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Research Article

The critical role of abiotic factors and human activities in the supply of ecosystem services in the ES matrix

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Abstract

In Western Europe, ecosystems have been shaped to maximise the supply of one specific biomass provisioning ecosystem service (ES), such as food or timber, with detrimental impacts on other ES. The ES approach has therefore been established to better understand the multiple interactions between human society and ecosystems. A variety of methods have been developed to assess ES and their relationships, for instance the ES matrix model based on land cover classes. This popular, flexible and simple method allows combining different data sources and easily comparing ES. However, in general, this method poorly takes into account landscape heterogeneity while abiotic factors and human activities seem to play an important role in ES supply. The objective of this paper is twofold: (1) to extent the methodology based on the ES matrix model by including abiotic factors and human activities and (2) to test the impacts of these two types of factors on ES supply and their relationships.

The assessment focused on the capacity of the forest to supply six ES depending on six types of soil ranging from productive soils to more constraining or less productive soils (i.e. abiotic factors) and two contrasting forest management strategies (i.e. human activities). This amended ES matrix was applied on one hand, to map the supply of ES and their relationships in four municipalities in the Ardenne ecoregion (Southern Belgium) and on the other hand, to investigate the impacts of three scenarios (i.e. three different management strategies) on ES supply and their relationships.

The amended ES matrix shows large differences in ES supply between the two forest management strategies on the more constraining and less productive soils, creating differences in the spatial pattern of ES. The changes in ES supply amongst the three scenarios and the current supply were quantified to identify the best management options.

In conclusion, one particular forest is not like another in terms of ES supply and their relationships. To capture this heterogeneity, we propose an amended ES matrix including abiotic factors and human activities. The maps, based on this matrix, allow identifying the hotspots (i.e. high capacity to supply different ES) and coldspots (i.e. low capacity to supply different ES or strong trade-offs between provisioning ES and regulating/cultural ES). Forest management should be adapted to the abiotic conditions, in particular in the coldspots, to ensure a more balanced supply of ES.

Keywords

Forest management, abiotic factors, land sparing versus land sharing framework, ecosystem services supply, ecosystem services relationship, ecosystem services matrix

Introduction

Over time, human societies have shaped ecosystems to optimally produce the desired provisioning ecosystem services (ES), such as food or timber (Kareiva et al. 2007, Rodríguez et al. 2006), disregarding the fact that the various ES interact in complex and dynamic ways (Rodríguez et al. 2006). This issue has resulted in unexpected and undesirable declines in most of the ES (e.g. pollination, flood control, patrimonial landscape), while the demand for common goods and services is increasing (IPBES 2018). Hence, the ES approach has been established to address more comprehensively the interactions between human society and ecosystems (Vandewalle et al. 2009), both the reliance of human welfare on ecosystem functions and biodiversity and the influence of human activities on ecosystems (Millennium Ecosystem Assessment 2005). The integrated ES assessment particularly highlights the hidden costs and multiple contradictory benefits (individuals and collective interests) of a management decision on stakeholders (Howe et al. 2014).

Fig. 1 illustrates the relationships between ES and stakeholders. The manager shapes the ecosystem to maximise one provisioning ES (e.g. thinning to increase wood quality). This maximised ES is then bought by specific stakeholders, termed beneficiaries (e.g. the wood industry), at a certain price determined by the market. The provisioning ES represent individual interests because they generate a private benefit resulting from a personal use of the ES (Baral et al. 2013). The management can also have unexpected negative or positive impacts on other ES, generally regulating and cultural ES (i.e. impacted ES) (Lorilla et al. 2018) and different stakeholders (Howe et al. 2014). In general, the regulating and cultural ES represent the common and collective interests because they provide shared benefits associated with a potentially wide access to these benefits from a range of beneficiaries, including future generations (Baral et al. 2013). However, some cultural ES can deliver individual benefits (e.g. the revenues from a touristic activity). In general, the maximisation of one provisioning ES by a stakeholder or a group of stakeholders holding a private interest, without considering the other ES, leads to trade-offs between ES and conflicts between stakeholders (referred to as non-beneficiaries) (Howe et al. 2014). For example, clear cutting ensures an immediate supply of timber, but reduces the ecosystem capacity to provide other ES, such as carbon sequestration, erosion protection or patrimonial landscape (Sutherland et al. 2016) which could benefit other beneficiaries. Conversely, more environmentally friendly management could benefit a larger set of stakeholders (termed beneficiaries) and other ES (Howe et al. 2014). In that sense, regulation and incentives such as specific aid, labels, awareness-raising campaigns and payment for ecosystem services (PES) can be introduced by the governance system (Edwards et al. 2014).

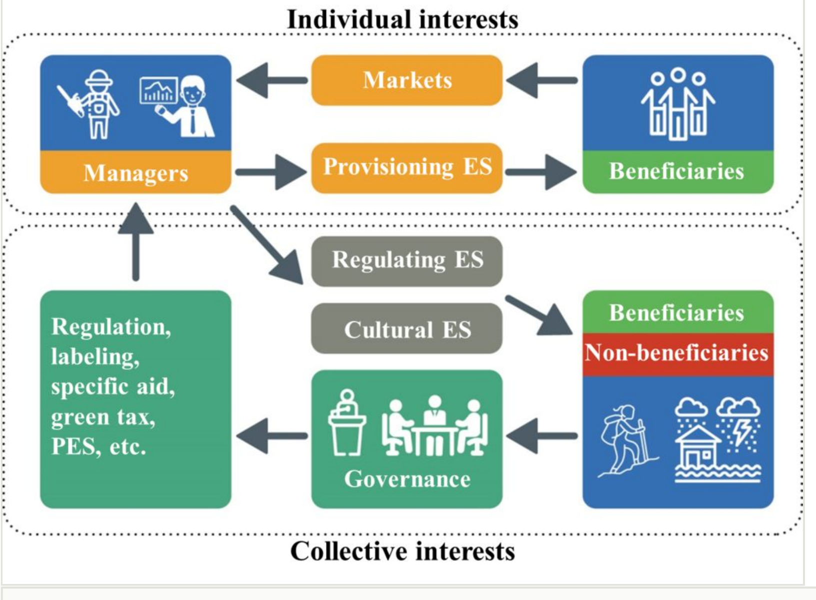

Figure 1.

Schematic representation of the balance between collective (i.e. regulating and cultural ES) and individual interests (i.e. provisioning ES). The managers shape the ecosystem to supply provisioning ES which benefit specific beneficiaries (i.e. individual interests). The price of these provisioning ES is determined by the market. The managers can also impact positively or negatively regulating and cultural ES and their stakeholders, respectively, termed beneficiaries and non-beneficiaries (i.e. collective interests). The governance system can influence the balance between collective and individual interests by regulation, labelling, specific aid etc. Adapted from Maebe et al. (2018).

The assessment of ES and their relationships can help with respect to analysing the balance between collective and individual interests. However, ES assessment is not a simple exercise (Burkhard et al. 2014) for many reasons: the high complexity of the topic itself (Burkhard et al. 2014) while rather universal and easy-to-apply assessment methods are required (Crossman et al. 2013); the various understandings of the ES concept (Fisher et al. 2009); the diversity of assessment methods (Baral et al. 2016) and the large amount of data necessary because the ES concept is holistic and comprehensive (Stoll et al. 2015) while a significant amount of data are missing (Seppelt et al. 2011). For all these reasons, ES assessment can be expensive and time consuming (Burkhard et al. 2009) and must deal with many uncertainties (e.g. data scarcity, knowledge gaps, demand variability) (Jacobs et al. 2015). Nevertheless, even imperfect ES assessments are better than simply ignoring ES (Daily 1997).

A variety of methods, such as biophysical and environmental models (e.g. Boumans et al. 2015, Nelson et al. 2009, Staes et al. 2017), expert opinion (e.g. Burkhard et al. 2012, Vihervaara et al. 2010), participatory approaches (e.g. Boeraeve et al. 2018, Fagerholm et al. 2012) and remote sensing and GIS tools (e.g. Burkhard et al. 2014, Vihervaara et al. 2012), were and are still being developed to assess ES. Each method meets specific objectives, has its own advantages and disadvantages, requires, to a certain extent, a significant investment in data collection and processing, has its own uncertainties and addresses some of the value dimensions (see Bagstad et al. 2013, Jacobs et al. 2018, Grêt-Regamey et al. 2017 for reviews on existing ES assessment methods and tools). Hence, the selection of the assessment method may be as relevant as the results of the assessment (Martín-López et al. 2014).

We focus on one specific ES assessment method: the ES matrix model. This two-dimensional matrix links the different land cover classes with their capacities to supply ES (Burkhard et al. 2009). These capacities are assessed on a scale, generally ranging from 0 (no relevant capacity to supply the ES) to 5 (very high relevant capacity), based on statistics (e.g. Kandziora et al. 2014), model results (e.g. Nedkov and Burkhard 2012), expert opinion (e.g. Kopperoinen et al. 2014), interview results (e.g. Kaiser et al. 2013), monitoring and/or other data sources (e.g. Baral et al. 2013). This matrix can then be linked to spatial data to map the supply of ES in the territory (Jacobs et al. 2018).

The matrix model is one of the most popular ES assessment methods (Jacobs et al. 2015) for several reasons. It is an efficient, fast, flexible and a simple way to obtain an overall spatially explicit picture of ES (Jacobs et al. 2018) which allows combining several data sources (Jacobs et al. 2015). In particular, the maps derived from the matrix bring to light the potential areas of opportunities and conflicts to guide spatial planning and management (Burkhard et al. 2014) and help to implement ES into decision-making (Daily and Matson 2008). The scaling system facilitates the comparison between ES, land cover classes and scenarios (Jacobs et al. 2015). Thanks to all these advantages, the ES matrix model can be used widely in science and decision-making (Burkhard et al. 2014).

Nevertheless, the ES matrix model also has disadvantages. First, it disregards landscape heterogeneity in the supply of ES by considering only individual land cover classes (Eigenbrod et al. 2010, Stoll et al. 2015). On one hand, by assuming land cover and management is in accordance with the abiotic conditions, land use intensity is neglected (Lavorel et al. 2017) leading to discrepancies between land cover and the capacity of the ecosystem to provide ES (Van der Biest et al. 2015). It is especially true in very densely populated areas where, for example, increasing population density and growing demand for timber can induce intensive forestry on less suitable soils. On the other hand, more extreme values are masked by using an average value for each land cover that does not take into account the varying capacity of an ecosystem to provide ES depending on the abiotic conditions and its management (Van der Biest et al. 2015). Then, the use of qualitative or semi-quantitative data such as expert opinion or interview results can be subjective, simplistic and error prone because they depend on the knowledge and experience of experts and respondents (Jacobs et al. 2015, Paudyal et al. 2015). Finally, uncertainty lies in various levels: ES concept (i.e. high complexity of the concept), data and methods used to assess the ES, land cover data, integration of various data etc., but most of these uncertainties are not specific to the matrix model (see Hou et al. (2013) for a list of all uncertainties of the ES matrix model).

In response to these critics, Jacobs et al. (2015) offered the following guidelines to improve the matrix model:

- to include other physical factors to better capture landscape heterogeneity;
- to analyse uncertainties (e.g. measures of confidence and of model reliability, validation with other data);
- to describe transparently the methods used to assess ES and
- to validate the ES scores by experts and stakeholders to provide legitimate results.

Specific recommendations were also discussed by Schröter et al. (2014) on how and where to map supply and demand of ES for policy-relevant outcomes and by Hou et al. (2013) regarding how to manage uncertainties related to the ES matrix model. Furthermore, Campagne and Roche (2018) provided a 7-step methodology to build the matrix, based on expert opinion. Some improvements have been made on the matrix model since the first publication of Burkhard et al. (2009). Some authors added other data to the land cover. For example, Yapp et al. (2010) applied vegetation data from the VAST (Vegetation Assets, States and Transitions) dataset to better capture the spatial heterogeneity and discrepancies between land cover or management and abiotic conditions. Other authors discussed the scoring of the matrix, based on expert opinion. For example, Campagne et al. (2017) compared three approaches to estimate the means and standard errors of the matrix scores.

Nevertheless, the matrix model can still be improved in the integration of other determinants rather than land cover (Burkhard et al. 2012). Indeed, the supply of ES is largely determined by three main components (Fig. 2):

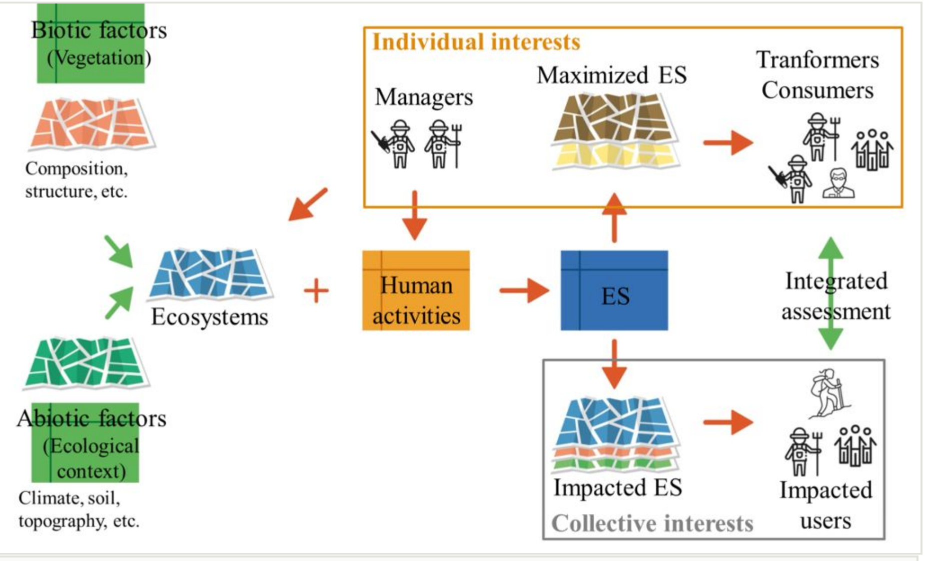

Figure 2.

Schematic representation of the integrated assessment of ES. The supply of ES is determined by three main components:

1. biotic factors;
2. abiotic factors and
3. human activities.

Ecosystems result from the interactions between biotic and abiotic factors. The managers shape the ecosystem to maximise the supply of some ES (i.e. maximised ES) which benefit some stakeholders (i.e. transformers and consumers) and which, in turn, impact the supply of other ES (i.e. impacted ES) and other stakeholders (i.e. impacted users). The integrated assessment should consider the different ES and stakeholders to balance the collective and individual interests. Adapted from Maebe et al. (2018).

1. biotic factors (e.g. species, land cover and vegetation, habitats) (Smith et al. 2017);
2. abiotic factors (e.g. precipitations, rock formations, soil texture, slope) the combinations of which determine different ecological contexts; and
3. human activities (Burkhard et al. 2012) (e.g. management practices, land use intensity, pollution).

The biotic and abiotic factors interact together to shape the ecosystem (Smith et al. 2017). The abiotic factors influence ES supply in varying manners (e.g. food production is highly influenced by abiotic factors while, for aesthetic landscapes, there is much less evidence) (Smith et al. 2017). They not only reflect the capacity of an ecosystem to provide ES but also provide information on the risks to impact ES supply by human activities (e.g. a clear cutting has a priori a higher negative influence on soil erosion on a steep slope than on a flat soil (Bansept and Fiquepron 2014)). Biotic factors also affect ES supply. In their review, Smith et al. (2017) found an influence of biotic factors (e.g. community, habitat, diversity, functional group and population dynamics) on ES. For example, larger trees in a forest store more carbon and intercept and absorb more water (Smith et al. 2017). Finally, human activities influence both deliberately some ES (i.e. maximised ES, representing individual interests) and inadvertently others (i.e. impacted ES, representing collective interests) (Schägner et al. 2013). Human activities can have both a positive and negative influence (Smith et al. 2017). For example, clear cutting provides wood (i.e. deliberate and positive influence) but causes nutrient loss that can pollute water (i.e. inadvertent and negative influence) (Bansept and Fiquepron 2014, Fiquepron et al. 2012).

As illustrated in Fig. 2, the stakeholders also interact with each other: the manager shapes the ecosystem to provide specific ES that are then used by the transformers and consumers and its management impacts other users (i.e. impacted users) (see also Fig. 1). The integrated assessment of ES should consider:

- the maximised ES;
- the impacted ES;
- the relationships between ES and
- the different stakeholders.

By adding information on abiotic factors and human activities in the ES matrix, this method gives up some of its simplicity and some of its utility in data scarce situations, but it considerably improves its accuracy while still considering the landscape heterogeneity. It is true that other tools which allow systematically taking into account abiotic factors and human activities such as InVEST (Integrated Valuation of Ecosytem Services and Tradeoffs) (Kareiva et al. 2011) or ECOPLAN-SE (ECOPLAN 2016) can be easily and transparently used. However, these tools remain more complex and time-consuming and require more data than the matrix, even the one we proposed in this paper. Furthermore, in general, they do not systematically present all the advantages of the matrix (i.e. fast and simple, spatially explicit, allowing combining different types of data, easy comparison between ES and worldwide use). For example, ECOPLAN-SE is only developed for Flanders (Nothern Belgium) while InVEST requires some expertise to run the models. Hence, the aim of this paper is to provide an amended version of the matrix for researchers who want to use the ES matrix to assess ES in their research.

To the best of our knowledge, no study has yet investigated systematically and widely both the abiotic factors and the human activities in the ES matrix. The studies have mainly considered land cover (e.g. Burkhard et al. 2009, Clerici et al. 2014) even if some added other data: biotic information (e.g. data on strata level, canopy cover, structural type and main-component tree in Roces-Díaz et al. (2017) or biotope data in Van der Biest et al. (2015) and in Geange et al. (2019)) and management information (e.g. Vihervaara et al. (2010) tested the impact of different management practices on the supply of ES).

The main objective of this study is to improve the method based on the ES matrix by taking into account both abiotic factors and human activities. A second objective is to study the impacts of abiotic factors and human activities on ES supply and their relationships.

Material and Methods

The assessment of ES supply and their relationships was performed based on an amended ES matrix. Two improvements were made to qualify the supply of ES from ecosystems: the inclusion of

1. the ecological context to synthesise abiotic factors and
2. the management to represent human activities.

Moreover, the guidelines provided by Jacobs et al. (2015) were followed.

Building the amended ES Matrix

This study focused on one class of land cover (i.e. forest) in order to study exclusively the influence of abiotic factors and human activities on the supply of ES and their relationships. The forest was chosen because of its particular importance in ES supply, diversity and trade-offs (Roces-Díaz et al. 2017).

The ecological context is defined as the physical and chemical conditions of the environment mainly determined by the elevation, topography and soil according to its texture, moisture, nutrient availability etc. Six ecological contexts were differentiated:

1. mesic brown forest soils, usually located on the plateau, considered as good soils as they are not constraining in terms of productivity or as they do not have a high ecological significance in contrast to the five sensitive soils listed just below;
2. steep slopes (slope ≥ 15°);
3. alluvial soils;
4. wet soils;
5. podzolic soils and
6. peat soils;

to characterise the forest capacity to provide ES and the risk to impact them by human activities.

Human activities were considered by differentiating two contrasting forest management strategies, the two most common in Wallonia:

1. uneven-aged broadleaved forests (natural regeneration, no clear cutting) and
2. pure even-aged spruce plantations (clear cutting, residue grinding, wet soil drainage, plantation).

These two forest management strategies have been deliberately defined in a highly contrasted way to highlight the differences in ES supply. However, even if spruce forests are no longer necessarily drained, while broadleaves are sometimes cultivated in even-aged forests, these two contrasting forest management strategies correspond quite well to the actual reality of forest management in the Ardenne (Southern ecoregion of Belgium) resulting from the silvicultural choices in the 20th century.

Six ES were selected from the classification of the Walloon platform on ES (Wal-ES 2016):

1. wood production;
2. global climate regulation by sequestration of greenhouse gases (GES);
3. flood protection;
4. erosion protection;
5. water purification and oxygenation and
6. natural areas for outdoor recreation.

They were chosen by considering their specific importance to the study area and their representative nature to represent the three main categories of ES (i.e. provisioning, regulating and cultural ES) and some of the main ES provided by forests (according to Swanson and Chapin (2009), Landsberg and Waring (2014)).

		Ecosystem Services							
Forest Management	Ecological Context	Wood Volume of mobilizable wood	Carbon Amount of carbon sequestered in forest vegetation and soil	Flood Capacity of soil infiltration and evapotranspiration of vegetation	Erosion Soil and sediment retention capacity	Water Nitrates and phosphorus retention capacity	Recreation Forest landscape attractivity	Surface (ha)	% surface
Pure even-aged spruce plantation	Mesic brown soil	7	6	6	5	4	4	10770	41
	Steep slope	5	4	3	2	3	2	257	1
	Alluvial soil	7	4	3	1	1	3	656	3
	Wet soil	4	3	2	2	2	2	1209	5
	Podzolic soil	5	4	4	3	2	4	337	1
	Peat soil	1	1	1	1	1	1	122	0
Uneven-aged broadleaved forest	Mesic brown soil	5	7	7	6	7	6	9582	37
	Steep slope	4	5	6	5	6	5	1016	4
	Alluvial soil	5	7	7	7	7	7	904	3
	Wet soil	3	4	6	6	6	6	597	2
	Podzolic soil	4	5	6	6	4	6	493	2
	Peat soil	1	5	5	6	6	5	47	0

Scale of the ES scoring

1	Minimal capacity
2	Very low capacity
3	Low capacity
4	Medium capacity
5	Good capacity
6	Very good capacity
7	Maximal capacity

Figure 3.

Amended ES matrix illustrating the capacity of the different combinations of a forest management strategy with an ecological context to supply the six ES. The meaning of the code name of the six ES can be found in Table 1. The supply indicator of each ES is provided. The surface and percentage of surface covered by each combination in the studied forest massif is given.

The amended ES matrix links the six ES (on the x-axis) to the two forest management strategies and the six ecological contexts, in total 12 combinations (on the y-axis) (Fig. 3). At the intersections (altogether 72), the capacity to supply ES, depending on the forest management and the ecological context, was assessed on a scale consisting of: 1 = minimal capacity to supply the corresponding ES; 2 = very low capacity; 3 = low capacity; 4 = medium capacity; 5 = high capacity; 6 = very high capacity and 7 = maximal capacity. This usual scale ranging from 0 to 5 was adapted by replacing 0 by 1 to avoid mathematical issues (i.e. empty product) and by adding a seventh score to enlarge the scale in order to further separate close capacities in the supply of ES. These scores indicate relative magnitudes rather than values (Maynard et al. 2010).

Table 1.

The six ecosystem services according to the classification of the Walloon Platform on ES (Wal-ES), with their code name and their corresponding name in the CICES-BE classification (Turkelboom et al. 2013), assessed in the amended ES matrix with their corresponding supply indicator, references and arguments.

ES category	ES (Wal-ES)	ES code	ES (CICES-BE)	Indicator	References	Uneven-aged broadleaved forests	Pure even-aged spruce plantations
Production	Wood production	Wood	Plant fibres and materials	Volume of mobilizable wood	Alderweireld et al. 2015, Rondeux and Thill 1989, Thill et al. 1988, Weissen et al. 1991	Less yield and volume due to slow growth	More yield but the volume produced is not stable over time (clear cutting)
Regulation	Global climate regulation by sequestration of greenhouse gases	Carbon	Global climate regulation by reduction of greenhouse gas concentrations	Amount of carbon sequestered in forest vegetation (BOC) and soils (SOC)	Alderweireld et al. 2015, Broadmeadow and Matthews 2003, Hargreaves et al. 2003, Jandl 2007, Laitat et al. 2004, Latte et al. 2013, Lettens et al. 2008, Lindsay 2010, Minkkinen et al. 2008, Schulp et al. 2008, Stevens and van Wesemael 2008, Vesterdal et al. 2013, Wiesmeier et al. 2013	BOC: less volume but larger wood density, larger volume of the tree (above- and below-ground) and more understory vegetation	BOC: more yield but lower wood density, lower volume of tree (above- and below-ground) and almost no understory vegetation
						SOC: higher due to leaf decomposition and increasing carbon stocks on wet and peat soils	SOC: lower despite a biomass accumulation in the first stages but clear cutting and soil drainage induces high mineralization
	Flood protection	Flood	Natural flood protection & sediment regulation	Capacity of soil infiltration and evapotranspiration of vegetation	Armbruster et al. 2004, Aussenac 1968, Aussenac and Boulangeat 1980, Carnol et al. 2014, Hein 2011, Nisbet and Thomas 2008, Nisbet et al. 2011, Piégay et al. 2003, Rotherham 2015, Wastiaux 2008	Lower tree evapotranspiration and interception of rainwater (deciduous trees) but continuous presence of vegetation cover and deep rooting allowing better infiltration. No drainage and even slowdown effect of water flows in alluvial zones thanks to vegetation	Higher tree evapotranspiration and interception of rainwater but clear cutting and the absence of understory vegetation have a negative impact. Existing huge drainage networks on wet and peat soils highly intensify floods

ES category	ES (Wal-ES)	ES code	ES (CICES-BE)	Indicator	References	Uneven-aged broadleaved forests	Pure even-aged spruce plantations
	Erosion protection	Erosion	Buffering and attenuation of mass flows + Protection against water and wind erosion	Soil and sediment retention capacity	Armbruster et al. 2004, Augusto et al. 2000, Aussenac 1968, Bansept and Fiquepron 2014, Carnol et al. 2014, Fontecilla Lechuga 2012, Gillijns et al. 2005, Grosclaude 1999, Marty and Bertrand 2011, Nisbet et al. 2011	High erosion protection in all ecological contexts thanks to deep rooting allowing better infiltration and the presence of a permanent vegetation cover especially on alluvial soils where the understory vegetation captures sediments	Low erosion protection on all sensitive soils: steep slopes (clear cutting), wet and peat soils (drainage networks) and alluvial soils (absence of understory vegetation)
	Water purification and oxygenation	Water	Water purification and oxygenation	Denitrification and phosphorus retention capacity	Armbruster et al. 2004, Augusto et al. 2000, Aussenac and Boulangeat 1980, Bansept and Fiquepron 2014, Broadmeadow and Nisbet 2004, Fiquepron et al. 2012, Fontecilla Lechuga 2012, Gagkas et al. 2006, Hegg et al. 2006, Hein 2011, Joosten and Clarke 2002, Lavabre and Andreassian 2000, Marty and Bertrand 2011, Nisbet and Thomas 2008, Nisbet et al. 2011, Nisbet et al. 1995, Nys 1981, Piégay et al. 2003, Reddy 1976, Rothe et al. 2002	Vegetation filters pollutants with lower effects on podzolic soils where nutrients leaching is high	Spruce plantations increase soil acidification and have a higher N deposition. The mineralisation of the litter induced by the clear cutting is a very high source of pollutants for surface water especially, in the presence of drains or slopes
Cultural	Natural areas for outdoor recreation	Recreation	Landscape for outdoor recreation	Forest landscape attractivity	Bodson 2005, Church et al. 2014, Colson 2009, Standaert and De Claevel 2011, Willis et al. 2003	Broadleaved forests are very much more preferred to spruce plantations for their naturality, complex structure, tree diversity, lighting, colours in autumn welcoming etc., as well as the presence of surface water (in Wallonia)	Spruce plantations are in general less popular, particularly in the presence of clear cutting and signs of intensive exploitation (e.g. ruts) (in Wallonia)

Such scores were gathered from master student works (Master bioengineer in Nature and Forest Management, Gembloux Agro-Bio Tech, University of Liège, Belgium) over five years (2013–2017). They scored the six ES by group from a literature review (47 references) according to a single supply indicator (Table 1) for the Ardenne ecoregion. The literature allowed discriminating the capacity of the forest to supply ES (i.e. ES potential) depending on the management and the ecological context. These scores were collectively compared. For each ES, students concerned in each group presented the arguments that allowed them to score the ES. Then, the students discussed the variability in ES scores and arguments to reach a consensus. Finally, they presented the new scores with revised arguments. The consensus scores from the five years were averaged and rescaled in order to have a minimal and maximal score for each ES. Finally, these scores were validated by the co-authors with some minor modifications.

Case Study

The amended ES matrix was applied on a forest massif of four municipalities (Libin, Libramont-Chevigny, Saint-Hubert and Tellin; 50.0°N; 5.3°E) of Wallonia (Southern Belgium) in the Ardenne ecoregion. These four municipalities take part in the First Forest Charter in Wallonia, led by a local organisation (Natural Resources Development asbl), aiming at the appropriate development of the social, ecological and economic functions of the forest massif. The assessment of ES was performed as part of the diagnostic of the forest. It was followed by a territorial game (i.e. spatial representations are used by stakeholders as a tool to describe and analyse their territory and to mediate the participative process) with the stakeholders to build a shared vision of the forest and to identify actions designed to improve the multifunctionality of the forest.

The four municipalities encompass an area of 48,500 ha mostly covered by forests (54% of the area), followed by agricultural land (35%), mainly pastures due to a colder climate and poorer soils characterising the Ardenne ecoregion compared to the rest of Wallonia. Urban areas (1%) are barely present, despite a growing urbanisation mainly at the expense of agricultural land.

The majority of the forest is public (66%), primarily owned by the four municipalities (92% of the public forest). Broadleaves and conifers are equally represented. Beech and oak dominate in uneven-aged broadleaved forests. The most frequent coniferous species are in decreasing order: spruce, Douglas fir, larch and Scots pine. They are almost always planted in pure even-aged stands. Only a few stands are becoming uneven-aged due to natural regeneration.

The four municipalities have many resources such as:

1. water provided by three main rivers (Lesse, Lhomme and Ourthe occidentale) and their numerous tributaries;
2. diversified landscapes ranging from plateau to the bottom of the valley more or less covered by forests or more rarely by open natural areas (e.g. peatlands on plateau or wet grasslands in the valley bottom);

3. high biodiversity with diverse habitats such as natural forests (38% of forests belong to the Natura 2000 network);
4. multiple cultural and heritage sites;
5. wood production (the annual wood volume is approximately 62,600 m³ for broadleaved forest and around 148,600 m³ for coniferous forest (data from the regional forest inventory of Wallonia, IPRFW, http://iprfw.spw.wallonie.be)) and
6. game (between 38 and 57 deer/1,000 ha (data from the Department of Nature and Forest, DNF)).

The amended ES Matrix

The amended ES matrix shows that uneven-aged broadleaved forests have a lower capacity to provide wood than pure even-aged spruce plantations, while they have a higher capacity to supply regulating and cultural services (Fig. 3). The arguments used to discriminate ES supply, depending on the forest management and the ecological context, are explained in Table 1.

	Ecological context	Wood	Carbon	Flood	Erosion	Water	Recreation
Pure even-aged spruce plantation	Mesic brown soil	Very high	High	Very high	Very high	Very high	High
	Steep slope	Very high	Medium	High	Very high	Very high	High
	Alluvial soil	Very high	High	Very high	Very high	High	High
	Wet soil	Very high	High	Very high	High	Very high	High
	Peat soil	Very high	Very high	High	Very high	High	High
Irregular broadleaved forest	Mesic brown soil	Very high	High	Very high	Very high	Very high	High
	Steep slope	Very high	Medium	High	Very high	Very high	High
	Alluvial soil	Very high	High	Very high	Very high	Very high	High
	Wet soil	Very high	High	High	Very high	Very high	High
	Peat soil	Very high	Very high	High	Very high	High	High

Figure 4.

Confidence of ES scores from the literature review. Confidence is determined by agreement and evidence quality of the literature review (see Jacobs et al. (2015)). The levels/colours of confidence indicate the following agreement and evidence quality: Very high/dark green = high agreement (i.e. data corroborate, no or minor disagreements) and robust evidence (i.e. data are supported by scientific argumentation or analysis); High/light green = high agreement and medium evidence (i.e. data are supported by argumentation or analysis) or medium agreement (i.e. disagreement exists but interpretations differ in quality) and robust evidence; Medium/yellow = medium evidence and medium agreement. The scores of ES on podzolic soils were only based on expert opinions because the literature review did not provide sufficient information. The meaning of the code name of the six ES can be found in Table 1.

The confidence of the ES scores was analysed according to Jacobs et al. (2015), who proposed a qualitative assessment of the literature review, based on the level of agreement in the literature regarding ES values and the evidence quality of the literature (i.e. the robustness of the evidence). In practice, for each score, the arguments used to assign the score from the different papers were analysed to estimate their evidence quality (e.g.

robust evidence was assigned when scientific evidence is provided, such as quantitative data) and they were compared to determine if they led to a similar score (e.g. if the arguments in the different papers led to a similar score, the level of agreement was considered as high). The uncertainties of the scores are relatively low. Most of the scores have a particularly high level of confidence from the literature review (Fig. 4). For two ES, global climate regulation by sequestration of GES and natural areas for outdoor recreation, the level of confidence is mainly lower because, for the first ES, there are some disagreements in the literature and, for the second one, the literature is rather poor.

The standard deviation of the scores from the master 1 student work between 2013 and 2017 was calculated. The standard deviation of 77% of the scores is lower than 1. Only 23% of scores have a standard deviation ranging from 1 to 2.1 and it is mainly on peat and alluvial soils.

Mapping of ES

The ES scores were linked to spatial data to map ES in spatially explicit units of similar biophysical settings (i.e. a combination of a forest management strategy with an ecological context). The spatial data included a map of the forest cover (Radoux et al. 2019) depicting forest management and the sensitivity soil map (Jacquemin 2015) representing the ecological context (see Suppl. material 1 for a detailed description of these two maps).

The forest cover and sensitivity soil maps were intersected with the software Arcgis version 10.2. A new column combining the forest management strategy with the ecological context was added to the attribute table. This attribute table was joined with the amended ES matrix using this new column as a common identifier field to create a map for each of the six ES.

To analyse the relationships between ES, a synthetic map was created based on the six ES maps to represent the balance between collective and individual interests. The average score of regulating and cultural services was subtracted from the score of wood production for each polygon in Arcgis. The scale ranges from -5 = collective interests are considerably lower than individual interests; via 0 = collective and individual interests are equal; to 4 = collective interests are considerably higher than individual interests.

Scenarios

The influence of human activities on the supply of ES was also studied through three scenarios. These three scenarios intended to improve the supply of ES and their relationships were designed:

1. all the spruce forests on sensitive soils are replaced by broadleaved forests (i.e. scenario ‘Restoration’);
2. the same transformation as scenario ‘Restoration’ while offsetting the loss of spruce plantations by transforming a corresponding area of broadleaved forests into spruce plantations (on good soils, outside Natura 2000 network) to maintain the

balance between broadleaved and coniferous forests as specified in the Walloon Forest Code (i.e. scenario 'Restoration + compensation') and

3. management of all existing spruce forests on good soils, on steep slopes < 20° and on half of the wet soils along the principles of continuous cover forestry using natural regeneration and without clear cutting, drainage or plantation. In this third scenario, on all the other ecological contexts, spruce stands are transformed into broadleaved forests. Indeed, on these sites, the balance between valuable wood production and the negative impacts on other ES and biodiversity is unfavourable (i.e. scenario 'Restoration + continuous cover forestry').

For the last scenario, the matrix of the scores of the ES supply provided by spruce forests was adapted to this new management through a literature review (see the references and the arguments of Table 1). The 'Continuous forest cover' matrix links the six ES (on the x-axis) to the three ecological contexts (on the y-axis). At the intersections (altogether 18), the capacity of uneven-aged spruce forests (continuous cover forestry), depending on the ecological context, was assessed on a scale from 1 (minimal capacity) to 7 (maximal capacity) (Fig. 5).

		Ecosystem Services					
Forest Management	Ecological Context	Wood	Carbon	Flood	Erosion	Water	Recreation
		Volume of mobilizable wood	Amount of carbon sequestered in forest vegetation and soil	Capacity of soil infiltration and evapotranspiration of vegetation	Soil and sediment retention capacity	Nitrates and phosphorus retention capacity	Forest landscape attractivity
Uneven-aged spruce forest (Continuous cover forestry)	Mesic brown soil	7	7	7	6	5	5
	Steep slope	5	5	5	4	4	3
	Wet soil	4	4	5	5	4	4

Scale of the ES scoring	
3	Low capacity
4	Medium capacity
5	Good capacity
6	Very good capacity
7	Maximal capacity

Figure 5.

'Continuous cover forestry' matrix illustrating the capacity to supply the six ES of the uneven-aged spruce forests (continuous cover forestry), depending on the ecological context. The meaning of the code name of the six ES can be found in Table 1. The supply indicator of each ES is provided.

In general, each ES is well provided for the three different ecological contexts, particularly with respect to mesic brown soils. Lower scores are present for some ES:

1. global climate regulation by sequestration of GES,
2. water purification and oxygenation and
3. natural areas for outdoor recreation in some ecological contexts.

The supply of the six ES was compared between each scenario and the current status. The area weighted difference between each scenario and the current status was calculated for each ES based on two equations (Equation 1 and Equation 2). In the first equation, only the areas affected by the scenario were considered while for the second equation, the entire forest massif was taken into account.

$$D_1 = \left(\sum_{i=1}^{n_{Scenario}} (x_i^{Scenario} * S_i^{Scenario}) - \sum_{i=1}^{n_{Scenario}} (x_i^{Currentstatus} * S_i^{Currentstatus}) \right) / \sum_{i=1}^{n_{Scenario}} S_i^{Currentstatus})$$

Equation 1. Difference in capacity to supply the ES between the scenario and the current status weighted by the area concerned by the scenario.

$$D_2 = (\sum_{i=1}^{12} (x_i^{Scenario} * S_i^{Scenario}) - \sum_{i=1}^{12} (x_i^{Currentstatus} * S_i^{Curentstatus})) / \sum_{i=1}^{12} S_i^{Curentstatus}$$

Equation 2. Difference in capacity to supply the ES between the scenario and the current status weighted by total area of the forest massif.

D_1 = Area weighted difference in the capacity to supply the ES between the scenario and the current status for the areas affected by the scenario

D_2 = Area weighted difference in the capacity to supply the ES between the scenario and the current status for the entire forest massif

i = Each combination of a forest management strategy with an ecological context

x = Score of the ES

S = Area (ha) covered by each combination of a forest management strategy with an ecological context

n = Number of combinations of a forest management strategy with an ecological context affected by the scenario

Data Resources

The data gathered from the ecotope map, the soil sensitivity soil map and the amended ES matrix are compiled in an Excel file (see https://doi.org/10.5281/zenodo.3228110). These data were used to map the six ES and the balance between collective and individual interests as well as to calculate the area weighted difference between each scenario and the current status for the case study.

Results

The assessment of the six ES in the forest massif highlights the influence of abiotic factors and human activities on the capacity of the forest to provide ES. First, the maps of the six ES and their relationships (Fig. 6) show their spatial distribution depending on the ecological context and the particular forest management. Furthermore, the comparison between the ES provided by each scenario and the current status illustrates the influence of human activities.

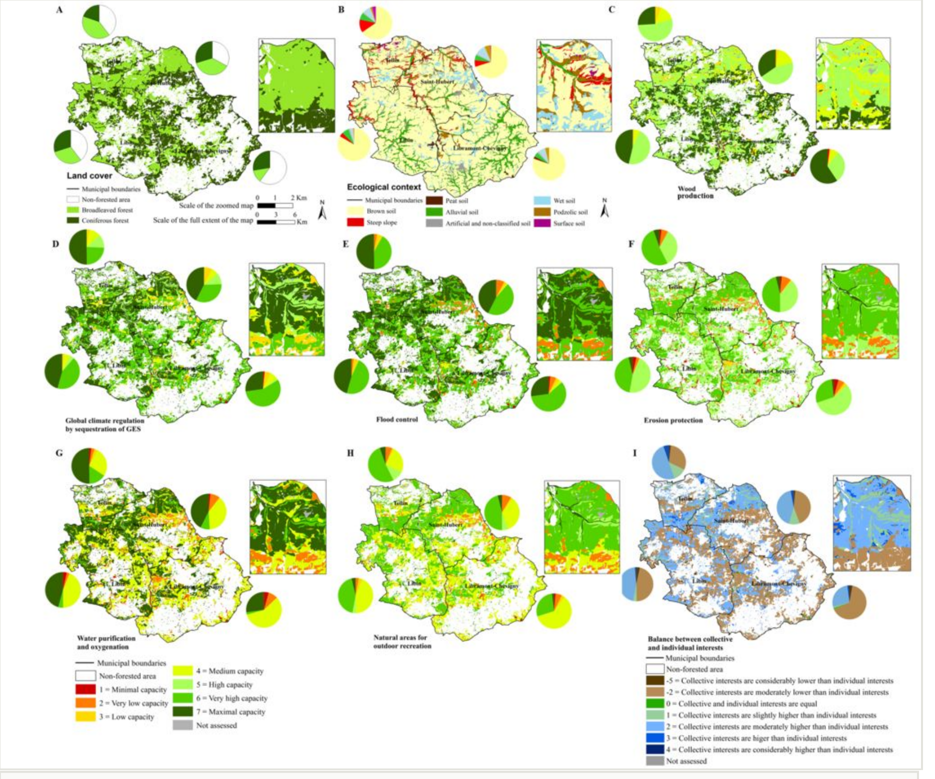

Figure 6.

Ecotopes land cover map 2015 (A), sensitivity soil map (B) and maps of wood production (C), global climate regulation by sequestration of GES (D), flood protection (E), erosion protection (F), water purification and oxygenation (G), natural areas for outdoor recreation (H) and the balance between collective and individual interests (I) of the forest massif of the four municipalities (Libin, Libramont-Chevigny, Saint-Hubert and Tellin, Ardenne, Belgium).

Mapping of ES and their Relationships

Map of Forest Management

The forest cover is analysed, based on the ecotopes land cover map of 2015, as a proxy of forest management (Fig. 6A). Broadleaved, equating to uneven-aged broadleaved forests and coniferous forests, equating to pure even-aged spruce plantations, are more or less evenly distributed depending on the municipality. Broadleaved forests range from 31% of the forest cover in Libramont-Chevigny to 67% in Tellin.

Map of Ecological Context

The distribution of the ecological contexts (Fig. 6B) shows that mesic brown soils (i.e. good soils) dominate largely in the four municipalities. Nevertheless, sensitive soils are well represented, particularly in Tellin (35% of the municipality area) and Saint-Hubert (30%) and compared to Wallonia (27% of the region).

Alluvial soils concentrate around the three main rivers and their tributaries:

1. Lesse in Tellin (7% of alluvial soils in the municipality) and Libin (7%),
2. Lhomme in Tellin and Saint-Hubert (5%) and
3. Ourthe occidentale in Libramont-Chevigny (5%).

Wet soils are present upstream of these rivers, particularly in Saint-Hubert (10%), Tellin (8%) and Libramont-Chevigny (7%). Lhomme and Lesse and their tributaries create deep valleys with steep slopes, especially in Tellin (13%) and Saint-Hubert (6%). Some podzolic soils are disseminated mainly in Saint-Hubert (6%) and Libramont-Chevigny (4%). Finally, peat soils are scarcely present, apart from in Libramont-Chevigny (2%).

Map of the Six ES

The repartition of the forest capacity to provide the six ES (Fig. 6C to Fig. 6H) is assessed, based on the forest cover (i.e. forest management) and the ecological context at a high spatial resolution of 1/25,000. The spatial pattern varies from one ES to another.

Global climate regulation by sequestration of GES (Fig. 6D) and flood protection (Fig. 6E) have the highest proportion of maximal (uneven-aged broadleaved forests on mesic brown and alluvial soils) and very high capacity (pure even-aged spruce plantations on mesic brown soils and uneven-aged broadleaved forests on some sensitive soils). Nevertheless, they also present a significant proportion of low to minimal capacity (from 5 to 13% of the forest cover in the municipality, particularly in Saint-Hubert and Libramont-Chevigny). These low capacities correspond to pure even-aged spruce plantations on sensitive soils because their drainage limits carbon sequestration, as well as water retention in soil and its clear cutting emphasises run-off (Jandl 2007, Wastiaux 2008).

Wood production (Fig. 6C) is also highly provided in the entire forest massif, especially in pure even-aged spruce plantations that have a higher productivity than uneven-aged broadleaved forests. Wood production decreases in sensitive soils where the productivity and operability are lower, as we can see mainly in Saint-Hubert and Tellin.

Finally, erosion control (Fig. 6F), water purification and oxygenation (Fig. 6G) as well as natural areas for outdoor recreation (Fig. 6H) have more contrasting capacities. These three ES are highly provided by uneven-aged broadleaved forests dissimilar from pure even-aged spruce plantations because of their drainage, the loss in nutrients and run-off generated by clear cutting (Bansept and Fiquepron 2014, Fiquepron et al. 2012) and a strong decrease in landscape attraction (Colson 2009). These lower capacities are mostly present in Libramont-Chevigny and Libin.

Map of Relationships between ES

The relationships amongst the six ES are examined depending on the particular forest management and the ecological context using the map representing the balance between collective (i.e. regulating and cultural ES) and individual interests (i.e. wood production) (Fig. 6I). Pure even-aged spruce plantations lead overall to higher individual interests, especially in Libramont-Chevigny, while the opposite trend is seen in uneven-aged broadleaved forests, particularly in Tellin. Indeed, spruce forests have a higher capacity to provide wood, while they have a lower capacity to provide regulating and cultural services than broadleaved forests. These trends are especially true for pure even-aged spruce plantations on alluvial soils for which the capacity to provide wood is maximal, while the capacity to supply regulating and cultural ES ranges from medium to minimal. On the contrary, uneven-aged broadleaved forests on wet and peat soils have a low to minimal capacity to supply wood and a medium to maximal capacity to provide regulating and cultural ES. The balance between collective and individual interests is only seen in pure even-aged spruce plantations on peat soils because the capacity of each ES is minimal.

Scenarios to improve ES Supply

For each scenario, two histograms illustrating the area weighted difference in ES supply between the scenario and the current status are analysed to understand the influence of human activities (reflected in the three scenarios) on each ES. They show that the three scenarios lead overall to an increase in the capacity to supply ES (Fig. 7). The lowest improvement concerns wood. A small increase is seen in the scenario ‘Restoration + compensation’ because the transformation of uneven-aged broadleaved forests into pure even-aged spruce forests on mesic brown soils slightly offsets the loss of wood due to the substitution of pure even-aged spruce forests by uneven-aged broadleaved forests on sensitive soils. This substitution also explains why this ES decreases in the scenarios ‘Restoration’ and ‘Restoration + continuous cover forestry’. The highest increase concerns erosion protection because the capacity of pure even-aged spruce stands to supply this ES was particularly low compared to uneven-aged broadleaved forests or uneven-aged spruce forests managed under the principles of continuous cover forestry.

The best scenario, leading overall to the highest increase in ES supply, differs from one histogram to another depending on the area considered. For the first histogram (Fig. 7A), considering only the areas affected by the scenario, the best scenario is ‘Restoration’ because the transformation of pure even-aged spruce forests into broadleaved forests on all the sensitive soils considerably increases the supply of regulating and cultural ES. For the second histogram (Fig. 7B), considering the entire forest massif, the best scenario is ‘Restoration + continuous forest cover’ because, even if the increase in ES supply is lower (Fig. 7A), it impacts larger areas (the capacity to supply ES changes in the entire spruce forest (51% of the forest massif)) than the scenario ‘Restoration’. For both histograms, in general, the smallest increase concerns the scenario ‘Restoration + compensation’ for which some uneven-aged broadleaved forests are transformed into pure even-aged spruce stands having a lower capacity to provide regulating and cultural ES.

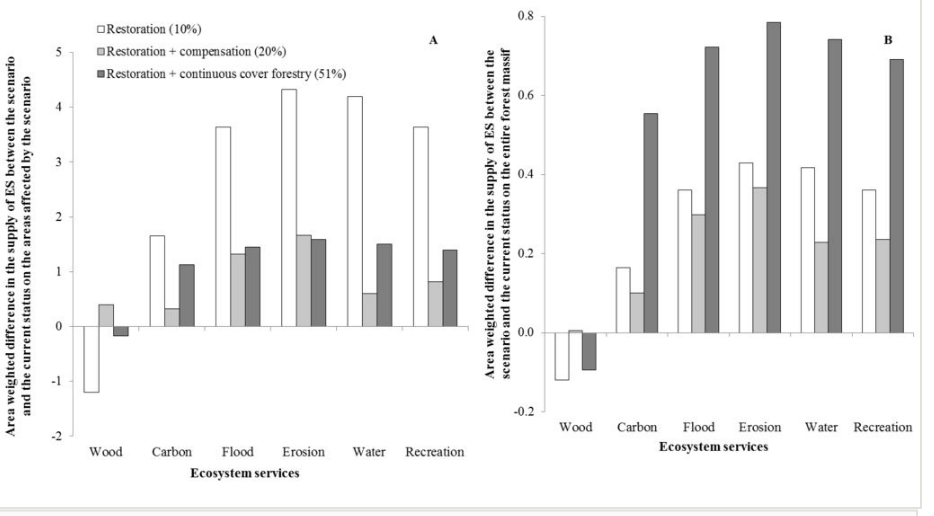

Figure 7.

Area weighted difference in supply of ES between the scenario 'Restoration' (white bar), 'Restoration + compensation' (light grey bar) and 'Restoration + continuous cover forestry' (dark grey bar) and the current status based on Equation 1 on areas affected by scenario (A) and on Equation 2 on the entire forest massif (B). The meaning of the code name of the six ES can be found in Table 1. The percentage of the area affected by each scenario is given next to its name.

Discussion

Amended ES Matrix

We made use of the ES matrix model to develop our methodology because this method has numerous advantages. It is efficient and flexible, allowing the combination of different types of data (e.g. survey, modelling, field measurement) from various sources (Seppelt et al. 2011). We took advantage of this benefit by combining a literature review with expert opinions. The scoring makes it easy to compare the supply of ES (Jacobs et al. 2015) and to analyse their relationships depending on the ecological context and the particular forest management. Finally, maps can be easily derived from this method (Jacobs et al. 2018).

We improved the original ES matrix from Burkhard et al. (2009) in several ways. First, the subjectivity of the method was reduced by combining a literature review with expert opinion. Then, the method was explained in depth and the errors related to the matrix scoring were calculated (see Fig. 4) to make the uncertainties explicit. Finally, the landscape heterogeneity was taken into account by considering the ecological context and the management strategy. These improvements make the ES matrix a better tool to assess ES even if, in some cases, other tools such as biophysical models can be more suitable to use, for example when the processes behind ES provisioning need to be understand.

Other authors also made some improvements in the original ES matrix but none of them systematically considered both abiotic factors and human activities. For example, Burkhard et al. (2014) distinguished between ES potential and ES flow (i.e. actual used services) and discussed temporal aspects of varying ES supplies. Stoll et al. (2015) included measures of uncertainty in each entry of their matrix. Geange et al. (2019) used detailed habitat data including the quality of the habitat to better take into account the spatial heterogeneity.

Our results (see Fig. 3) confirm the importance of systematically considering both abiotic factors and human activities in the ES matrix. They showed a strong influence of the ecological context on ES supply and their relationships. Indeed, on mesic brown soils, all the ES are generally well provided while, on sensitive soils, the ES are mostly lower, particularly in pure even-aged spruce plantations. These results are in accordance with literature, which also found a difference in ES supply amongst different types of soil and landform (Smith et al. 2017, Willemen et al. 2012). The same conclusions can be drawn for the management strategies. Forest management strongly influences ES supply and their relationships both by the tree species composition of the stand and by the level of artificialisation of the management practices. The more artificial the management is, the higher is the provisioning ES and the lower are the regulating and cultural ES (see Baral et al. (2013), Burkhard et al. (2014), Roces-Díaz et al. (2017) for similar conclusions).

Even if the influence of the ecological context and the management is, on average, strong, it varies in intensity. For example, ES supply on alluvial soils is more variable than on mesic brown soils and is, on average, more constant for uneven-aged broadleaved forests than for pure even-aged spruce plantations. Smith et al. (2017) also found that the influence of abiotic factors and of human activities is highly variable.

The impacts of the ecological context and the management on ES supply interact with each other. For example, the impacts of intensive management on regulating and cultural ES are exacerbated on sensitive soils. It is thus important to consider together the ecological context and the management in the assessment of ES supply.

Even if our results cannot be generalised, due to the fact that they are only applicable at the Ardenne ecoregion, our simple and fast methodology can be applied around the world to assess the trends in the capacity of ecosystems to supply ES and their relationships, depending on abiotic factors and human activities.

Nevertheless, our methodology can still be improved: temporal aspects (e.g. seasonal effects, dynamics) could be added (Burkhard et al. 2014), the scores could have been weighted depending on their relevance, as suggested by Burkhard et al. (2009) and biotic factors could have been more detailed by adding information on the strata level, the canopy cover, the main-component tree species or the age of the forest, seen as important determining factors by Roces-Díaz et al. (2017), Vihervaara et al. (2010).

Even if the methodology can be improved further, the shortcomings were reasonable because the main point of this paper is not to make an exact ES assessment for the area but to present an easy-to-apply methodology showing ES trends and taking into account both abiotic factors and human activities.

Mapping as a Tool for ES Assessment and Management

The maps (Fig. 6C to Fig. 6H) emphasise the importance of considering both the ecological context and the management strategy to better capture the spatial heterogeneity in ES supply. Eigenbrod et al. (2010) also found similar results: the land cover does not capture well enough the spatial heterogeneity of ES. The spatial heterogeneity of all the ES is high but with varying degrees. Indeed, we have shown, as have Roces-Díaz et al. (2017), that the spatial distribution of ES supply is more variable for some ES (e.g. water purification and oxygenation) than others (e.g. global climate regulation by sequestration of GES).

Maps are a useful tool in ES assessment. In contrast to the ES matrix, they highlight the variation in the abiotic conditions and human activities in the landscape explaining the variable distribution of ES scores (Burkhard et al. 2009). Moreover, they allow us to identify key areas: hotspots (i.e. high capacity to supply ES) and coldspots (i.e. low capacity to supply different ES or strong trade-offs between provisioning ES and regulating/cultural ES), where ES supply can be improved, as demonstrated by Eigenbrod et al. (2010), Roces-Díaz et al. (2017), Vihervaara et al. (2010). Due to the synthesis and spatialisation of the information it provides, ES mapping can be used to sensitise stakeholders on the existence and diversity of ES and their relationships to the management strategies and the ecological context. The results from the scenarios analysis (Fig. 7) can guide the choice of adequate management strategies to apply in those areas (i.e. coldspots) to ensure a more balanced supply of ES.

Scenarios to Improve ES Supply

For the case study, each of the three scenarios leads overall to an improvement in ES supply (Fig. 7). However, the scenario ‘Restoration + compensation’ shows the lowest improvement because the loss of spruce plantations is offset by transforming a corresponding area of uneven-aged broadleaved forests into pure even-aged spruce plantations which provide lower regulating and cultural ES. The maintenance of the balance between broadleaved and coniferous forests, as prescribed by the Walloon Forest Code, could be detrimental to ES supply when natural broadleaved forests are transformed into spruce plantations to compensate for a loss of spruce in another area, particularly when the primary objective was to restore natural broadleaved forests. The two other scenarios shared the first place. The highest increase in ES supply in the scenario ‘Restoration + continuous forest cover’ shown in Fig. 7B results from both the improvements of ES supply and the area covered. Indeed, this scenario concerns 51% of the forest massif, while the other scenario ‘Restoration’ concerns only 10%. To have the highest improvement in the supply of regulating and cultural ES, the scenario ‘Restoration’ is better because uneven-aged broadleaved forests provide, in general, a higher supply of ES than uneven-aged spruce forests that have a lower capacity to infiltrate water, an acidifying litter and are less attractive in the landscape. It does not mean that uneven-aged broadleaved forests should be restored everywhere because they provide less wood. It means that, on sensitive soils, broadleaved forests should be restored while on good soils, spruce forests should be managed under the principles of continuous cover forestry.

The test of other scenarios can bring new insights. For example, a scenario with mixed broadleaved and coniferous forests could be studied to determine how they can complement one another. Natural open habitats could be included in a scenario to compare their ES supply to forest habitats.

As the ecological context determines the impacts of the forest management on ES supply and their relationships, forest management should be adapted to the ecological context. The land-sharing versus land-sparing framework looks promising to better balance collective and individual interests (Fischer et al. 2014, Maskell et al. 2013). Land sparing is defined as the spatial segregation of land dedicated to production from areas prioritised for other ES, while land sharing promotes, on the same land, the supply of multiple ES (Maskell et al. 2013). In that sense, it is a useful approach to determine where the current land allocation is not efficient in terms of ES and where ES can be improved with having minimal impacts on other ES (Fischer et al. 2014). Therefore, we propose to perform land sparing on one hand, on good soils with spruce forests to maximise wood production and, on the other hand, on wet and peat soils with uneven-aged broadleaved forests where the productivity of the forest is low to maximise regulating and cultural ES (Fig. 8). In the remaining areas, where all the ES can be well provided, we propose to perform land sharing.

This framework can be combined with functional zoning to minimise as much as possible the trade-offs between ES while maintaining wood production. This approach of functional management divides the forest into three zones:

1. conservation,
2. ecosystem management and
3. wood production (Côté et al. 2010).

It has several advantages:

- clear, specific and effective management directions;
- reduction of conflicts between stakeholders and
- concentration of the harvesting activities (Côté et al. 2010).

Three functional zones can be proposed in the studied forest massif:

1. a production zone with spruce forests on good soils that should be managed as uneven-aged stands along the principles of continuous cover forestry to improve the supply of regulating and cultural services;
2. a conservation zone on wet and peat soils where spruce forests should be transformed into uneven-aged broadleaved forests that provide higher regulating and cultural ES and

3. an ecosystem management zone on mesic brown soils covered by broadleaved forests and on alluvial and podzolic soils, as well as on steep slopes where all the ES are well provided, particularly if the spruce forests are transformed into uneven-aged broadleaved forests (Fig. 8).

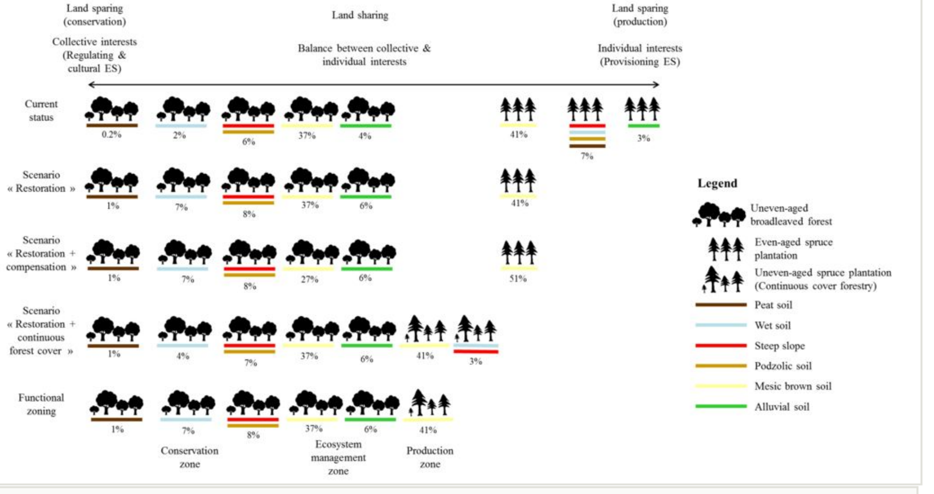

Figure 8.

Position of each combination of a forest management strategy with an ecological context along the gradient of land sparing for conservation (collective interests: regulating and cultural ES) to land sharing (balance between collective and individual interests) to land sparing for production (individual interests: provisioning ES) for the current status, the three scenarios and the functional zoning. The percentage of surface covered by each combination is provided.

The transformation of spruce forests into uneven-aged broadleaved forests on sensitive soils also makes sense for biodiversity. The potential habitats of most of the ecological contexts (97% of the forest massif) are included in the list of the protected habitats of the European Commission (Natura 2000 network) and three of them are priority habitats (Table 2) and should be restored with natural vegetation (i.e. broadleaved forests in Wallonia) in view of the negative impacts of spruce plantations on biodiversity.

Nevertheless, to implement this proposition on the ground, it should be reviewed with relevant stakeholders to determine what is socially preferable (Fischer et al. 2014). Furthermore, the existing constraints such as the Natura 2000 network and the forestry code should be included (Edwards et al. 2014). Finally, the potential spatial and temporal multi-scaled and cross-scaled impacts on ES supply and their relationships should be investigated further (Lindenmayer and Cunningham 2013). For example, intensive management can be displaced to another region in response to the management strategy being proposed (Fischer et al. 2014).

Table 2.

Natural forest and open habitat for each ecological context under Natura 2000.

* Priority habitats.

Ecological context	Natural forest habitat (Natura 2000 code)	Natural open habitat
Mesic brown soil	Acidophilous beech forest (9110)	Dry heath (4030)
Steep slope	Forest of slopes, screes and ravines (9180*) + Acidophilous beech forest (9110)	Upland siliceous scree (8150)
Alluvial soil	Riparian alluvial forest (91E0*)	Alluvial meadow (6430)
Wet soil	Old acidophilous oak wood (9190)	Wet heath (4010)
Peat soil	Bog woodland (91D0*)	Degraded raised bog (7120*)

Conclusions

An easy-to-apply methodology, based on the ES matrix model, was developed to assess ES supply and their relationships based on abiotic factors and human activities. This methodology capitalises on the advantages of the ES matrix model (e.g. efficient, flexible, combination of several data sources, mapping possible, easy comparison between ES), whilst minimising its disadvantages. On one hand, the inclusion of abiotic factors and human activities in the ES matrix allows capturing part of the landscape heterogeneity. On the other hand, the combination of various data sources reduces the uncertainties while the quantification of the errors and the detailed description of the methodology make them transparent. Nevertheless, this methodology can be developed further, notably by specifying the biotic factors (e.g. composition and structure of the forest) and by including the temporal dimension. Finally, the scores of the ES matrix should be updated to new insights obtained from literature.

This amended ES matrix showed that one particular forest is not like another in terms of ES supply: depending on its management and the ecological context, it provides different sets of ES at different levels. This heterogeneity is important in terms of mapping in order to identify the hotspots and coldspots in ES supply. This ES mapping could be an efficient tool to increase awareness amongst the stakeholders on the diversity of ES and their relationships, as well as on the influence of abiotic factors and human activities on ES supply. Forest management plans should be adjusted to the heterogeneity in ES supply to ensure the best balance between collective and individual interests. In this way, they should be adapted to the ecological context by a functional zoning approach which combines land sparing and land sharing. These management propositions should be investigated further to integrate societal preferences, existing constraints and their spatial and temporal cross-scaled effects.

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Supplementary material

Suppl. material 1: Detailed description of the spatial data (ecotope map and soil sensitivity map) used to map ES doi

Authors: Maebe, L., Claessens, H. & Dufrêne, M.
Data type: Description of the spatial data
Download file (97.11 kb)