

Supplementary Information

Analysing spatial congruencies and mismatches between supply, demand and flow of ecosystem services and sustainable development

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Table 1: Indicators of ecosystem services (modified from Schirpke et al. [1]).

Category	Ecosystem service	Component	Indicator	Method	Unit	Full details on data sources and methods
Provisioning service	Fresh water	Supply	Water availability	Quantity of water runoff from subcatchments of the Alpine space estimated by the hydropower model from the InVEST toolbox based on root restricting layer depth (mm), plant available water content, average annual precipitation, average annual potential evapotranspiration and land use/land cover [2,3]	$\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$	http://www.wikialps.eu/doku.php?id=wiki:water_availability
		Flow	Water use	Water usage based on regional water statistics downscaled to municipality level using touristic and demographic data [3]	$\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$	http://www.wikialps.eu/doku.php?id=wiki:water_use
		Demand	Water abstraction	Drinking water requirements of households based on regional data downscaled to municipality level using touristic and demographic data [3]	$\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$	http://www.wikialps.eu/doku.php?id=wiki:water_abstraction
	Grassland biomass	Supply	Gross fodder production	Forage production on permanent grassland estimated based on growth functions for different grassland management types depending on the length of the growing season and with consideration of site parameters such as precipitation and sum of radiation [4]	$\text{t DM ha}^{-1} \text{ y}^{-1}$	http://www.wikialps.eu/doku.php?id=wiki:gross_fodder_production
		Flow	Net fodder energy content	Actual used fraction of forage production based on the energy content of the raw material including losses from harvest and storage [4]	$\text{MJ NEL ha}^{-1} \text{ y}^{-1}$	http://www.wikialps.eu/doku.php?id=wiki:net_fodder_energy_content
		Demand	Feed energy requirements	Energy demand of forage feeding livestock species based on agricultural census data, age class, herd composition and performance demand for cows' milk production [4]	$\text{MJ NEL ha}^{-1} \text{ y}^{-1}$	http://www.wikialps.eu/doku.php?id=wiki:feed_energy_requirements
	Fuel wood	Supply	Wood biomass increment	Annual increment of above-ground biomass in forests based on IPCC equations [5]	$\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$	http://www.wikialps.eu/doku.php?id=wiki:wood_biomass_increments

Category	Ecosystem service	Component	Indicator	Method	Unit	Full details on data sources and methods
		Flow	Wood removals	Timber removals for fuel wood production considering forest accessibility and in-site conditions [6]	m ³ ha ⁻¹ y ⁻¹	http://www.wikialps.eu/doku.php?id=wiki:wood_removals
		Demand	Potential fuel wood requirements	Fuel wood requirements based on statistics of fuelwood consumption, building areas and heating degree days	m ³ y ⁻¹	http://www.wikialps.eu/doku.php?id=wiki:fuel_wood_requirements
Regulating service	Filtration of surface water	Supply	Potential nitrogen removals	Potential nitrogen filtration capability based on the InVEST NDR model [2]	%	http://www.wikialps.eu/doku.php?id=wiki:nitrogen_removals
		Flow	Effective nitrogen removals	Amount of nitrogen filtered by ecosystems based on InVEST NDR model [2]	kg ha ⁻¹ y ⁻¹	http://www.wikialps.eu/doku.php?id=wiki:nitrogen_removal_2
		Demand	Nitrogen loads	Amount of nitrogen introduced in ecosystems based on: nitrogen emitted in the atmosphere and then deposited in the landscape, nitrogen used for fertilisation in agriculture	kg ha ⁻¹ y ⁻¹	http://www.wikialps.eu/doku.php?id=wiki:nitrogen_loads
	Protection against mountain hazards	Supply	Site-protecting forest	Forest area with a protective effect against potential avalanches, rock falls and channel processes [7]	%	http://www.wikialps.eu/doku.php?id=wiki:protection_forest_calc
Flow		Object-protecting forest	Forest area with a protective effect for human infrastructure against potential avalanches and rock falls [7]	%		
Demand		Infrastructure in hazard zones	Area of human infrastructure located in avalanche and rock-fall hazard zones [8]	%		
	Carbon sequestration	Supply/flow	CO ₂ sequestration by forests	Annual rate of CO ₂ sequestration by above- and below-ground biomass in forests based on IPCC equations [5]	t CO ₂ ha ⁻¹ y ⁻¹	http://www.wikialps.eu/doku.php?id=wiki:co2_sequestration

Category	Ecosystem service	Component	Indicator	Method	Unit	Full details on data sources and methods
		Demand	CO ₂ emissions	Annual rate of CO ₂ emissions based on different emission inventories [9,10]	t CO ₂ ha ⁻¹ y ⁻¹	http://www.wikialps.eu/doku.php?id=wiki:co2_emissions
Cultural service	Outdoor recreation	Supply	Outdoor recreation availability	Recreation opportunities provided by ecosystems based on six landscape indicators (naturalness, protected areas, presence of water, landscape diversity, terrain ruggedness, density of mountain peaks), weighted by accessibility [11]	Index	http://www.wikialps.eu/doku.php?id=wiki:recreational_offer
		Flow	Visitation rates	Annual visitation rates estimated from the density of georeferenced photographs referred to user-days [11]	Index	http://www.wikialps.eu/doku.php?id=wiki:visitation_rate
		Demand	Potential beneficiaries	Density of potential beneficiaries derived from the number of residents and overnight stays of tourists [11]	Resident equivalent (index)	http://www.wikialps.eu/doku.php?id=wiki:beneficiaries
	Symbolic plants and animals	Supply	Habitats of symbolic species	Spatial distribution of habitats of selected symbolic plants and animals using habitat models or distribution maps [12]	Area-weighted index	http://www.wikialps.eu/doku.php?id=wiki:habitats_of_symbolic_species
Flow		Occurrence in hotel names	Mapping of the occurrence of selected symbolic plants and animals in hotel names [13]	Number of hotels (n)	http://www.wikialps.eu/doku.php?id=wiki:occurrence_in_hotel_names	

Table S2. Sustainability indicators related to economic, environmental and social dimensions (adapted from [14]).

Category	Indicator name	Unit	Description	Data source
Environment	Artificial areas	%	The indicator represents the percentage of artificial areas per total municipal area based on Corine Land Cover 2012. The following land cover classes were used: 1.1 – Urban fabrics, 1.2 – Industrial, commercial and transport units, 1.3 – Mine, dump and construction sites, and 1.4 – Artificial, non-agricultural vegetated areas.	Corine land cover 2012 [15], resolution: 100x100 m
	Forest areas	%	The indicator represents the percentage of area covered by forests per total municipality area. All land cover types falling in the classes 1 – broadleaved forests, and 2 – coniferous forests, were used.	Copernicus Land Monitoring Services: High Resolution Layer, Forests 2015 [16], resolution: 20x20 m
	Near-natural and natural open areas	%	The indicator represents the percentage of area covered by near-natural and natural open areas in each municipality based on Corine Land Cover 2012. The following land cover classes were used: 3.2 – Shrub and/or herbaceous vegetation associations, 3.3 – Open space with little or no vegetation, 4.1 – Inland wetlands, 4.2 – Coastal wetlands and 5.1 – Inland waters were used to identify near-natural and natural open areas.	Corine land cover 2012 [15], resolution: 100x100 m
	Land-cover diversity of agricultural areas	n km ⁻²	The indicator represents the number of different land-cover types found in agricultural areas per km ² . The following land cover classes were used: 2.1 – Arable land, 2.2 – Permanent crops, 2.3 – Pastures, 2.4 – heterogeneous agricultural areas.	Corine land cover 2012 [15], resolution: 100x100 m
	Land-cover diversity of near-natural and natural areas	n km ⁻²	The indicator represents the number of land-cover types found in near-natural and natural areas per km ² .	Corine land cover 2012 [15], resolution: 100x100 m
	Road density	m km ⁻²	The indicator represents the road density of all paved roads. It was calculated dividing the road length by the total municipal area (m/km ²).	OpenStreetMap (road network) [17]
	Special protected areas	%	The indicator represents the percentage of municipal area that is covered by special protection of SPA sites. For Switzerland and Liechtenstein, IBA (Important Bird Areas) were selected as comparable protected areas to the European SPAs.	EU: Natura2000 database (SPA sites only) [18]; CH&LI: BirdLife Switzerland (IBA sites) [19]
	Natura 2000 areas	%	The indicator represents the percentage of area covered by a Natura 2000 site, to the total municipal area. For Switzerland and Liechtenstein comparable protected sites were chosen: namely, “Smaragd Gebiete” and the Swiss Important Bird Areas (IBA), and Liechtenstein’s nationally designated areas (CDDA).	EU: Natura2000 database [18]; CH: Smaragd Gebiete (Bundesamt für Umwelt [20], IBA sites

Category	Indicator name	Unit	Description	Data source
				(BirdLife CH) [19]; LI: CDDA boundaries (EEA Europe) [21]
Society	Population	n	The indicator represents the number of residents for each municipality within the Alpine Space for the reference year 2011.	National statistical offices 2011 [22]
	Natural population growth	%	The indicator represents the natural population, calculated by taking the difference between births and deaths registered in the year 2011, in relation to the total population of each municipality.	National statistical offices 2011 [22]
	Youth rate	%	The indicator is calculated as the ratio between the number of young persons (under 15), and the number of persons in working age (between 15 and 64 years old), expressed as a percentage.	National statistical offices 2011 [22]
	Old age rate	%	The indicator is calculated as the ratio between the number of persons in retirement age (over 64), and the number of persons in working age (between 15 and 64 years old), expressed as a percentage.	National statistical offices 2011 [22]
	Old to young age ratio	%	The indicator is calculated as the ratio of the number old persons (over 64) to the number of young persons (under 15).	National statistical offices 2011 [22]
	Single-person households	%	The indicator is calculated as the ratio of single-person households to the total number of private households, expressed as a percentage.	National statistical offices 2011 [22]
	Average household size	n	The indicator is calculated as the ratio of residents to the total of private households of a municipality. It gives a measure of how many people on average share a household.	National statistical offices 2011 [22]
	Divorced residents	%	The indicator is calculated as the percentage of divorced to the total number of residents of the municipality.	National statistical offices 2011 [22]
Economy	Total employment rate	%	The indicator is calculated as the ratio of the number persons of unemployable age to the number of persons aged 15-64, expressed as a percentage.	National statistical offices 2011 [22]
	Cultural and recreational facilities	n	The indicator represents the number of cultural and recreational facilities per 1000 residents for each municipality.	National statistical offices 2011 [22] OpenStreet Map data [16]

Category	Indicator name	Unit	Description	Data source
	Farm density	n. of farms km ⁻¹	The indicator represents the number of farms per square kilometer of municipal area.	National statistical offices 2011 [22]
	Enterprise density	n	The indicator is calculated as the ratio of enterprises in the secondary and tertiary sector to the total number of residents of a municipality.	National statistical offices 2011 [22]
	Out-commuters ratio	%	The indicator represents the percentage of out-commuters in relation to the total number of employed persons of each municipality.	National statistical offices 2011 [22]
	In-commuters ratio	%	The indicator represents the percentage of in-commuters in relation to the total number of employed persons in each municipality.	National statistical offices 2011 [22]
	Commuter balance	%	The indicator is calculated as the difference between in-commuters and out-commuters in a municipality, divided by the total number of employed persons in that municipality, expressed as a percentage.	National statistical offices 2011 [22]
	Livestock size units (LSU) per farm	n	The indicator represents the average number of LSU per farm for each municipality.	National statistical offices 2011 [22]

Table S3: Mean sustainability values (\pm s.e.) for municipalities within or outside hot spots of ecosystem services related to environment, society and economy; bold = $p < 0.05$ (t-test with bootstrapping, equal variances not assumed; significance level = 99%).

	Ecosystem service	N		Environment		Society		Economy	
		Hot spot	Other	Hot spot	Other	Hot spot	Other	Hot spot	Other
Supply	Fresh water	6068	10717	0.440 (\pm.097)	0.397 (\pm.078)	0.810 (\pm.028)	0.818 (\pm.033)	0.333 (\pm.052)	0.321 (\pm.050)
	Grassland biomass	4168	12617	0.423 (\pm .074)	0.410 (\pm .092)	0.815 (\pm .021)	0.815 (\pm .034)	0.319 (\pm .047)	0.328 (\pm .052)
	Fuel wood	6025	10760	0.443 (\pm.080)	0.397 (\pm.088)	0.810 (\pm.026)	0.818 (\pm.034)	0.323 (\pm .050)	0.327 (\pm .051)
	Filtration of surface water	6339	10446	0.455 (\pm.091)	0.388 (\pm.075)	0.808 (\pm.035)	0.819 (\pm.029)	0.329 (\pm .056)	0.324 (\pm .047)
	Protection against mountain hazards	4072	12713	0.471 (\pm.084)	0.395 (\pm.081)	0.807 (\pm.028)	0.817 (\pm.032)	0.333 (\pm.055)	0.323 (\pm.049)
	Carbon sequestration	6053	10732	0.445 (\pm.080)	0.395 (\pm.087)	0.809 (\pm.029)	0.818 (\pm.033)	0.324 (\pm .050)	0.327 (\pm .051)
	Outdoor recreation	6019	10766	0.469 (\pm.086)	0.382 (\pm.072)	0.807 (\pm.031)	0.819 (\pm.031)	0.331 (\pm .055)	0.323 (\pm .048)
	Symbolic plants and animals	4015	12770	0.469 (\pm.089)	0.396 (\pm.080)	0.808 (\pm.027)	0.817 (\pm.033)	0.336 (\pm.055)	0.323 (\pm.049)
Demand	Fresh water	3337	13448	0.357 (\pm.088)	0.427 (\pm.082)	0.820 (\pm .025)	0.814 (\pm .033)	0.338 (\pm.047)	0.323 (\pm.051)
	Grassland biomass	4577	12208	0.366 (\pm.069)	0.431 (\pm.088)	0.823 (\pm.020)	0.812 (\pm.034)	0.334 (\pm.044)	0.323 (\pm.053)
	Fuel wood	2118	14667	0.387 (\pm.080)	0.417 (\pm.088)	0.818 (\pm .054)	0.814 (\pm .027)	0.322 (\pm .055)	0.326 (\pm .050)
	Filtration of surface water	5276	11509	0.378 (\pm.079)	0.429 (\pm.087)	0.819 (\pm.020)	0.813 (\pm.035)	0.326 (\pm .044)	0.326 (\pm .054)
	Protection against mountain hazards	2686	14099	0.455 (\pm.091)	0.405 (\pm.085)	0.813 (\pm .022)	0.815 (\pm .033)	0.335 (\pm.053)	0.324 (\pm.050)
	Carbon sequestration	2737	14048	0.364 (\pm.093)	0.423 (\pm.084)	0.820 (\pm.038)	0.814 (\pm.030)	0.332 (\pm.053)	0.325 (\pm.050)
	Outdoor recreation	3368	13417	0.354 (\pm.085)	0.428 (\pm.082)	0.820 (\pm .025)	0.814 (\pm .033)	0.336 (\pm.046)	0.323 (\pm.052)
	Symbolic plants and animals	4015	12770	0.469 (\pm.089)	0.396 (\pm.080)	0.808 (\pm.027)	0.817 (\pm.033)	0.336 (\pm.055)	0.323 (\pm.049)
Actual use	Fresh water	3391	13394	0.358 (\pm.087)	0.427 (\pm.082)	0.818 (\pm .020)	0.814 (\pm .034)	0.339 (\pm.043)	0.323 (\pm.052)
	Grassland biomass	4177	12608	0.420 (\pm .073)	0.411 (\pm .092)	0.815 (\pm .021)	0.815 (\pm .034)	0.319 (\pm.047)	0.328 (\pm.052)
	Fuel wood	5072	11713	0.417 (\pm .082)	0.412 (\pm .090)	0.816 (\pm .037)	0.815 (\pm .029)	0.325 (\pm .046)	0.326 (\pm .053)
	Filtration of surface water	5008	11777	0.370 (\pm.066)	0.432 (\pm.090)	0.827 (\pm.018)	0.810 (\pm.035)	0.319 (\pm.050)	0.329 (\pm.051)
	Protection against mountain hazards	3314	13471	0.465 (\pm.088)	0.400 (\pm.083)	0.812 (\pm .024)	0.816 (\pm .033)	0.336 (\pm.054)	0.323 (\pm.050)
	Carbon sequestration	6053	10732	0.445 (\pm.080)	0.395 (\pm.087)	0.809 (\pm.029)	0.818 (\pm.033)	0.324 (\pm .050)	0.327 (\pm .051)
	Outdoor recreation	5564	11221	0.401 (\pm.098)	0.419 (\pm.082)	0.814 (\pm .026)	0.816 (\pm .034)	0.339 (\pm.048)	0.319 (\pm.051)
	Symbolic plants and animals	1162	15623	0.479 (\pm.082)	0.408 (\pm.086)	0.815 (\pm .041)	0.815 (\pm .031)	0.344 (\pm .064)	0.325 (\pm .049)

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