Ecosystem Service	**Soil quality by decomposition and fixing processes**
CICES class name	Decomposition and fixing processes and their effect on soil quality
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.4.2

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	**Unit**	**Indicator values from**
[1] Nutrient cycling: -pH -Cation exchange capacity -Water-filled pore space	Not provided	
[1] C cycling: -Soil organic carbon -$KMnO_4$ oxidizable C -Beta-glucosidase activity -Metabolic CO_2 quotient	Not provided	
[2] Soil organic carbon depletion	kg C * ha^{-1} * yr^{-1}	
[1] N cycle: -Total nitrogen -Potentially mineralizable nitrogen -Leucine aminopeptidase activity -N-acetyl glucosamine activity	Not provided	
[3] Biological nitrogen fixation	kg N * ha^{-1} * yr^{-1}	-
[1] P cycle: -Available inorganic P -Alkaline phosphomonoesterase activity -Phosphodiesterase activity	Not provided	

[4, 20] Soil organic carbon in topsoil (0-20cm)	g * kg^{-1}	
[6] Soil organic carbon (0-20 cm), calculated from loss on ignition	%	
[5] Carbon stocks in soil biomass (0-30 cm)	Mg * ha^{-1}	
[7] Soil organic carbon stock over a 2.5 m deep soil profile	kg * ha^{-1}	
[12] Total soil organic carbon (0-20 cm, 20-60 cm)	g * kg^{-1}	
[12] Soil carbon stock in 0 -20 and 20 – 60 cm depth	Mg * ha^{-1}	
[14] Soil organic carbon concentration in top soil (0-5 cm) and rooting layer (5-60 cm)	%, g * g^{-1}	
[14] Soil organic carbon stock in top soil (0-5 cm) and rooting layer (5-60 cm)	kg * ha^{-1}	
[17] Soil carbon (0-100cm)	kg C * m^{-2}	
[18] Carbon stock in soil: organic C contained in topsoil (0–30 cm) after 20 years of management	t * ha^{-1}	
[19] Carbon stock in soil: organic C contained in topsoil (0–30 cm) after 20 years of management	t * ha^{-1}	
[21] C_{tot}: Total carbon content in soil sample (0-7.5 cm), measured as weight loss on ignition	%	
[21] C_{org}: Organic carbon content in soil sample (0-7.5 cm,) measured by wet combustion (Cr_2O_7 oxidation) and colorimetric analysis	%	
[21] C_{labile}: Labile carbon content in soil sample (0-7.5 cm), measured by oxidation with 333 mM $KMnO_4$ and spectral analysis at 565 nm	%	
[21] CMI: Carbon management index, calculated as: $$CMI = \frac{C_{totagr}}{C_{totnat}} * \frac{C_{labileagr}}{C_{non-labileagr}} * \frac{100}{\frac{C_{labilenat}}{C_{non-labilenat}}}$$ With: C_{totagr} – C_{tot} in agricultural site, C_{totnat} – C_{tot} under native vegetation, $C_{labileagr}$ – C_{labile} inagricultural site, $C_{non\text{-}labileagr}$ – $C_{non\text{-}labile}$ in agricultural site, $C_{labilenat}$ – C_{labile} under native vegetation, $C_{non\text{-}labilenat}$ – $C_{non\text{-}labile}$ under native vegetation	Index 0 - 100	
[21] LCMI: Landscape carbon management index, calculated as:	-	

$LCMI = CMI_{nat} * S_{nat} + CMI_{grass} * S_{grass} + CMI_{crop} * S_{crop}$ With: CMI_{nat} – CMI (native vegetation), S_{nat} – share of native vegetation in landscape, CMI_{grass} – CMI (grassland), S_{grass} – share of grassland in the landscape, CMI_{crop} – CMI (cropland), S_{crop} – share of cropland in the landscape		
[13] Litter cover	cm	📖
[13] Biological soil cover	cm	📖
[12] Soil carbon/nitrogen ratio (0-20cm)	-	🔬
[17] C/N ratio in soil (0-100 cm)	-	🔬
[4] TN - total nitrogen in topsoil (0-20cm)	g * kg^{-1}	🔬
[4] Net N mineralisation	mg * kg^{-1}	🔬
[6] Total N content in soil samples (0-20 cm), calculated from dry combustion data	%	🔬
[7] Nitrogen mineralization	kg TN * ha^{-1} *yr^{-1}	🖥
[20] Net N mineralisation	mg * kg^{-1}	🔬
[8] Soil nitrogen availability: Soil organic nitrogen variation	kg N * ha^{-1} * yr^{-1}	⊘, 📖
[8] Soil nitrogen availability: Mean, maximal and minimal soil nitrate concentration over a time period	mg NO_3-N * kg dry $soil^{-1}$	⊘, 📖
[12] Total nitrogen in soil (0-20 cm, 20-60 cm)	g * kg^{-1}	🔬
[14] Soil total nitrogen concentration in top soil (0-5 cm) and rooting layer (5-60 cm)	%, g * g^{-1}	📖
[14] Soil total nitrogen stock in top soil (0-5 cm) and rooting layer (5-60 cm)	kg * ha^{-1}	📖

[15] Amount of organic nitrogen stocked or destocked within the soil	kg N * ha^{-1} * yr^{-1}	
[15] Mean nitrate concentration in topsoil (0–30 cm)	mg NO_3^-N * kg dm^{-1}	
[17] Nitrate leaching	kg NO_3^-N * ha^{-1} * yr^{-1}	
[19] Nitrate concentration in seepage water	mg * l^{-1} * yr^{-1}	
[18] Nutrient use efficiency (N): Total harvested biomass in dry matter (DM) produced per unit of nutrient assimilated	kg * kg $biomass^{-1}$	
[20] TN - total nitrogen in topsoil (0-20cm)	g * kg^{-1}	
[4] Plant available phosphorus in topsoil (0-20cm): Bray P	mg * kg^{-1}	
[6] Soil phosphorous content (0-20 cm), calculated from acetate extraction & ICP data	mg P * kg $soil^{-1}$	
[14] Soil total phosphorus concentration in top soil (0-5 cm) and rooting layer (5-60 cm)	%, g * g^{-1}	
[14] Soil total phosphorus stock in top soil (0-5 cm) and rooting layer (5-60 cm)	kg * ha^{-1}	
[18] Nutrient use efficiency (P): Total harvested biomass in dry matter (DM) produced per unit of nutrient assimilated	kg * kg $biomass^{-1}$	
[19] Nutrient use efficiency (N & P): Total harvested biomass in dry matter (DM) produced per unit of nutrient assimilated	kg * kg $biomass^{-1}$	
[19] Phosphorus loss - particulate	kg * ha^{-1} * yr^{-1}	
[20] Plant available phosphorus in topsoil (0-20cm): Bray P	mg * kg^{-1}	
[6] Soil potassium content (0-20 cm), calculated from acetate extraction & ICP data	mg P * kg $soil^{-1}$	
[12] Soil cation exchange capacity (CEC)	cmol * kg^{-1}	
[12] Exchangeable Ca, Mg, K and Na	cmol * kg^{-1}	

[4,20] pH in topsoil (0-20cm)	-	
[6] Soil pH (water)	-	
[12] pH (soil:water = 1:5)	-	
[12] Total equivalent $CaCO_3$	%	
[12] Electrical conductivity (soil:water = 1:5)	mS * cm^{-1}	
[5] Indicator of chemical soil quality in topsoil (0-10 cm), based on pH H_2O; CEC; exchangeable K^+, Ca^{2+}, Mg^{2+}, Al^{3+} & NH_4^+ and extractable phosphorus concentrations	0.1 - 1	
[13] Soil nutrients (0–10 cm)	kg * ha^{-1}	
[9] Soil composition: -pH (in H_2O) -total soil organic matter (SOM) [%] -available phosphorus (P) [mg * kg^{-1}] -potassium (K) [mg * kg^{-1}] -calcium (Ca) [cmolc * kg^{-1}] -magnesium (Mg) [cmolc * kg^{-1}] using the Mehlich-3 method -bulk density [g * cm^{-3}]	-	
[10] Chemical soil fertility indicator based on a principal component analysis (PCA) of 20 variables evaluated at 0–10 cm and 10–20 cm. Variables included: -C and N contents -Cation exchange capacity (CEC) -Al saturation -Concentrations of Ca, K, Mg, P Bray II, Al, B, Fe, Mn, Cu, Zn -Soil pH measured in 2:1 water solution Variables with significant contribution (>50 % of the maximum value) to either of the first two principal component axes were selected and their contribution to PCA axes 1 and 2 multiplied by the overall variability explained by each PCA axis. These weighted factors were summed up and scaled to a range of 0.1 - 1.0.	Index 0.1 - 1.0	
[12] Decomposition rate of commercially available tea bags (weight loss)	g * d^{-1}	
[12] Decomposition rate of commercially available tea bags (stabilization factor); factor associated with labile compounds that become recalcitrant and do not decompose.	Range 0 - 1	

[4] Microbial biomass of bacteria and fungi in topsoil (0-20cm), based on characterization by extracted phospholipid fatty acids (PLFAs)	mg C * g^{-1}	🔬
[6] Biomass of bacteria, saprophytic fungi and arbuscular mycorrhizal fungi (0-20 cm), calculated from phospho- and neutral lipid fatty acid analysis data (PLFA, NLFA) data	nmol * g $soil^{-1}$	🔬
[20] Microbial biomass of bacteria and fungi in topsoil (0-20cm), based on characterization by extracted phospholipid fatty acids (PLFAs)	mg C * g^{-1}	🔬
[12] Enzyme activity: soil analysis for -N-acetyl-β-glucosaminidase (NAG) -β-glucosidase (β-G) -butyrate esterase (BUT) -acid phosphatase (AP) -arylsulphatase (ARYL) -β-xylosidase (XYL) -cellulose (CELL) -acetate esterase (AC) activity	kat	🔬
[12] Sum of soil enzyme activity: sum of the percentage of the maximum value found for a specific enzymatic response across all enzymes investigated	-	🔬
[11] Indicator value calculated as: $$I=\frac{\sum \left\| \log\left(\frac{i}{i_{max}}\right)\right\|}{n}$$ With: i – variable I measured, i_{max} – maximum ecological potential of variable I in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\left\|\log\left(\frac{i}{i_{max}}\right)\right\|$ is subtracted from the sum instead of added. a) with a focus on "nutrient retention and release", variables for this ecosystem service were: -Soil organic matter [% dw] -Earthworm abundance [number * m^{-2}] -pH in KCl -Potential C mineralization [mg C * kg $soil^{-1}$ * $week^{-1}$] -Potential N mineralization [mg N * kg $soil^{-1}$ * $week^{-1}$] -Water-soluble P (Pw) and extractable P (PAL) b) with a focus on "fragmentation and mineralization of soil organic matter ", variables for this ecosystem service were: -Soil organic matter [% dw] -Earthworm abundance [# * m^{-1}] -Bacterial biomass [mg C * g dw^{-1}] -Physiological diversity bacteria [biolog. CLPP: Hill's slope]		🔬, 📖

-Potential C mineralization [mg C * kg soil^{-1} * week^{-1}] -Potential N mineralization [mg N * kg soil^{-1} *week^{-1}]		
[16] Soil fertility, indicated by high organic matter, low bulk density, high soil nutrient contents: -Soil organic matter [%] -Bulk density [g * cm^{-3}] -Percent weight of C [%] -Percent weight of N [%] -C:N Ratio [-]		

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[22] Topsoil carbon stock: calculated from bulk density and total C content at 0–10, 10–20, and 20–30 cm depths	Mg C * ha^{-1}	
[22] Soil chemical quality index based on exchangeable Ca^{2+}, Mg^{2+},K^{+}, Al^{3+} and NH_4^{+}, and extractable P contents at a 0–10 cm depth	0.1 - 1	
[24] Index of soil quality BISQ (richness; structure; function)	Not provided	
[23] Vegetation diversity: four-level index based on the number of plant species	poor-fair-good-excellent	
[24] Earthworm biomass and diversity	g * m^{-2}, species # * m^{-2}	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[26] Soil organic carbon stock (30 cm)	t C * ha^{-1}	
[28] Soil organic carbon content (0-30 cm)	%	
[30] Soil organic carbon stock	t C * ha^{-1}	
[35] Soil organic carbon content	g * kg^{-1}	
[27] Organic matter layer thickness in topsoil (0-10cm)	cm	

[27] Organic matter content in topsoil (0-10 cm)	% Weight	
[33] Topsoil organic carbon content	%	
[36] Carbon storage in aboveground, belowground, soil, and dead organic carbon, calculated with InVEST model based on land use/land cover information	Mg * ha^{-1}	
[37] Soil carbon stock	kg C * ha^{-1}	
[23] C_{tot}: Total carbon content in soil sample (0-7.5 cm), measured as weight loss on ignition	%	
[23] C_{org}: Organic carbon content in soil sample (0-7.5 cm,) measured by wet combustion (Cr_2O_7 oxidation) and colorimetric analysis	%	
[23] C_{labile}: Labile carbon content in soil sample (0-7.5 cm), measured by oxidation with 333 mM $KMnO_4$ and spectral analysis at 565 nm	%	
[23] CMI: Carbon management index, calculated as: $$CMI = \frac{C_{totagr}}{C_{totnat}} * \frac{C_{labileagr}}{C_{non-labileagr}} * \frac{100}{\frac{C_{labilenat}}{C_{non-labilenat}}}$$ With: C_{totagr} – C_{tot} in agricultural site, C_{totnat} – C_{tot} under native vegetation, $C_{labileagr}$ – C_{labile} inagricultural site, $C_{non\text{-}labileagr}$ – $C_{non\text{-}labile}$ in agricultural site, $C_{labilenat}$ – C_{labile} under native vegetation, $C_{non\text{-}labilenat}$ – $C_{non\text{-}labile}$ under native vegetation		
[23] LCMI: Landscape carbon management index, calculated as: $$LCMI = CMI_{nat} * S_{nat} + CMI_{grass} * S_{grass} + CMI_{crop} * S_{crop}$$ With: CMI_{nat} – CMI (native vegetation), S_{nat} – share of native vegetation in landscape, CMI_{grass} – CMI (grassland), S_{grass} – share of grassland in the landscape, CMI_{crop} – CMI (cropland), S_{crop} – share of cropland in the landscape		
[34] Nitrogen loss	kt N	
[35] Total nitrogen content	g * kg^{-1}	
[35] Total phosphorus content	mg * g^{-1}	

[25] Total "Emergy" of the amounts of nitrogen, potassium and phosphorus in the soil	seJ	
[35] pH	-	
[29] Soil chemical fertility index. The index is based on the parameters: pH, SOM, total N, available P, Al saturation, cation exchange capacity, and macronutrient concentrations at the 0–10 cm and 10–20 cm depths.	0.1 - 1	
[32] Maintenance of soil fertility: expert based index for ecosystem service provision by land cover class [1-5], multiplied by the area of the land cover class	km^2	
[32] Maintenance of soil fertility value: expert based index for ecosystem service provision by land cover class [1-5]. multiplied by the area of the land cover class and a literature-based monetary value of the ecosystem service	$\$ * ha^{-1} * yr^{-1}$	
[24] Index of soil quality BISQ (richness; structure; function)	Not provided	
[31] Natural soil production capacity: (for historic analyses in Germany) Prussian Taxation soil production capacity index	1 - 8	
[31] Natural soil production capacity: (for Germany) German soil inventory production potential index (for historical analyses); index value represents the percentage of potential yield relative to most productive soils in Germany.	1 - 100	
[29] Bio-indicator: Presence of specific ant species is used as an indicator for high, medium or low provision of this ES. Suitable indicator species must first be identified by a correlation between presence of species and ecosystem service provision.	low-medium-high	
[24] Earthworm biomass and diversity	$g * m^{-2}$, species # $* m^{-2}$	

Table 4: National Scale

Indicator	**Unit**	**Indicator values from**
[39] Soil organic carbon in topsoil layer	t	
[38] Soil fertility: Expert assessment for each land use class based on chemical (e.g., N, P, K, Ca), physical (e.g., aggregate stability; bulk density; percolation stability), and biological (e.g., mycorrhizae; microbial biomass; earthworm biomass) indicators	very negative (−3) to very positive (+3)	

[40] Area of N fixing crops	ha, m^2	
[24] Index of soil quality BISQ (richness; structure; function)	Not provided	⊘
[24] Earthworm biomass and diversity	g * m^{-2}, species # * m^{-2}	⊘

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[41] Nutrient regulation: Index values for Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	
[24] Index of soil quality BISQ (richness; structure; function)	Not provided	⊘
[24] Earthworm biomass and diversity	g * m^{-2}, species # * m^{-2}	⊘

Table 6: Global Scale

Indicator	Unit	Indicator values from
[24] Index of soil quality BISQ (richness; structure; function)	Not provided	⊘
[24] Earthworm biomass and diversity	g * m^{-2}, species # * m^{-2}	⊘

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