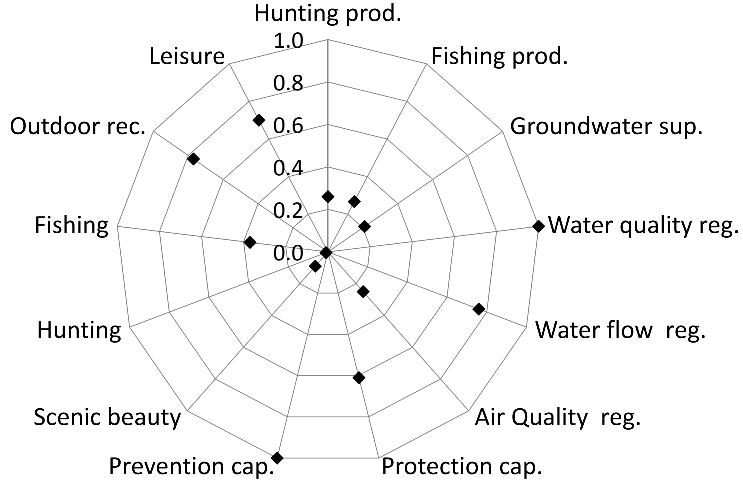
Cluster 4



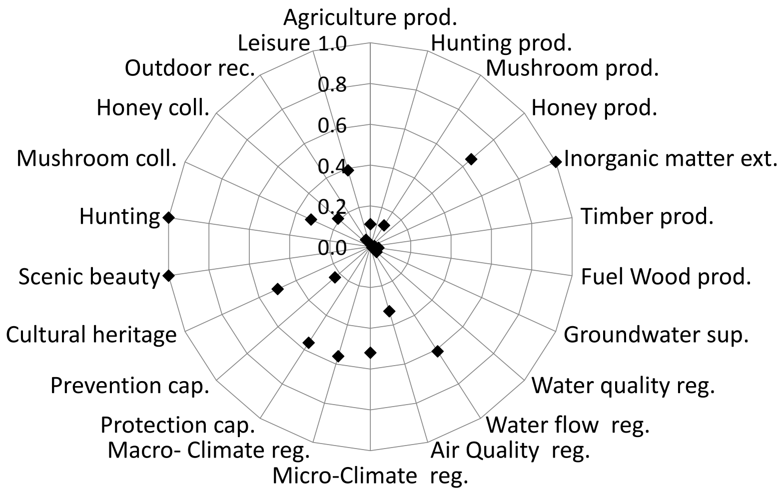
Cluster 5



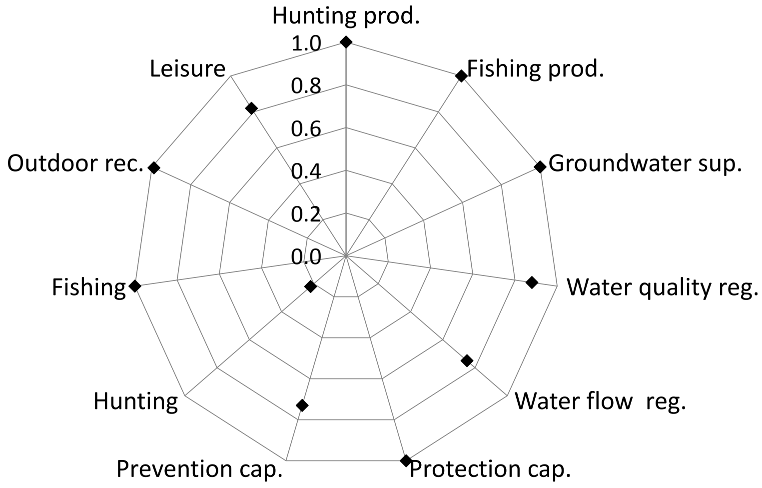
Cluster 6

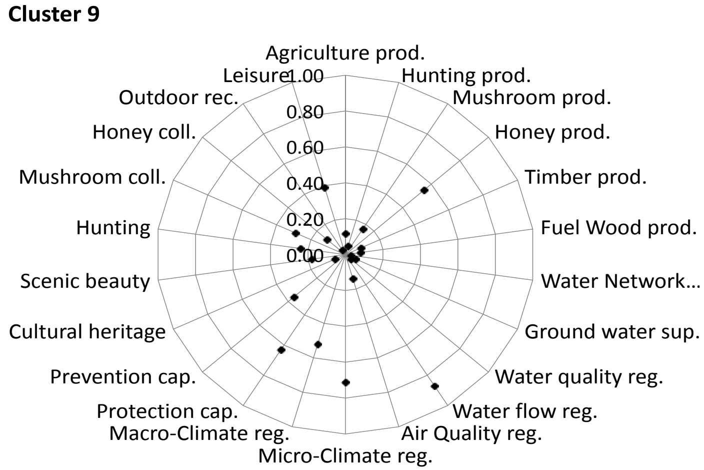


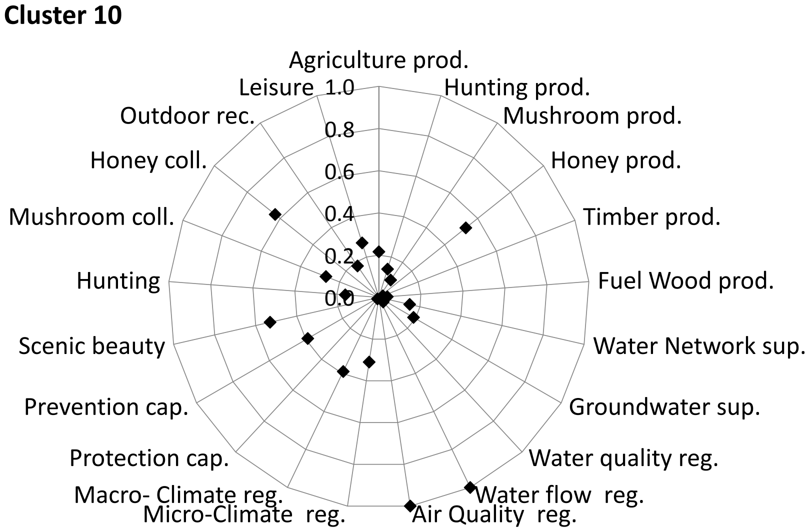
Cluster 7



Cluster 8







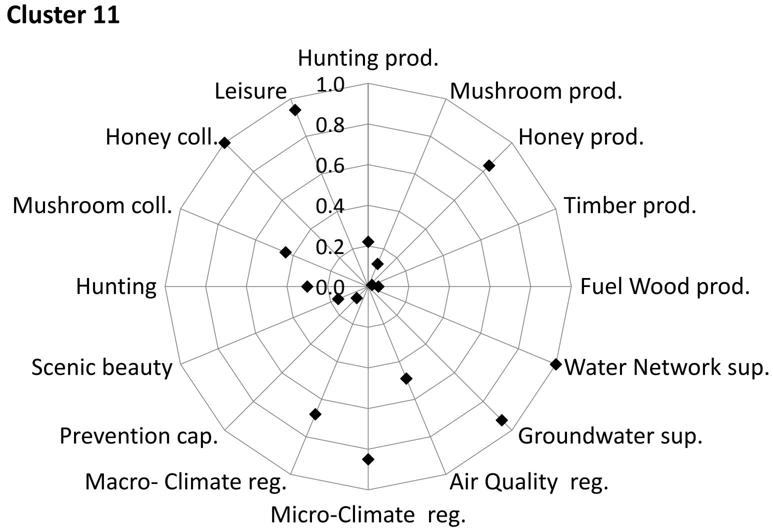


Figure 7. Contribution of the ecosystem services to 11 bundles. Each ecosystem service is represented by one indicator, whose values are normalized from 0 (minimum provision of the service) to 1 (maximum provision).

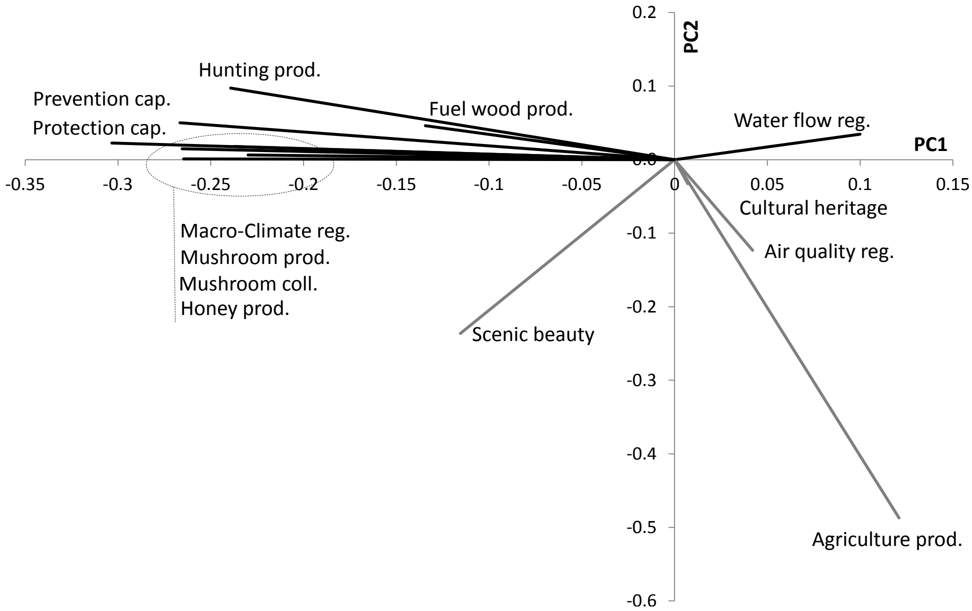


Figure 8. Biplot of the first two principal components

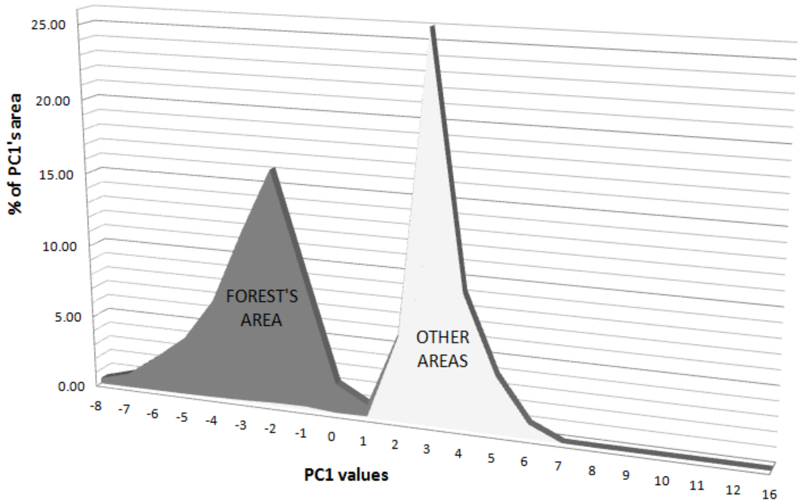


Figure 9. Distribution of PC1 scores among forest areas and other areas. 56% of Trentino is forest (the grey area in the picture); lowest values of PC1 are in forest areas.