Article

Biophysical accounting of forests' value under different management regimes: conservation vs exploitation

Vassallo Paolo[1], Turcato Claudia[2], Rigo Ilaria [1*], Scopesi Claudia [3], Costa Andrea[1], Barcella Matteo[4], Dapueto Giullia [1], Mariotti Mauro [1], Paoli

1 DISTAV (Department of Earth, Environmental and Life Sciences), University of Genoa, Corso Europa 26, 16132 Genova, Italy
2 CESBIN S.r.l. Via San Vincenzo 2, 16121 Genova, Italy
3 GEOSCAPE coop. soc. Via Varese 2, 16122 Genova, Italy
4 Section of Landscape Ecology, Department of Earth and Environmental Sciences, University of Pavia, Via S. Epifanio 14, I-27100 Pavia, Italy

* correspondence: Ilaria Rigo, 1DISTAV (Department of Earth, Environmental and Life Sciences), University of Genoa, Corso Europa 26, 16132 Genova, Italy. Phone +39 0103538069. E-mail paolo.vassallo@unige.it

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Abstract: Forest ecosystems are important providers of ecosystem functions and services belonging to four categories: supporting, provisioning, regulating, and cultural ecosystem services. Forest management, generally focused on timber production, has consequences on the ability of the system to keep providing services. Silviculture, in fact, may affect ecological structures and processes from which services arise. In particular, the removal of biomass causes a radical change in the stocks and flows of energy characterizing the system. Aiming at the assessment of differences in stored natural capital and ecosystem functions and services provision, three differently managed temperate forests of common beech (Fagus sylvatica) were considered: (1) a forest in semi-natural condition, (2) a forest carefully managed to get timber in a sustainable way and (3) a forest exploited without management. Natural capital and ecosystem functions and services are here accounted in biophysical terms. Specifically, all the resources used up to create the biomass (stock) and maintain the production (flow) of the different components of the forest system were calculated. Both stored emergy and empower decrease at increasing human pressure on the forest, resulting in a loss of natural capital and a diminished ability of the natural system to contribute to human well-being in terms of ecosystem services provision..

Keywords: *Fagus sylvatica*, emergy accounting, natural capital, ecosystem functions

1. Introduction

Forests store a relevant portion of the global natural capital and provide a multitude of ecosystem services, economic goods and social amenities to society [1]. The ecosystem services provided by forests are extremely diverse and include, among others, production of raw materials for food, fuel and shelter, availability of wildlife habitat, generation and maintenance of soils, air and water purification, dampening storm flows, regulate the climate and recycle nutrients and waste [2].

The economy of forests is dominated by the exploitation of timber, which is used in wood and paper industry. But forests provide a wider range of ecosystem services. For instance, people gain benefit also from non-consumptive use of nature through activity such as hiking, birdwatching and other kinds of outdoor recreation [3]. Markets can set the price for an economic good like timber and are able to infer the economic impact of social amenities but fail in evaluate many other ecosystem services.

When we make decisions to alter natural forest ecosystems, we often give little thought to the consequences that change may have on forest ecosystem services or to the ultimate cost of losing those services. This inherent inability stems from our incomplete knowledge about how changes in ecosystems affect the level of services that the systems provide and our inadequate understanding of the roles played by the complex set of ecosystem components. In addition, few ecosystem services have clearly established monetary values. And this can have a strong impact, considering that many decisions about resource use are made by comparing benefits and costs. The decision to log a forest tract, for example, should be based on a comparison of the expected monetary value of the timber and the costs associated with the ecosystem goods and services foregone as a result of logging. Any ecosystem goods and services that do not have monetary values are generally not accounted for in the decision calculus [4]. A system of environmental accounting for energy invested in all studied aspects of a system, called emergy synthesis, was developed by Odum [5, 6] to provide valuation independent of the market and economy, adherent to the fundamental laws of thermodynamics and able to define a monetary values for any ecosystem services. The emergy approach is based on a donor-side perspective of system functioning so that the environmental cost required to generate and maintain a system is associated to its value. Therefore, the greater is the investment of nature in the generation and maintenance of a system, the greater its value.

This valuation allows the connections between nature's production of ecosystem goods and services and people's consumption of them to be quantified in the same physical unit (i.e., solar energy) and then translated into monetary terms [2].

This conversion provides a mean for materializing the hidden value of nature to managers and policy-makers, whose decisions are mainly based on monetary considerations. The undervaluation of ecosystems contributions to human welfare in public and business decision-making can be partly explained by the fact that they are not adequately quantified in terms comparable with economic services and manufactured capital [7]. Making non-marketed ecosystem services visible and accountable as positive externalities is a possible way to incorporate nature in decision-making process and may lead the way toward sustainable management strategies [8]. As a matter of fact, the design, implementation and management of policies that incorporate services provided by ecosystems are dependent on the availability of explicit information about them [9]. The basis for the development of these policy decisions lies on reliable estimates of nature’s value and its capability to provide ecosystem services together with their economic values [10].

Information about the ecosystem services provisioning and demand, provides a baseline to measure nature’s losses and gains. These measures can be inserted in policy impact assessment and can be employed to address the development of financial instruments to finance investments in ecosystems [11, 12].

In this regard, here we apply emergy to three differently managed temperate forests of common beech (Fagus sylvatica) in Northern Italy characterized by different levels of exploitation: (1) a forest in semi-natural condition, (2) a forest carefully managed to get timber in a sustainable way and (3) a forest exploited without management. The evaluation is aimed at the assessment of differences in stored natural capital and ecosystem functions and services provision. A whole system evaluation is here proposed aiming at the assessment of the impacts, both on the economic and environmental side, arising from the F. sylvatica exploitation in a certain territory.

2. Materials and Methods

2.1 Study area

The study area is located in the so-called Oltrepò Pavese, an area in the north-west Italian region of Lombardy, which lies to the south of the Po river (Figure 1). Study sites are located along the northern facing slope of Mount Terme at an altitude of 1400 m a.s.l., , very close to “Val Boreca, Monte Lesima” Special Area of Conservation (44°43’ N, 9°15’E) and to “Le Torraie - Monte Lesima” Site of Community Importance. Here, beech forests belong to the protected habitat (EU Habitat Directive 92/43, Annex I) named “Asperulo-Fagetum beech forests” (cod. 9130). Mount Terme vegetation comprises beech forest and semi-natural dry grasslands and scrubland facies on calcareous substrates.

2.2 Field sampling

Three plots were identified as representative using remote sensing (Landsat cartography) and field surveys (GPS technology). In particular three geographic coordinates were randomly selected and used as centroids of three rectangular plots of 500 m2 (20 x 25 m) (Table 1). The three plots are different in terms of maintenance conditions. A plot is located in a forest in semi-natural condition (P-nat), a second in a forest carefully managed to get timber in a sustainable way (P-sus) and a third plot in a forest exploited without management and where trees were totally removed (P-exp). The forest in semi-natural condition is the result of the natural recovery of the forest from a cut made more than twenty years ago. Natural forests do not exist in this territory, which has been managed for hundreds of years.

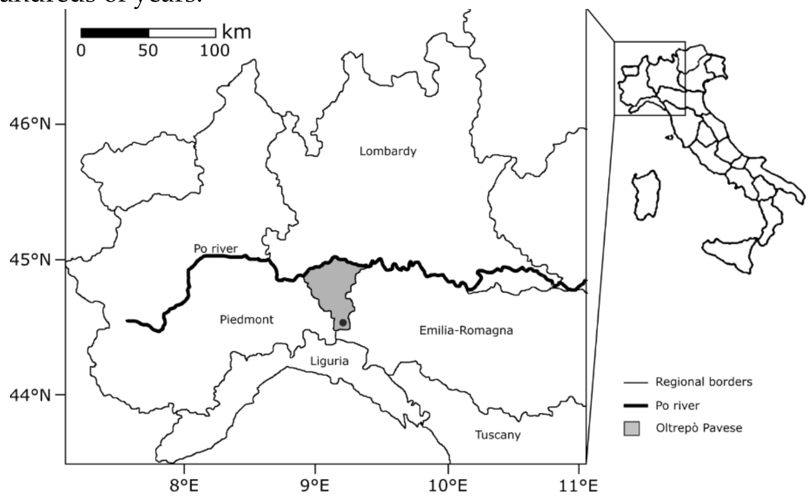

Figure 1: Location map of study area. Oltrepò Pavese area is indicated in gray, the black dot indicates plots site.

Table 1: main characteristics of the sampled plots

	P-nat	P-sus	P-exp
Coordinates	44°43′08′′N, 9°15′30′′E	44°43′07′′N, 9°15′31′′E	44°43′01′′N, 9°15′32′′E
Surface (m²)	500		
Max altitude (m)	1389	1412	1408
Min altitude (m)	1384	1399	1405
Annual rainfall (mm)	1474		
Slope (%)	48	48	26

Two sampling campaigns were performed in each plot during summer 2017 and 2018 aiming at counting and measuring trees, shrubs (in understorey vegetation) and invertebrates. Trees aboveground and belowground biomasses, shrubs aboveground biomass, invertebrate biomass and the relative annual biomass increase within each plot were accounted. At this purpose, all Fagus sylvatica trees and understorey vegetation were measured in each plot together with pitfall traps deployment and soil cores extraction for the invertebrate collection. Biomass annual increment, for trees understorey vegetation and invertebrates, was calculated as difference between biomass measured in 2017 and biomass measured in 2018.

2.3 Biomass estimation

2.3.1 Biomass from trees

Total Fagus sylvatica aboveground and belowground biomass (trunk, stem, branches, leaves, roots) was estimated using equations reported in Table 2.

Also standing dead trees were measured, but obviously their increment was registered like zero.

2.3.2 Biomass from understorey vegetation

Understorey vegetation biomass was reckoned measuring mean above-ground shoot length and cover of each species.

Understorey vegetation in the plots was composed by 62 different species of vascular plants (shrubs and herbaceous plants) and 8 different species of bryophytes. Allometric equations were applied to estimate biomass in the plots as reported in Table 2. In particular, the function constants a, b, c are selected according to 13 growth form groups identified by [13]. The species found within the plots, having considerable coverage (greater than 5%), were brought back to the 13 growth form groups and subsequently considered for the biomass estimation.

Table 2. Allometric equations considered in vegetation biomass estimation

Species		**Allometric equation**	**Author**
Fagus sylvatica	Trunk	$Y=0.0676*(d)^2+0.0182*(d)^2*h$	[14]
	Stem (>7 cm)	$Y=0.83*(d-22.5)^2-0.0248*(d-22.5)^2*h$	
	Stem (from 2 to 7 cm)	$Y=0.0792*(d)^2$	
	Stem (<2 cm)	$Y=0.093*(d)^2-0.00226*(d)^2*h$	
	Leaves	$Y=0.0145*(d)^{1.9531}$	[15]
	Roots	$Y=0.106*(d)^2$	[14]
Understorey	Above-ground biomass	$TS= a*D^b *ML^c$	[13]

Y: biomass (g); d: diameter at breast height (cm); h: plant height (m); TS: Above-ground biomass (g/m2); D: coverage ratio (%); ML: Mean above-ground shoot length (cm); a,b,c: Function constants.

2.3.3 Net primary production

Net Primary Production on a yearly base (NPP) is the net amount of carbon captured by plants through photosynthesis each year [16]. NPP is measured as the quantity of new organic matter that is retained by live plants at the end of a time interval (biomass increase), and the amount of organic matter that was both produced and lost by the plants during the same interval [17].

In this context NPP was estimated as biomass annual increase in trunk, stem and roots together with the biomass of leaves, being Fagus sylvatica a deciduous species.

2.3.4 Biomass of invertebrates

In order to sample the invertebrates' community, we used two different sampling methods: pitfall traps and soil cores extraction. Ground-dwelling invertebrates were sampled with three pitfall traps for each plot. Pitfall traps consisted of a 500 cm3 container, partially filled with a killing/preserving solution [18]. Traps were active for 14 days (October - November 2017). Soil invertebrates, instead, were sampled by using a 1000 cm3 soil core (i.e. a soil core measuring 10x10x10cm in length width and height, respectively). Three replicates were realized for each plot. Invertebrates, collected using Berlese-Tullgren extraction funnels traps, , were preserved in 90% ethanol. Then invertebrates were sorted and determined at the Order level while their length was digitally measured using a dissecting microscope and software ImageJ [19]. Biomass has been then estimated using arthropod length measures and following Ganihar's [20] Taxon-specific equations.

2.4 Soil erosion assessment

The quantitative rill-interill erosion was assessed by means of the Revised Universal Soil Loss Equation (RUSLE) [21, 22]. RUSLE is the most common methodology for the assessment of rill and interrill erosion processes and has been widely used for the estimation of soil erosion and to guide development and conservation plans in order to control erosion under different land-cover conditions [23, 24]. RUSLE is considered a simple model since it incorporates data that are easily available and/or accessible and since it provides reliable results [25]. RUSLE simulates rill and interrill soil erosion considering the effects of soil, topography, and land use. The model employs the following expression:

$$A = R\ K\ L\ S\ C\ P$$

where

A is the mean soil loss per year [Mg ha−1 y−1];

R is the rainfall–runoff erosivity factor [MJ mm ha−1 h−1 y−1];

K is soil-erodibility factor [Mg h MJ−1 mm−1]; L is the slope–length factor and S is the slope–steepness factor (dimensionless);

C is the cover-management factor (dimensionless) and

P is the support-practice factor (dimensionless).

To assess and adjust physical parameters included in the model a bibliographical survey and basic data collection (including pluviometric, soil, landuse/cover, and topographical data) was performed [8].

2.5 Ecosystem functions evaluation and emergy analysis application

The general methods for employing emergy synthesis were developed by Odum [6, 26]. Emergy synthesis concept is based on the assumption that the emergy value of a flow (of energy or material) is the sum of all emergy associated to the resources required (directly and indirectly) to create it. As a consequence, all inputs to a system must first be determined (emergy input analysis) and then allocated to internal system pathways and exported items (emergy allocation) [27]. Once the fluxes to the system have been identified, it is possible to calculate the solar emergy of each environmental and anthropic (e.g. fuels, human service) input by quantifying either its exergy (i.e. available energy), mass or money value and translating it to solar emergy by means of appropriate unit emergy values (UEV). Unit emergy values are also reckoned as transformities (seJ/J) or specific emergy values(e.g. seJ/g, or emergy per unit money value).

UEVs are calculated on the basis of the total annual emergy inflow to the biosphere from three primary exergy sources of different origins interacting to drive processes within the geobiosphere (the sun, moon, and deep-earth heat) that make up the whole annual emergy budget called baseline [28]. The baseline emergy is the reference system for every process, good or service being the basis of everything physically happening in the biosphere [29, 30]. The evaluations we are proposing are based on the 9.26E+24 sej/yr baseline [31] and emergy and transformity values based on different baselines were accordingly modified.

The emergy analysis of Fagus sylvatica forests was developed following the approach proposed by Vassallo [32] which allows to assess the value of natural capital and of the fluxes that it generates. The former accounting is applied to assess the biophysical value of the stock of resources accumulated in the living structures of the system, whereas the latter is focused on the evaluation of the natural flows supporting the annual biomass production (empower) [33]. These two measures were here considered respectively as evaluation of natural capital stored and of the ecosystem functions released by the beech stands.

Input items to common beech stands are solar energy, wind, geopotential and chemical energy of rain, geothermal heat, runoff, transpiration and nutrient consumption (here considered as C, N and P uptake required from environment to realize the photosynthesis).

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When total stored emergy (capital) or annual emergy flow (empower) of each plot is calculated, an emergy share can be ascribed to every internal processes occurring in beech forests and to each product or service maintained by the system. Identified forest services are: aboveground biomass increase, roots biomass increase, litterfall generation, understorey vegetation biomass increase, invertebrate biomass increase and soil retention.

The solar emergy amount ascribed to each service was determined through the emergy allocation procedures which include the emergy algebra rules that were sketched in Brown and Herendeen [34] and Odum [6]. According to emergy algebra the output of a process can be identified as split or co-product. Splits that are represented by flows of the same kind, with different emergy but the same UEV (for example, a water stream that divides into two). Co-products are outflows of a different kind and with different UEV (for example, flows of wool and mutton produced by the sheep agricultural system are co-products). Co-products have different UEVs because they emerge from different stages in the series of transformations during the same process [35].

Since processes on the common beech system provide different products (both from a physical and a functional perspective) they are here considered co-products meaning that the solar transformity of each service was calculated as the total solar emergy divided by its energy content. Transformity has been proposed as a measure of efficiency when comparing two similar products: a lower transformity of a product reflects the ability to use less past and present work of the biosphere (emergy) to produce a unit of product [10, 36].

Once all the internal products or exports are accounted in emergy terms, it is possible to translate these figures in the corresponding monetary value. Emergy is usually translated to money value, expressed in emergy-euros (i.e. em€), by dividing emergy amount by the average emergy-to-money ratio of an economic system. Nonetheless, several authors (e.g. [2, 37]) stated that emergy and ecosystem services values have to be independently evaluated from each other because economic evaluation and ecosystem functioning work on different scales. Therefore, a direct quantitative relation between the two does not seem appropriate [38, 39]. It is instead proposed to compare the global emergy budget, required to maintain the entire biosphere, together with the global value of services yearly provided by terrestrial ecosystems [7, 40]. Dividing the monetary value of the world ecosystem services by the emergy flow to the biosphere, it is possible to obtain the amount of ecosystem services monetary value that is, in average, produced by one seJ of solar emergy. This ratio can be considered as an estimate of the ability of the biosphere in providing a kind of economic wealth for humans and has been named Environmental Emergy Money Ratio (EnEMR hereinafter). EnEMR has a value between 5.09 E+11 seJ·€-1 and 1.51 E+11 seJ·€-1 depending on the minimum and maximum values of global ecosystem services calculated by Costanza [7]: we precautionary employed the highest value.

The monetary value of a natural good or services can be then calculated by dividing its emergy content by EnEMR..

3. Results

3.1. Biomass evaluation

Trees, shrubs, herbaceous vegetation and invertebrate biomasses were evaluated, and results are reported in Table 3.

Table 3: trees, shrubs, herbaceous vegetation and invertebrate biomasses in the three considered plots

Compartment	Species/Taxon	Part	P-nat (kg/500 m²)	P-sus (kg/500 m²)	P-exp (kg/500 m²)
Tree	*Fagus sylvatica*	Trunk	13219.81	3691.89	
		Stem (>7 cm)	1306.02	127.34	
		Stem (2 to 7 cm)	2511.08	853.13	

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		Stem (<2 cm)	1573.18	633.76	
		Leaves	398.84	134.81	
		Roots	3360.79	1141.81	
Total *Fagus sylvatica*			**22369.71**	**6582.73**	
Understorey	*Rubus hirtus*				48.32
	Rubus idaeus			1.80	8.94
	Agrostis capillaris			1.53	39.68
	Brachypodium sylvaticum				7.14
	Carex flacca				7.14
	Cirsium arvense				7.37
	Digitalis lutea			5.22	5.22
	Luzula nivea			8.81	
	Poa pratensis				11.19
	Sesleria argentea			77.06	7.14
	Veronica officinalis				0.33
	Fissidens taxifolius			0.26	
	Brachythecium glareosum		0.01	0.26	
	Pterigynandrum filiforme		0.03	0.31	
	Tortula marginata		1.58	1.58	0.15
	Hypnum cupressiforme		1.58	8.28	
Total understorey			**3.21**	**105.12**	**142.63**
Invertebrates	Acarina		0.16	0.17	0.26
	Araneae		0.01	0.01	0.03
	Opiliones		0.16	0.16	0.16
	Chilopoda/Diplopoda		0.67	1.04	1.16
	Coleoptera larvae		1.46	1.45	2.61
	Collembola		4.56	2.15	3.97
	Hymenoptera		0.05	0.04	0.34
	Anellida		2.48	3.72	1.86
Total invertebrates			**9.56**	**8.75**	**10.39**

In P-nat (not affected by human activity) 50 trees of F. sylvatica were measured while in P-sus (recently harvested for timber yield) 46 trees were identified even if 22 among them showed only shoots from their stumps. Finally, P-exp does not have any tree anymore.

Total tree biomass resulted 3.4 times higher in P-nat than P-sus. This is due to both the higher number of small size trees in P-nat and to the presence of a consistent number of trees with high and very high biomasses. In P-sus, on the other hand the biomass distribution showed a continuous decrease in number of trees at increasing size (Figure 2) never exceeding 1000 kg per tree.

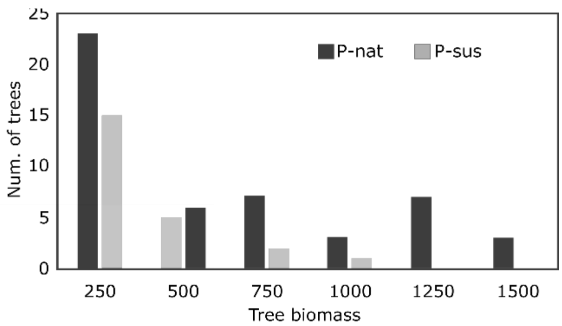

Figure 2: distribution of F. sylvatica trees in function of tree biomass

The lack of a consistent tree canopy in P-exp has led the way to a more abundant and complex understorey community which is represented by 11 species in P-exp compared to 10 in P-sus and 4 in P-nat. The total understorey biomass copes with the distribution of number of species with the highest value displayed by P-exp. Extremely low values are displayed by P-nat.

Invertebrate sampling produced a total number of 3160 invertebrates (1087, 888 and 1185 for P-nat, P-sus and P-exp respectively), belonging to 8 Taxa. A multivariate analysis of similarity revealed no significant differences in the invertebrates community composition (ANOSIM; R = -0.007; p = 0,540; 9999 Bootstrap replicates). The Shannon diversity index applied to invertebrate community (H; 1.44, 1.37 and 1.42 for P-nat, P-sus and P-exp respectively) are similar in the three plots. Finally, the estimated invertebrates' biomass was quite similar between the three stands (Table 3).

3.2. Soil erosion

The application of the RUSLE methodology allowed the quantification of the rill and interill erosion in the three plots (Table 4).

In the P-nat (not affected by human activity) loss rate is lower (3.294 kg/ha/year) than in the P-sus recently harvested for timber yield (6.367 kg/ha/year) and than in the P-exp that does not have any F. sylvatica tree anymore (83.692 kg/ha/year).

Table 4: Factors and results of the RUSLE methodology

	Methodology	**P nat**	**P sus**	**P exp**
R factor	[41]	100.44	100.44	100.44
LS factor	[42]	10	6	8
K factor	[22]	0.032799109	0.035214941	0.02083131
C factor	[43]	0.0001	0.0003	0.05
P factor	[44]	1	1	1
RUSLE		**0.003294343**	**0.00636658**	**0.836918715**

This is due to the different soil and environment characteristics that make P-exp more subject to erosion than the others in natural condition.

This is also in accord with the general theory revealing that vegetation protect soil of erosion [45, 46, 25, 47, 48].

3.3. Emergy of common beech stands

The energy system diagram of a F. sylvatica stand is reported in Figure 3 showing the external sources feeding the system, the internal processes and the provided services. The input of different types of energies (solar radiation, kinetic energy of wind, precipitation and geothermal heat) and resources (nutrients) interact with the trees, understorey and invertebrates biomasses to generate the living structures in the system and to maintain internal cycles such as biomass increase, litter generation, water and soil cycles.

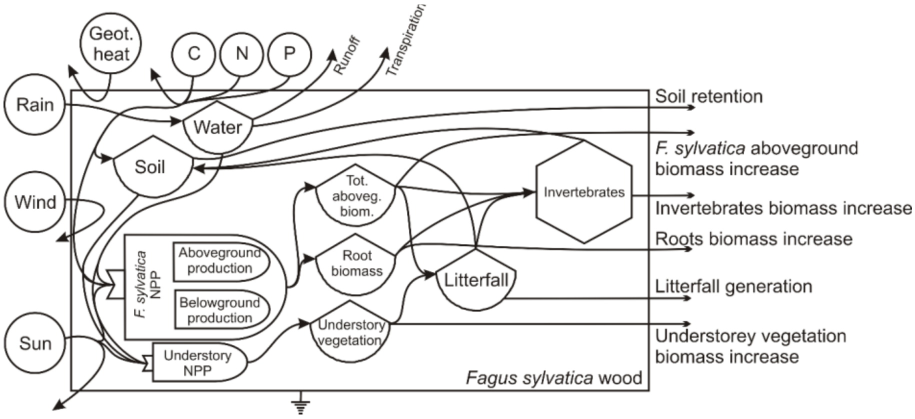

Figure 3: System diagram of the F. sylvatica forest functioning and ecosystem functions provisioning, natural capital components are indicated as storages while functions are outflows arrows

The energy and materials flows identified in Figure 3 are also listed in Table 5 and Table 6 and translated in emergy equivalents by means of appropriate unit emergy values.

3.3.1 Natural capital evaluation

Total stored emergy resulted highest in P-nat and displayed decreasing values moving to more and more exploited stands. The highest input contributing to stored solar emergy (Table 5) is always due to rain (varying from chemical to geopotential in different cases).

Table 5: calculation in emergy units of the flows required in space and time to create the natural capital (item 1-9) stored in the F. sylvatica forests and emergy required for different system components (items a-e). Equations are reported in appendix Table A1.

	Input		**Quantity**			**Uni**	**UeV**	**Emergy**		
			P-nat	**P-sus**	**P-exp**			**P-nat**	**P-sus**	**P-exp**
1	Sun		1.93E+10	9.71E+09	5.81E+09	J	1.00E+00	1.93E+10	1.01E+10	5.81E+09
2	Wind		1.53E+12	7.70E+11	4.61E+11	J	2.41E+03	1.93E+15	1.86E+15	1.11E+15
3	Rain									
	3°	Chemical	3.88E+11	1.96E+11	1.17E+11	J	2.93E+04	1.14E+16	5.95E+15	3.43E+15
	3b	Geopotential	2.01E+12	1.41E+12	1.21E+11	J	1.69E+04	3.39E+16	2.48E+16	2.04E+15
4	Geothermal heat		1.17E+08	5.88E+07	3.52E+07	J	2.00E+04	2.34E+12	1.18E+12	1.22E+12
5	Runoff		6.05E+11	4.26E+11	3.65E+10	J	2.72E+04	1.65E+16	1.21E+16	9.92E+14
6	Evapotranspiration		2.18E+11	6.72E+10	1.41E+10	J	2.81E+04	6.12E+15	1.89E+15	1.96E+15
7	C		1.02E+07	3.17E+06	3.12E+05	g	1.02E+08	1.04E+15	3.25E+14	3.19E+13
8	N		4.48E+05	1.61E+05	5.32E+04	g	7.40E+09	3.32E+15	1.19E+15	3.94E+14
9	P		6.09E+04	2.20E+04	7.60E+03	g	2.86E+10	1.75E+15	6.31E+14	2.18E+14
	Total emergy							**4.34E+16**	**2.80E+16**	**4.22E+15**
a	Roots biomass							5.81E+15	3.05E+15	0.00E+00
b	Aboveground biomass							3.29E+16	1.46E+16	0.00E+00
	b.1			Stems				3.22E+16	1.42E+16	0.00E+00
	b.2			Leaves				6.89E+14	3.60E+14	0.00E+00
C	Understorey vegetation							3.98E+15	8.47E+15	4.78E+14
d	Invertebrates							7.31E+14	1.94E+15	3.74E+15

The distribution of natural capital among different system components is heterogeneous (Table 5). The highest share of natural capital is stored in the wooden part of the trees (stems) apart from P-exp whose capital is mainly driven by invertebrates that play a major role due to the absence of trees. Over 10% of the total capital is stored belowground in roots in both P-nat and P-sus (Table 5). Understorey contribution is especially significant in P-sus, with a 30% share of natural capital.

3.3.2 Ecosystem functions evaluation

3.3.2.1. Total system functioning

Total empower, given by the resources annually required to maintain the natural capital, is higher in P-sus while the lowest value is showed again by P exp. Nitrogen uptake is the highest annual flow in P-nat and P-exp, while P-sus annual emergy flow is mainly driven by the geopotential energy of rain (Table 6). In all the considered cases the annual empower is mainly driven by resources conveyed to invertebrates.

Table 6: calculation in emergy units of the flows exploited on a yearly base (empower) in the F. sylvatica forests. Equations are reported in appendix Table A2.

			Annual flow			Unit	UeV	Empower		
			P-nat	P-sus	P-exp			P-nat	P-sus	P-exp
1	Sun		1.95E+08	1.95E+08	1.95E+08	J	1.00E+00	1.95E+08	1.95E+08	1.95E+08
2	Wind		1.55E+10	1.55E+10	1.55E+10	J	2.41E+03	3.73E+13	3.73E+13	3.73E+13
3	Rain									
	3°	Chemical	3.93E+09	3.93E+09	3.93E+09	J	2.93E+04	1.15E+14	1.15E+14	1.15E+14
	3b	Geopotential	2.03E+10	2.85E+10	2.03E+09	J	1.69E+04	3.43E+14	4.81E+14	3.43E+13
4	Geothermal heat		1.18E+06	1.18E+06	1.18E+06	J	2.00E+04	2.37E+10	2.37E+10	2.37E+10
5	Runoff		6.13E+09	8.58E+09	1.23E+09	J	2.72E+04	1.67E+14	2.33E+14	3.33E+13
6	Evapotranspiration		2.20E+09	1.35E+09	4.74E+08	J	2.81E+04	6.19E+13	3.80E+13	1.33E+13
7	C		5.84E+05	5.05E+05	2.87E+05	g	1.02E+08	5.97E+13	5.15E+13	2.93E+13
8	N		5.23E+04	4.81E+04	4.90E+04	g	7.40E+09	3.87E+14	3.13E+14	3.62E+14
9	P		6.84E+03	6.38E+03	7.00E+03	g	2.86E+10	1.96E+14	1.67E+14	2.00E+14
	Total							**7.92E+14**	**8.32E+14**	**4.91E+14**
a	Roots biomass							1.23E+13	1.36E+13	0.00E+00
b	Aboveground biomass							2.33E+14	1.18E+14	0.00E+00
	b.1	Stems						1.13E+14	6.62E+13	0.00E+00
	b.2	Leaves						1.20E+14	5.14E+13	0.00E+00
c	Understorey vegetation							0.00E+00	5.38E+12	1.79E+13
d	Invertebrates							5.47E+14	6.95E+14	4.73E+14

3.3.2.2. Co-functions evaluation (emergy allocation to ecosystem functions)

The solar emergy values of the functions generated by the common beech stands are listed in Table 7. Here the transformity of the different functions is calculated according to emergy algebra rules.

Table 7: Ecosystem functions of Fagus sylvatica forests.

P-nat

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		Annual flow	Unit	Transformity (seJ/J)
1	F. sylvatica aboveground biomass increase	7.45E+09	J	1.06E+05
	1a - Stem wood	2.96E+09	J	2.68E+05
	1b - Stem bark	3.48E+09	J	2.28E+05
	1c - Thick branches	6.01E+08	J	1.32E+06
	1d - Thin branches	4.02E+08	J	1.97E+06
2	roots biomass increase	8.05E+08	J	9.85E+05
3	litterfall generation	7.85E+09	J	1.01E+05
4	understorey vegetation biomass increase	0.00E+00	J	Function not
5	Invertebrate biomass increase	2.94E+06	J	2.69E+08
6	soil retention	2.34E+07	J	3.38E+07
	P-sus			
		Annual flow	**Unit**	**Transformity (seJ/J)**
1	F. sylvatica aboveground biomass increase	3.41E+09	J	2.44E+05
	1a - Stem wood	2.26E+09	J	3.69E+05
	1b - Stem bark	2.41E+08	J	3.45E+06
	1c - Thick branches	5.25E+08	J	1.59E+06
	1d - Thin branches	3.92E+08	J	2.12E+06
2	roots biomass increase	7.02E+08	J	1.18E+06
3	litterfall generation	2.65E+09	J	3.14E+05
4	understorey vegetation biomass increase	4.74E+07	J	1.76E+07
5	Invertebrate biomass increase	2.51E+06	J	3.32E+08
6	soil retention	2.33E+07	J	3.56E+07
	P-exp			
		Annual flow	**Unit**	**Transformity (seJ/J)**
1	F. sylvatica aboveground biomass increase	0.00E+00	J	Function not
	1a - Stem wood	0.00E+00	J	Function not provided
	1b - Stem bark	0.00E+00	J	Function not provided
	1c - Thick branches	0.00E+00	J	Function not provided
	1d - Thin branches	0.00E+00	J	Function not provided
2	roots biomass increase	0.00E+00	J	Function not
3	litterfall generation	0.00E+00	J	Function not
4	understorey vegetation biomass increase	3.10E+08	J	1.58E+06
5	Invertebrate biomass increase	6.79E+01	J	7.23E+12
6	soil retention	0.00E+00	J	Function not

In this study F. sylvatica aboveground biomass increase, roots biomass increase, litterfall generation, understorey vegetation biomass increase, invertebrate biomass increase and soil retention were considered co-products and thus they resulted with the same solar emergy but different transformities (Table 7).

The highest solar transformity was displayed by invertebrate biomass increase in all the stands considered. Invertebrates' production and maintenance are extremely expensive in terms of resource flows per unit of energy and require a huge amount of emergy to be produced and kept in the system, despite their low biomass and their limited yearly production.

The stands in natural condition is able to generate wood, root and litterfall in a more efficient way that P-sus as demonstrated by its lower transformities. Also soil is more effectively retained in P-nat than in P-sus, even if slightly. On the contrary, the more natural system is unable to generate understorey biomass and less efficient to maintain the invertebrate fauna than the exploited stand. The P-exp plot is then able to provide only a couple

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of functions (understorey vegetation biomass increase and Invertebrate biomass increase) but in a very efficient way.

4. Discussion

Wood harvesting is an activity exploiting the provisioning of raw material from forests to generate economic flows and wealth. Being a direct withdrawal of living structures from a complex ecosystem the wood yield has consequences on the natural stocks and functioning of the forest that are generally neglected or poorly considered when the decision to harvest is taken. In this study we applied a donor-side approach to evaluate the effect of wood harvesting on common beech forests. At this purpose a natural system and two exploited stands, harvested with different levels of invasiveness, were compared to quantify, from a biophysical perspective, the effect of wood harvesting.

The natural stand (P-nat) is able to store the highest natural capital (1.5 times the P-sus and 10.3 times the P-exp) being the one where the wood harvesting is not performed. Here the understorey system is poorly developed but the trees are higher in number and bigger in size. In fact, the natural capital in P-nat is mainly stored in the tree biomass (89% of total natural capital) while understorey (9% of total natural capital) and invertebrates (2% of total natural capital) are less able to stock value in the system.

The same ratio is also shown in the forest harvested in a sustainable way (P-sus) even if reduced tree coverage, due to the withdrawal of trees, in particular big and mature ones, allows the lower vegetational levels of the forest to obtain more solar radiation. Thus the diversity and abundance of understorey vegetation increases as revealed by its greater capability to store natural capital (30 % of total natural capital).

The natural capital of the strongly exploited forest (P-exp) has been heavily impacted. The complete removal of the trees from the stand brought to 1) a massive natural capital loss and 2) a reversal in the relevance of the forest's components in terms of natural capital stored. In P-exp invertebrates store the 89% of the total natural capital. The remaining capital of P-exp is associated to understorey biomass which is well established, abundant and diversified due to the lack of mature trees in the plot.

Taking into consideration the ability of the system to annually convey flows and resources, P-nat and P-sus displayed light differences despite natural capital evident disparities. This is expectedly due to the higher productivity of the trees standing in P-sus that take advantage of the reduced competition and increase the net primary production rate of the system. P-exp displayed again the lowest emergy value being the trees absent and being the vegetation unable to maintain as much complex structures that call for intense natural fluxes as P-nat and P-sus. The total amount of resources yearly exploited is here considered as the biophysical measure of the ecosystem functions provided by the system. Beside the total amount of functions provided, it has been possible to evaluate the efficiency in functions provisioning thanks to the evaluation of the cost per unit of product generated (Table 7). It should not be forgotten that the semi-natural common beech forest (P-nat) is actually the result of a cut of the forest, made more than twenty years ago, therefore the ecological dynamics within it are more similar to those of P-sus than those that would exist in a hypothetical natural forest never cut. In fact, natural forests do not exist in most of Europe territory, which has been managed for hundreds of years (natural forest ecosystems account for less than 2% of forests in Western Europe [49]). P-nat, where the ecosystem is undisturbed and able to develop towards mature stages, is able to provide with the maximum efficiency the entire set of ecosystem functions considered apart from understorey vegetation and invertebrate biomass increase. These functions which are not directly related to the abundance and biomass of trees in the system are most efficiently generated by P-exp. The reduced tree coverage due to the timber yield let solar radiation to reach the lower levels of the forest increasing understorey vegetation diversity and growth rate that is mirrored by greater efficiency of this compartment. Together with the greater quantity of understorey vegetation, an increased ability to maintain a more

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abundant and productive invertebrate community was assessed identifying harvested stands as more able to supply these services when compared to healthier and more mature forest.

4.1. Economic valuation

More and more environmental and resource economists are taking a particular interest in research on forest ecosystem services. Interdisciplinary research involving ecological and economic disciplines is a prerequisite for the more effective management of forest ecosystems [50]. In this context, several authors proposed a number of market and non-market evaluations of services provided by forests. A list of recent evaluations developed adopting different methodologies is reported in table 8.

Table 8: Comparison of forests' ecosystem services and natural capital estimations. Data have been updated to 2021 value by power of the dollar over time (U.S. Labor Department's Bureau of Labor Statistics).

Authors	**Methods**	**System**	**Minimum**	**Maximum**	
Annual services					
Merlo and Croitoru [51]	non-market evaluations	Italian forests	403		$/ha/yr
Croitoru [52]		Mediterranean forest	74	263	
Bernetti et al. [53]		Protected Italian forests	3'306		
Costanza et al. [54]		World's forests	311	18'375	
Campbell and Brown [55]	emergy	US national forests	158		em$/ha/yr
Campbell and Tilley [2]		Maryland forest	302	824	
Turcato et al. [8]		Italian Pinewood	9'576	12'096	
This study		Italian beechwood	19'000	32'000	
Stored capital					
Campbell and Brown [55]	emergy	US national forests	361'920		em$/ha
This study		Italian beechwood	166'000	1'700'000	

The range of values is wide both because of different methodologies adopted and because of the variety of services and function provided by forests. Among studies reported in Table 8, several studies estimated forests' value basing on users' perception of the supplied services. Recently, an increasing number of economists are advocating biophysical measurements as a basis for valuation [56]. Despite useful to get a valuation of the user's perception of nature's value, these measures are intrinsically affected by the comprehension of the system, by preferences and by the contingencies of the market [57]. Nonetheless, ecosystem functions neglected or poorly evaluated by humans and market, may play key role for the ecosystem functioning and for the provisioning of other services useful and valuable for mankind [58]. As a consequence, the total value of a system (and of a forest in the specific case) cannot disregard an assessment based on a biophysical accounting based on the amount of resources invested by nature to maintain the system, independently from the presence of direct users and from the value they ascribe to a generated service [37]. Emergy analysis allows obtaining this evaluation adopting a donor side perspective and ascribing the cost of directly and indirectly exploited resources. Moreover, with a donor-side biophysical evaluation, it is possible to estimate the value of the natural capital stored in a system and of generated functions alike [32].

The natural capital stored in common beechwoods, according to the evaluation performed in this work, drops abruptly in case of timber harvesting. The monetary equivalent of the capital stored in a wood in natural condition (P-nat) sums up to 1.7 million Em€ ha-1 decreasing to 1.1 million Em€ ha-1 in case of a wood harvested in a sustainable way (P-sus) and falling to 166,000 Em€ ha-1 when the wood is completely exploited for timber production (P-exp). By the way, forest cutting, in the face of a decrease in natural capital, causes an increase in terms of both plant and animal diversity. In our analysis this is represented by the highest value of annual flows in P-sus. In a management perspective this has to be interpreted as an operation of capital liquidation to increase the gains. Even according to market rules, financial capital liquidation presents a certain level of risk and it is un-realistic to foresee a continuous liquidation or the bankrupt is inevitable. Borrowing this framework from the economy, the same concept (mutatis mutandis) is applicable to the management of a natural system. Eroding natural capital is always a risk since in a precautionary approach, to maintain services provisioning at the current level, natural capital must be kept intact [59, 60]. At least, the loss should be carefully accounted and possibly balanced by an increase in functionality, otherwise the system is likely to be compromised (like in P-exp). If not ruled and managed in and ecologically sustainable way, markets will tend to over-produce market goods and services, erode natural capital and under-produce ecosystem functions [61]. An ecological system of valuation is thus necessary because human assessments do not measure the real contributions of natural ecosystems to human wellbeing [62].

The application of emergy analysis brought to the identification of six different functions provided by F. sylvatica forest. The services were here considered all co-products of the common beech wood system maintained by all the inputs listed in Table 6. As a consequence of emergy algebra rule application, the total emergy of the entire system is assigned to each service. As a consequence, P-nat functions are worth 31,135 Em€ ha-1 year-1, P-sus 32,688 Em€ ha-1 year-1 while P-exp services summed up to 19,293 Em€ ha-1 year-1. The timber harvesting activity does not provoke ecosystem services provision loss when performed in a sustainable way, while if the forest is strongly exploited the estimated loss equals up to 13,391 Em€ ha-1 year-1. This difference might be interpreted as the loss of value due to the shift backward on the succession of a beechwood after timber harvesting and it is the final consequence of the reduction in complexity of the system.

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Appendix A

Table A1: equations and factors for the natural capital accounting

1	**Solar radiation = Area x solar radiation intensity x lifetime†**		
	Area	500	m2
	Solar radiation intensity	3.90E+05	J m-2 year-1
2	**Wind=Area x (wind speed)3 x air density x drag coeff x lifetime†**		

	Area	500			m2
	wind speed	1.19E+08			m year-1
	drag coefficient	0.003			
	air density	1.3			Kg m-^{3}
3a	**Chemical = area x rain x water density x water Gibbs energy x lifetime†**				
	Area	500			m^2
	rain	1.66			m $year^{-1}$
	water density	1.00E+06			g m^{-3}
	Water Gibbs energy	4.74			J g^{-1}
3b	**Geopotential = area x rain x water density x (mean elevation- min elevation) x g x lifetime†**				
	Area	500			m^2
	rain	1.66			m $year^{-1}$
	water density	1.00E+06			g m^{-3}
	mean elevation	1387	1404	1405	m
	min elevation	1384	1400	1404	m
	g	9.8			m s^{-2}
4	**Geothermal heat = area x heat flow x lifetime**				
	Area	500			m^2
	heat flow	2370			J $year^{-1}$
5	**Runoff = area x runoff x (mean elevation- min elevation) x water density x g x lifetime†**				
	Area	500			m^2
	runoff	0.5			m $year^{-1}$
	mean elevation	1387	1404	1405	m
	min elevation	1384	1400	1404	m
	water density	1.00E+06			g m^{-3}
	g	9.8			m s^{-2}
6	**Transpiration = area x transpiration x water density x water Gibbs energy x lifetime†**				
	Area	500			m^2
	transpiration	1.47			m $year^{-1}$
	water density	1.00E+06			g m^{-3}
	Water Gibbs energy	4.74			J g^{-1}
7	**C = carbon stored in living organisms**				
	carbon fixed	1.02E+07	3.17E+06	3.12E+05	g
8	**N = carbon stored * C:N ratio**				
	carbon fixed	1.02E+07	3.17E+06	3.12E+05	g
	C:N ratio	0.04			
9	**P = carbon stored * C:P ratio**				
	carbon fixed	1.02E+07	3.17E+06	3.12E+05	g
	C:P ratio	0.01			

†Lifetime is accounted following Vassallo et al., 2017 and sums up to 98.8 years in P-nat, 51.7 in P-sus and 29.8 in P-exp

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Table A2: equations and factors for the ecosystem functions accounting

1	**Solar radiation = Area x solar radiation intensity**				
	Area	500			m2
	Solar radiation intensity	3.90E+05			J m-2 year-1
2	**Wind=Area x (wind speed)3 x air density x drag coeff**				
	Area	500			m2
	wind speed	1.19E+08			m year-1
	drag coefficient	0.003			
	air density	1.3			Kg m^{-3}
3a	**Chemical = area x rain x water density x water Gibbs energy**				
	Area	500			m^2
	rain	1.66			m $year^{-1}$
	water density	1.00E+06			g m^{-3}
	Water Gibbs energy	4.74			J g^{-1}
3b	**Geopotential = area x rain x water density x (mean elevation- min elevation) x g**				
	Area	500			m^2
	rain	1.66			m $year^{-1}$
	water density	1.00E+06			g m^{-3}
	mean elevation	1387	1404	1405	m
	min elevation	1384	1400	1404	m
	g	9.8			m s^{-2}
4	**Geothermal heat = area x heat flow**				
	Area	500			m^2
	heat flow	2370			J $year^{-1}$
5	**Runoff = area x runoff x (mean elevation- min elevation) x water density x g**				
	Area	500			m^2
	runoff	0.5			m $year^{-1}$
	mean elevation	1387	1404	1405	m
	min elevation	1384	1400	1404	m
	water density	1.00E+06			g m^{-3}
	g	9.8			m s^{-2}
6	**Transpiration = area x transpiration x water density x water Gibbs energy**				
	Area	500			m^2
	transpiration	1.47			m $year^{-1}$
	water density	1.00E+06			g m^{-3}
	Water Gibbs energy	4.74			J g^{-1}
7	**C = carbon fixed annually in living organisms**				
	carbon fixed	1.17E+03	3.64E+05	2.87E+05	g $year^{-1}$
8	**N = carbon fixed * C:N ratio**				
	carbon fixed	1.17E+03	3.64E+05	2.87E+05	g $year^{-1}$
	C:N ratio	0.04			
9	**P = carbon fixed * C:P ratio**				
	carbon fixed	1.17E+03	3.64E+05	2.87E+05	g $year^{-1}$

	C:P ratio	0.01	

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