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Soil retention (regulating) ecosystem services

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Short summary

Soil retention is very relevant for the maintenance of healthy ecosystem conditions (including ecosystem structures and processes), functions and for the delivery of many other ecosystem services (ES) (certainly many provisioning, a couple of other regulating ES and a few cultural ES). Thus, the (indirect) benefit of soil retention is to prevent a reduction of soil-related ES supply by soil erosion. In this Chapter, soil retention was treated as an ecosystem service and its natural base, quantification and valuation approaches were described. The authors are aware of the fact that soil retention could, however, perhaps also be denoted as an "intermediate ES" or even an ecosystem function.

Another - conceptually very interesting - issue concerns the quantification and valuation of soil retention benefits, because what basically would be valued related to soil retention ES are avoided soil erosion events (in the sense of if soil retention is high, soil erosion is usually low and thus, the ES supplied is high/sufficiently meeting the demand for it). Demand for soil retention can be identified based on soil erosion risk assessments. On the other hand, there are also beneficiaries of soil erosion/avoided soil retention, for instance downstream flood plain areas that profit from sediment and nutrient delivery.

The future flows of soil retention ES depends on various factors, so some potential future pathways are provided based on factor combinations. Some areas may profit from climate change, as warming may lead to increased vegetation cover, other areas will be threatened by desertification and higher intensity rainfall events and increased risk for soil erosion.

The Chapter provides an overview on the most relevant issues related to soil retention ES in the context of ecosystem accounting. The topic is, however, so complex, involving various conceptual, methodological and valuation issues, that it would be worth to develop a dedicated SEEA thematic account for soil that mapped out the various supporting and intermediate type services together with suitable indicators, quantification and valuation approaches.

1. Description of the ecosystem service

Soils are vital not only for biomass production in agriculture and forestry, but are also highly relevant for instance for water quality regulation, climate regulation, as carrier for manifold human activities and infrastructure, or as geoarchives. Soils also hold high biodiversity and provide direct and indirect human health benefits. As soils can be rather fragile and unstable systems, they are threatened by erosion by wind, water, ice or simply gravity, soil compaction, pollution and biodiversity loss. Agriculture is one main user of soils, but exposes at the same time large threats on soil ecosystems. Especially croplands are affected by various land use activities such as soil tillage, cropping, harvesting and pesticide/herbicide applications. Regular plant growth - harvest cycles lead to constantly changing land cover conditions, including temporally bare soils that are exposed to soil erosion by water. These impacts can lead to further direct and indirect effects such as changes in soil structures and functions as well as biodiversity shifts. Thus, soil retention is a major regulating ecosystem service on which multiple human activities and related ecosystem services depend.

a. Common nature of the ecosystem service

Soil retention is a process that is in contrast to the movement of soil materials caused for instance by various forms of erosion. Soil retention can reduce soil movement and help to keep soils at their current place. Several natural and anthropogenic system components impact soil retention, whereof land use and land cover change (LULCC) by humans is one key factor. Bare soils without protecting vegetation cover resulting from LULCC are highly susceptible to soil erosion. Additional influencing factors besides land use and land management measures include climate (especially precipitation and wind), organic matter content, topography (slope and slope length), soil type and texture, and geology/bedrock. The soil erosion cycle includes three key processes: soil detachment, movement and deposition. Related processes take place on various spatio-temporal scales and in different quantities. Soil erosion can be linear or laminar and can take place either rather slowly (and often unnoticed on short term, e.g. wind erosion of dune systems) or suddenly, causing significant losses of topsoil and mass movements in relatively short time (e.g. gully erosion, landslides).

b. Similar and related ecosystem services

Soil retention ecosystem services are a) closely linked to ecosystem functions such as soil formation, nutrient and water cycling, and b) relate to soil erosion and natural hazard regulating ecosystem services. Ecosystem functions (or supporting ecosystem services according to the MEA 2005) are usually not seen as ecosystem services because most of them provide only indirect benefits to humans. Soil retention ecosystem services offer direct as well as indirect benefits to humans (see Paragraph 1c. below).

Erosion regulating ES have been defined by the MEA as *Erosion control* (i.e. vegetative cover playing an important role in soil retention and the prevention of landslides) and as *Erosion prevention and maintenance of soil fertility* (i.e. soil erosion is a key factor in the process of land degradation and desertification. Vegetation cover provides a vital regulating service by preventing soil erosion. Soil fertility is essential for plant growth and agriculture and well-functioning ecosystems supply the soil with nutrients required to support plant growth) by TEEB. A related ecosystem service defined by TEEB would be *Moderation of extreme events*. In CICES 5.1, the Class *Control of erosion rates* falls in the Group *Regulation of baseline flows and extreme events* in the Division *Regulation of physical, chemical, biological conditions* of the *Regulation & Maintenance* (Biotic) Section. A related CICES Class would be *Buffering and attenuation of mass movement*.

As soil retention is the base for stable and fertile soils, this ecosystem service is related to many provisioning ecosystem services such as food, raw materials, water and regulating ecosystem services such as climate, water quality or flood regulation. Soils also provide habitats for numerous animal and plant species. Besides their role as geoarchives, soils seem to provide cultural ecosystem services only less directly.

c. The associated benefits and definitional boundary with respect to the ecosystem service

Soil retention (soil erosion prevention) encompasses on-site and off-site effects. On-site effects of erosion include the loss of topsoil material, which decreases cropland productivity and can potentially lead to further erosion. Topsoil material, usually rich in organic matter, nutrients and soil fauna, can be transported by wind, water or ice. Off-site effects occur at places of soil material accumulation and can lead to sedimentation or pollution of water channels, roads or other ecosystems. A critical threshold for soil retention is the ratio between soil formation *vs*. soil degradation/loss. In cases were more soil material is lost than can be build up in a long term, an irretrievable ecosystem degradation occurs.

The supply of soil retention across ecosystems can therefore mitigate these impacts with direct effects on the retention of soils and fertility, but also on above- and belowground biodiversity and soil carbon sequestration and pools. These direct and indirect benefits, including more sustainable crop yields, have very significant implications for human wellbeing (e.g. increased stability of soil conditions correlates with a reduced propagation of soil and plant pathogens), climate change (e.g. supporting higher carbon pools), and nature conservation (e.g. by promoting more stable habitats for both above- and belowground biodiversity).

d. The key users and beneficiaries

Key users and beneficiaries of soil retention can be located in areas of on- and off-site effects. On-site effects usually lead to improved soil quantity and quality, which is benefiting land users especially from agriculture or forestry and the ecosystem services they produce. Especially intensive forms of land use such as agricultural production systems involve complex interplays of ecosystem service users (mainly benefiting from regulating ecosystem services such as soil retention, water, nutrient and local climate regulation, pollination), providers (many provisioning ecosystem services and agricultural products) and (partly external) environmental effects such as biodiversity loss or greenhouse gas emissions.

Off-site effects of soil retention regulating ecosystem services include reduced sedimentation, benefiting water users by supporting water quality regulating and water supply provisioning ecosystem services. However, there are not only positive off-site effects of soil retention. Soil fertility in river areas and floodplains is often strongly dependent on regular sediment inputs from upstream areas to increase or maintain soil fertility downstream (see also paragraph 2a below).

Indirect effects of soil retention regulating ecosystem services include flood regulation by reduced surface runoff, climate regulation by retaining soil organic material such as carbon or methane and pollution control by not further spreading pollutants. Soil retention is furthermore very relevant by providing stable substrate for housing, infrastructure, habitats or other activities.

Thus, beneficiaries of soil retention regulating ecosystem services can be found on all spatial scales, from local to global. The spatial patterns of service provision include *in situ* relations (where the Service Providing Area (SPA) is the same as the Service Benefiting Areas (SBA)) or directional (omni-directional as well as directional relations with or without slope-dependence). Linear landscape structures such as hedgerows or ridges are important elements hindering or interrupting soil erosion processes.

Soil retention can, as many other regulating ecosystem services, in landscapes not take place spatially separated. The SPA and SBA, if not in an *in situ* relation, always need to be physically connected (via a Service Connecting Area SCA), e.g. by natural sediment flows on slopes, hydrological flows within watersheds, human-made infrastructural measures or natural elements. Soil retention can neither be transported nor imported from other regions. In specific cases of wind erosion and material transports over long distances (e.g. Sahara sand transported to Europe), the SPA and SBA could be considered physically disconnected.

e. A summary "mapping" of the ecosystem services supply chain

Figure 1 illustrates the soil retention regulating ecosystem service supply chain. Soil in its different dimensions, together with the land use, is the central ecosystem asset in this case and its extent and condition are together with the soil type and land cover determining factors for the quantity and quality of service delivery. Economic inputs such as land use and land use change, soil management (e.g. tillage) and protection measures (e.g. no-tillage agriculture) are key anthropogenic factors further influencing soil retention ecosystem services. The actual soil retention is enabled by the natural factors climate, geology, soil type and texture, landscape topography and soil biodiversity. One way to value soil erosion is by calculating damage costs without sufficiently provided soil prevention ecosystem services. Beneficiaries (as described in paragraph 1d above) profit from healthy (stable and fertile) soils, which are the base for various forms of land use with agriculture as a key beneficiary and provider (and user) of many other ecosystem services.

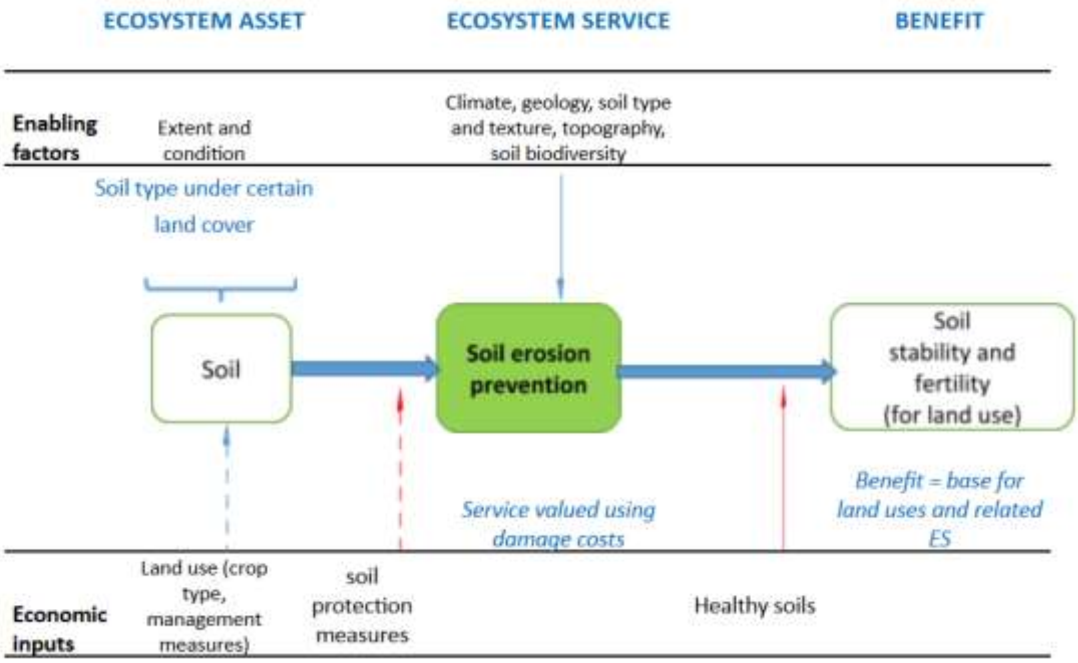

Figure 1: Illustrative logic chain for soil retention regulating ecosystem services.

2. Measuring the ecosystem service

a) Relevant ecosystem characteristics and context

Measuring soil retention should consider two main environmental processes: (i) soil erosion by water and (ii) soil erosion by wind. Soil erosion by ice is considered to be a rather specific case limited to comparably small areas, which are usually less relevant for human activities. Water- and wind-caused soil erosion processes comprise different mechanisms and can be affected by different drivers. Namely, in the case of soil erosion by water, precipitation and vegetation cover are two very significant factors when addressing soil retention, while in the case of soil erosion by wind, the equivalent factors are wind speed and direction together with vegetation structure. Also, in the case of soil retention, it is important to separate between the supply of the service and the benefit generated. Soil erosion is a ubiquitous process and, therefore, in one way or the other, always present in multiple ecosystem types. The retention of this eroded soil generates a benefit when the ecosystem type or the specific territory is used and benefits from having more stable soils.

This multidimensional problem of benefit generation can be extended to direct and indirect benefits being generated at multiple scales. In terms of direct benefits, the increased soil stability can have important effects on soil biodiversity (e.g. by creating a stable habitat for microbes and other macro-organisms), contain available soil fertility, contribute to maintaining mycorrhization and higher water efficiency, among others. Indirectly, by increasing the stability of soils and local soil conditions, soil retention can also contribute to increasing local soil fertility and, therefore, promoting a more stable and resilient productivity with less economic inputs from land managers. In this context, benefit generation can be quantified by the absence of impact, i.e., by quantifying the amount of impact avoided by the land manager, and by the amelioration of production factors, i.e., by the increase in productivity through the improvement of soil fertility.

Given the complexity of the phenomenon, it is important to refer that increasing soil retention without accounting for local ecosystem conditions may have severe unexpected implications. As an example, large river systems such as rivers Nile, Yangtze or Mekong benefit from having constant loads of sediments coming from upstream ecosystems. Overexploitation of these upstream systems may result in an overload of the river system, but completely eliminating sediment generation may also impose significant impacts downstream, e.g., like the reduction of soil fertility and the disruption of floodplain ecosystems. Here, when considering the downstream benefits of soil erosion, sediment transport and deposition, one could argue that an associated/complementary ecosystem service should be considered and assessed based on sediment loads and their quality (e.g., for downstream soil fertility). At the same time, soil displacement can also contribute to propagating invasive species (e.g. by displacing propagules attached to soil aggregates) and contaminants (e.g. phosphorus dispersal into the river systems by soil transport after a fire event). These teleconnection problems elevate soil retention from a local benefit sharing problem to a larger scale cross-boundary discussion.

Considering the multiple dimensions of soil erosion and soil retention, a number of enabling factors can be identified (Table 1, Figure 1). Starting from soil erosion by water, climate, topography, soil characteristics, vegetation dynamics and land practices and the main factors involved, while in the case of wind erosion, vegetation structure, wind speed and direction also play an important role. In this context, soil erosion is mainly enabled by land practices that favour ecosystem change (e.g. deforestation) or the disruption of ecosystem dynamics, and the occurrence of extreme events (e.g. climatic changes, fires). These enabling factors contribute in different ways to a higher exposure of soils and a consequent higher detachment of soil particles. While changes in land use may have more drastic effects, e.g. as a consequence of deforestation activities, these may also happen in long-term periods by depleting soils as a consequence of land specialization and land use intensification (e.g. cattle related impacts in Mediterranean savanna type systems). At the same time, climate-induced extreme events (e.g. heavy droughts, extreme rain events, increased fire intensity) can trigger cascade effects that result in very significant soil losses.

Therefore, there is an important distinction between the sustained soil retention within a given habitat, and the capacity of a system to reduce the impacts from extreme events. The later requires a system with a higher buffer capacity (as these extreme events are normally associated to negative ecosystem impacts), while the first often contributes to higher system stability, biodiversity and ecosystem functions. While most of the current approaches focus on the long-term effects of soil retention, related assessments should not exclude the capacity of a system to deal with extreme events, as these can happen even in areas with a usually low demand for soil retention services.

Soil retention benefits from the introduction of landscape structural elements (e.g. tree lines acting as wind- or mass-movement breakers) and especially from conservation practices either in agricultural (e.g. by introducing non-tillage, in-line cultivation, or legume rotations, among others) or in forest areas (e.g. by introducing integrated forest management resulting from certification procedures). Moving beyond land management practices, soil retention can also be improved - if targeted - by nature conservation measures that favour higher species richness and more complex and stable communities. Nevertheless, it is important to note that if soil retention is the only criteria (which in many cases should not be the case), its immediate improvement does not necessarily depend on having more diverse and more ecologically stable ecosystems. In fact, there are several examples where the introduction or colonization by invasive species greatly increased the retention of soils, despite the direct ecosystem impacts of these colonisations. This example shows that, although promoting vegetation cover or better land use practices that favour soil retention is critical to obtain tangible benefits from this ecosystem service, if done in an unbalanced way, favouring this service can contribute to higher impacts and a decrease in the overall ecosystem service supply.

Table 1: Enabling factors and examples for soil erosion and soil retention (Nearing and Hairsine 2010; Morgan and Nearing 2016).

Enabling factor	**Soil erosion**	**Soil retention**
Land use change	deforestation agricultural intensification increased landscape homogeneity	afforestation introduction of soil conservation practices increased landscape heterogeneity
Vegetation	monocultures	vegetation structure and cover ground surface cover leaf area vertical structure of the vegetation
Climate change	variability of weather conditions rainfall intensity increase drought events increased extreme events increased glacial dynamics	indirect effects on vegetation growth reduced rainfall intensity
Soil	poor soil structure mechanical soil disturbance high soil erodibility	soil aggregate stability organic matter richness low soil erodibility

Land degradation	changes in soil conditions extreme fire events	-
Nature conservation	-	increased species richness green infrastructure

Although there is a logical interpretation that better soil protection techniques and a denser vegetation cover contribute to an increase in soil retention ecosystem service supply, there are non-linear correlations between conservation practices, vegetation cover and soil retention. This is because the improvements obtained by such practices and increased vegetation can be overcome by significant increases in the driving factors of soil erosion, e.g. dramatic increases in precipitation and wind speeds caused, for instance, by climate change. Therefore, it is necessary to separate between soil erosion risk, i.e., the risk or potential risk of soils to be eroded in the near future, and soil retention, i.e., the process by which soil is retained in a given location calculated as a ratio of avoided soil erosion. In this context, within specific climate dynamics, an increase in soil retention doesn't correspond necessarily to a decrease in soil erosion.

b) Metrics for measuring the ecosystem service flow in physical/quantitative terms

Conceptually speaking, soil retention differs from soil erosion in the sense that the first corresponds to the mitigation of the second by a given ecosystem. This ecosystem can be defined in many ways but here we define it as being a permeable social-ecological system (within a given spatial scale) where environmental and social-ecological networks interact to potentiate or mitigate (by promoting soil retention) the effects of soil erosion (Figure 2).

In this context, the soil retention ecosystem service supply corresponds to the avoided soil loss (when compared with the potential soil loss in the absence of an ecosystem service provider) promoted by the ecosystem, which includes the interactions and functions of both above- and below-ground biodiversity (e.g. bioturbation, soil cover, etc.). Therefore, here, the ecosystem service provider corresponds to all living organisms that, through their presence or related functions, contribute to the supply of the ecosystem service. These include, plants (e.g. by promoting vegetation cover and the reduction of rainfall intensity on the soil), soil micro- and meso-organisms (e.g. bacteria, fungi, nematodes; by promoting the development of biofilms and improved soil aggregate stability), and soil macro-organisms (e.g. earthworms; by contributing to bioturbation and increases in soil organic matter content). Although vegetation and plant diversity remain as major driving forces to retain soils, other soil organisms have also important contributions, particularly to the long-term soil retention and in the stability of soil conditions.

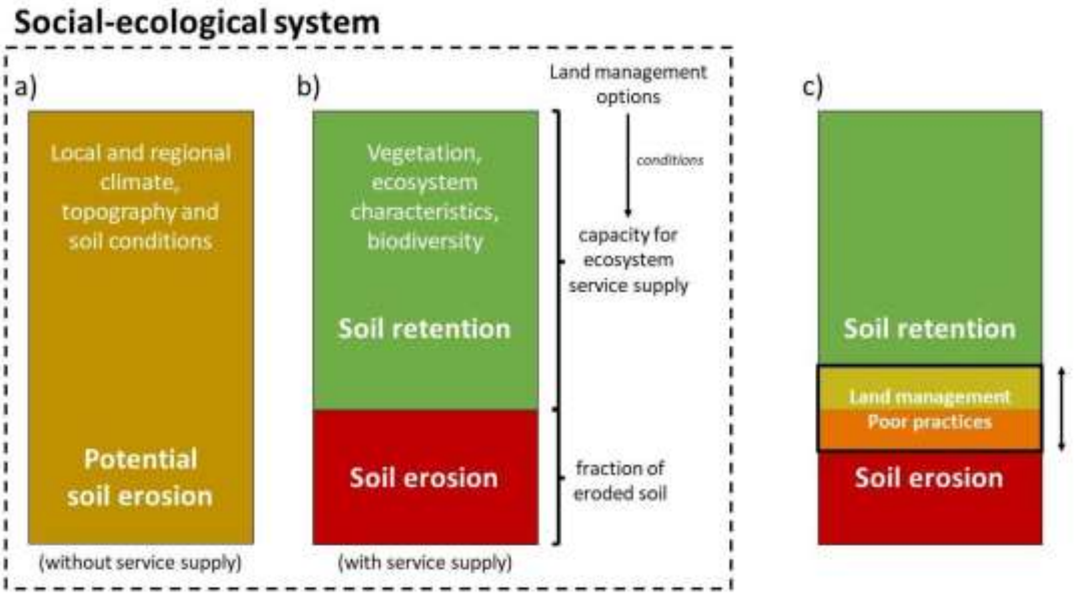

Figure 2: General framework for the estimation of soil retention from an avoided impact perspective: a) corresponds to the estimation of the potential soil erosion, i.e., the soil erosion that would happen if no ecosystem service is provided by the ecosystem; b) corresponds to the estimation of soil retention as a ratio between the fraction of eroded soil and the potential soil erosion, conditioned by the capacity of the ecosystem to prevent erosion. c) illustrates the potential changes in soil retention by sustainable or poor management practices. Here the expectation is that in a given social-ecological system, management practices can contribute positively to enhance the capacity of the ecosystem to prevent soil erosion.

In the context of avoided impact assessments, in order to measure ecosystem service supply in quantitative terms, one has to determine first the potential soil loss of a given location. This can be achieved by direct measurements in experimental designs where ecosystem service providers are removed from the soil and soil loss measurements are done, or (more frequently) by implementing modelling approaches that allow obtaining a reference value for these conditions. In general terms, this potential soil erosion is determined as a function of soil conditions, climate, and topography. Once this first estimation is done, the proportional impact of the ecosystem service provides needs to be assessed. In current empirical models, this is mostly assessed by impedance value that relates to the potential reductions of rainfall intensity, runoff, or wind speed. Independently of the methodological approach, the ecosystem service supply can be conceptually calculated by:

$$E_s = \Upsilon \times c$$

where c, corresponds to the capacity of ecosystem service supply typically represented by the proportional mitigation capacity of the ecosystem service provider considered in relation to the potential soil erosion, Υ is the potential soil erosion, and E_s the ecosystem service supply (Table 2).

The capacity of ecosystem service providers to supply soil erosion retention is an important element to be assessed, as it is the main limiting factor for ecosystem service supply. As represented in Figure 2, this capacity can be positively (or negatively) influenced by land management practices. These include, but are not limited to, mechanical soil disturbances (e.g. soil compaction or soil mobilization by tractor ploughing), in-line cultivation, fertilizer application, among others (more examples can be found in the World Overview of Conservation Approaches and Technologies; https://www.wocat.net). As mentioned before, although commonly used, the capacity to supply the service does not correlate completely with the ecosystem service supply. This implies the use of more than one complementary indicators to assess the supply of the ecosystem service (Table 2).

Table 2: Commonly used indicators to estimate soil erosion retention.

Indicator	Description	Unit
potential soil erosion	amount of soil loss when no ecosystem service provider is present and no service is supplied	$t.ha^{-1}.y^{-1}$
actual soil erosion	fraction of soil loss after the ecosystem service is supplied	$t.ha^{-1}.y^{-1}$
soil retention	amount of ecosystem service supply	$t.ha^{-1}.y^{-1}$
supply capacity	proportional mitigation capacity of the ecosystem service provider considered in relation to the potential soil erosion	0 to 1
soil erosion risk or erosion protection	area of land use (e.g. forest) designated to the prevention of soil erosion; area eroded by wind and water, forest cover in high slope areas; sediments removed from dams, lakes, rivers	ha; t

c) Summary of common data sources and models for physical flow estimates

Date sources

Currently, there is a wide number of data sources for the estimation of soil retention at multiple scales. Starting from the global scale (Table 3), a variety of datasets can be found on the different parameters used to estimate soil erosion and its prevention, from soil components (e.g. SoilGRIDS), to multiple elevation, land cover and precipitation datasets. Still, the major difficulties at this scale are related to the inference of meaningful ways to estimate vegetation cover and to be able to parameterize the effects of land management at the global scale, with some examples from literature making first approximations. Particularly at the global scale, standardized measurements of soil erosion and sedimentation that can be used to validate global estimates are also missing. This hampers the capacity of properly model and estimate in quantitative terms soil erosion and the related soil retention.

Table 3: Common data sources available at global and continental scales.

Relevant Domain	Data Source	References
Soil	SoilGRIDS	(Hengl et al. 2014)
Vegetation	Fractional Green Vegetation	(Filipponi et al. 2018)
	NDVI	
Land cover	ESA Land Cover	
	Globe Cover	

	Forest loss	(Hansen et al. 2013)
	CORINE Land Cover (EEA; for Europe)	
Elevation	ASTER	
	SRTM	
Climate	WorldClim	(Fick and Hijmans 2017)
	CHELSA	(Karger et al. 2017)

At the regional scale, many of the data sources used for global assessments are still relevant (e.g. (Hansen et al. 2013)) since the spatial and thematic discrimination are suited for regional scale and cross-boundary assessments. Nevertheless, across the globe, a large number of countries have invested in common cross-boundary datasets that are very relevant to the determination of soil retention at finer scales (e.g. Europe (Panagos et al. 2014), Asia (Brovelli et al. 2015; Jokar Arsanjani et al. 2016)). Although some countries benefit from these collective efforts, many also have much more relevant data sources that can support local analysis and infer locally relevant management strategies.

Direct measurement

Soil erosion can be quantified by empirical measurement and observation methods. Respective monitoring programmes should combine the continuous measuring of erosion damages with farmer surveys. Field measurements should be conducted in seasons of erosive events, such as bare soils and heavy erosive rainfalls or winds. Linear erosion forms can be measured with their depth and widths, so that relocated amounts of soil (as volumes or weights) can be calculated. Laminar erosion can be visually estimated. Soil material transported by wind can be quantified by using sediment traps. Remote sensing methods such as unmanned aerial systems (UAS)/drones or laser scanners (terrestrial or air-borne) producing high resolution 3D landscape models offer new potentials to accurately locate and quantify soil erosion by water and wind.

Models

Across scales, a major limitation for soil erosion modeling is the availability of validation data and proper monitoring of soil erosion and sediment loads. This limitation generates significant uncertainty when soil erosion and soil retention are modelled and assessed. Nevertheless, models and modelling frameworks are very useful tools to simulate ecosystem processes over space and time. Models are furthermore essential tools to determine priority areas and trends in ecosystem service supply, particularly to estimate physical flows related to the retention of soil by ecosystems. In the past decades, using mostly empirical approaches, several models/modelling frameworks to estimate soil erosion and soil erosion retention have emerged. The models presented here focus on soil erosion by water. For wind erosion, mainly regional examples (e.g. indices on land and soil susceptibility to wind erosion for Europe developed by the JRC) are available, but in general wind erosion is often missing from the ecosystem services literature.

The empirically derived Universal Soil Loss Equation (USLE) is a commonly applied mathematical model to quantify potential soil loss and avoided impact. Several USLE modifications such as the Revised Universal Soil Loss Equation (RUSLE), RUSLE2015, Modified Universal Soil Loss Equation (MUSLE), or national standards have been derived. USLE applies the following equation based on six factors to calculate mean annual soil loss rates (in t per ha per year):

$$A = R * K * LS * C * P$$

R = rainfall erosivity factor; K = soil erodibility factor; LS = topographic factors; C and P = land management and conservation factors

USLE proved to deliver useful results in many studies. USLE is, however, also known to produce less-reliable results with increasing size of the study area or in areas under specific erosion threats like gully erosion. USLE was derived based on long-term data from US American agricultural fields. Hence, the transferability to other regions, biomes, climate zones and land management regimes needs to be checked before applying USLE.

Within ecosystem services science, the currently most commonly applied model suite is probably InVEST[1] (Integrated Valuation of Ecosystem Services and Tradeoffs), developed and promoted by the Natural Capital project. InVEST includes a module to estimate soil sediment delivery ratios for land parcels based on information on geomorphology, climate, vegetation cover and management practices. The model outcomes include information on the sediment retention capacity and avoided sedimentation, including water quality maintenance, avoided reservoir sedimentation and land use change-related costs of sediment removal.

ESTIMAP[2] (Ecosystem services mapping at European scale) is a set of separate process-based models that assess supply, demand and flow of currently eight ecosystem services (including protection from soil erosion) within a Geographic Information System (GIS), developed and supported by the European Commission's Joint Research Centre. Other process-based models that are commonly used to calculate soil erosion or matter transport are SWAT[3] (Soil and Water Assessment Tool) supported by the Texas A&M University and Erosion 3D[4] to model soil erosion by water.

ARIES[5] (ARtificial Intelligence for Ecosystem Services) maps ecosystem services flows from nature to society. Soil retention is modeled based on a sediment flow model, simulating spatial connections between sediment sources, areas promoting sediment deposition and users that benefit from or are harmed by sediment transportation. LUCI[6] (Land Utilisation Capability Indicator) calculates erosion risk and sediment delivery based on a digital elevation model (DEM), land cover and soil information. Additional information such as stream network, rainfall and evapotranspiration can be included to improve LUCI outputs. Most soil retention/soil erosion models are using USLE (see above) or USLE-derivates as basis for simulation.

Model uncertainties

In most cases, to obtain estimates of soil retention and soil erosion it is necessary to use models that support the prediction of areas where surveys are not available or are not possible. Nevertheless, in the case of soil erosion modelling, there are indications that models often overestimate observed erosion rates (García-Ruiz et al. 2015). This is mostly due to

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[1] https://naturalcapitalproject.stanford.edu/invest/

[2] https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/estimap-ecosystem-services-mapping-european-scale)

[3] https://swat.tamu.edu/

[4] https://tu-freiberg.de/fakult3/tbt/boden/forschung/erosion-3d

[5] http://aries.integratedmodelling.org

[6] https://lucitools.org/

model uncertainty but also to the lack of proper validation datasets for large-scale models of soil erosion and soil retention. Another source of uncertainty is the lack of local parameterization of empirical models, for instance, the relationships between different parameters influencing soil erosion may vary across regions or land cover types and these differences are often not considered when using empirical models (e.g. USLE, see above).

This uncertainty is also amplified by two other sources of miss estimation, namely (i) thematic completeness, i.e., most models just tackle one type of erosion process, and (ii) quality and resolution of inputs, i.e., often model inputs themselves have a given uncertainty associated and are produced at spatial resolutions that are not coincident with the objectives of the analysis.

3. Measuring future flows of ecosystem services

Soil erosion has severe impacts not only on current conditions and benefits but also, and more importantly, on the option value of the land. This includes the capacity of the land to generate benefits (e.g. potential income *versus* the level of artificial inputs) but also the capacity to hold and sustain above- and below-ground biodiversity. Nevertheless, very few studies have assessed the future of soil erosion retention, how this is spatially distributed and how it may change the conditions of soils. Despite this, there are very strong indications that the current climate pathway and carbon concentrations have a positive greening effect on the global flora, increasing in some cases the leaf area index of forest areas. If remaining constant, this trend may lead to an increase on the overall global capacity for ecosystem service supply. In contrast, global desertification processes also contribute to ever-increasing expansion of dry lands. These, coupled with changes in the patterns and intensity of extreme events (e.g. tornados, heavy rainfall, snow blizzards), can induce higher soil losses in the future (see examples in Table 4).

Table 4: Expected variations considering future scenarios of climate and land use change. Upper, downwards and levelled arrows refer to increases, decreases and non-significant changes, correspondingly. The colours refer to positive (green), negative (red), and non-significant (yellow) expected trends for both soil erosion and soil retention.

Main driver	**Soil erosion**	**Soil retention**
Global greening	↔	↗
Desertification	↗	↘
Increased extreme events	↗	↘
Land intensification	↗	↘
Sustainable land management	↘	↗
Deforestation	↗	↔ ↘
Expanding food markets	↗	↔ ↘

At the same time, there are significant results that show an increased need for food and energy crops and that this trend is expected to continue across the different shared socio-economic pathways outlined by the IPCC. Most of these crops are at the same time based on highly productive plants and prone to high soil rotation and land use intensity. Coupled, these two trends may have important impacts on soil erosion and soil retention, as the underlying soils may continue to be affected by soil degradation and, with the expansion to new areas, more soils can also be exposed to this problem.

From the ecosystem service supply point of view, this combination of future projections can mislead decision makers to have the expectation that an increased soil retention capacity can be translated to a higher soil retention. As many examples show already, although soil erosion rates can be maintained globally, the impacts on soil and on soil retention can just be displaced, leaving depleted soils behind. A good example of this is the prediction of a displacement of impacts (e.g. logging) or increased food capacity in continental Africa. As a result, many of the current areas affected by land degradation would restore their capacity to retain soils but extensive areas in central Africa would suffer radical changes in their soil systems with implications for their long term sustainability.

In combination with such land use changes, climate is expected to change substantially, even within the Paris agreement scenario, which may lead to a higher frequency of direct (e.g. higher rainfall intensity, higher frequency of alternation between drought and extreme rain events) or indirect (e.g. fire regimes) extreme events. These can significantly reduce soil retention and increase the pressure on soil resources, reducing also the option value associated with important biogeochemical cycles, food production, water supplies, and others. In this context, a recent study shows the implications of soil erosion for net soil C flux in Europe and illustrates how important is the inclusion of soil erosion in the estimation of future carbon pools.

4. Economic valuation of the ecosystem service

a. Common institutional contexts for valuation

Soil retention is important in diverse institutional settings, ranging from international institutions such as the United Nations, and the UNFCCC to local decision-makers. It is useful to classify these settings according to why the economic valuation is undertaken as there must be a clearly defined reason for the valuation.

First, it is useful to illustrate the economic importance of soil natural capital and thus of soil retention in the context of human welfare (welfare value) based on total cost to society if the service is lost.

Examples include the welfare implications of carbon sequestration and air quality. Soils store significant amounts of carbon, and thus soil retention is important in a climate change context implying significant welfare implications. Institutional context ranges from the global to the local level, from the UNFCCC and the IPCC to local actors that decide on actions that are to result in carbon sequestration. Welfare implications of deteriorating air quality relate for example to health-related impacts of particulate pollution (particulate matter) and its institutional context. In this case as in the case of climate change, institutions range from international institutions (World Health Organization) to institutions providing healthcare at the local level. As the welfare value of soil retention is revealed the case is made for various soil conservation institutions worldwide that engage in soil retention, from the global to the local level.

Second, economic valuation of soil-derived ecosystem services can be used to illustrate the relative importance of various soil types in different ecosystem contexts. Such differences can affect land-use patterns such as use of agricultural land or conservation of wetlands.

Third, economic evaluation of soil-derived ecosystem services can be used to rationalize or dispute a particular decision in a particular place, for example in a cost-benefit framework where trade-offs in relation to a set of decision-making alternatives are to be made. Examples of relevant decisions include regulating agricultural methods/development and payment of ecosystem services schemes (PES). The US Federal government 'rents' ~140,000 km² of land annually to enhance soil retention. This is achieved by payments of ~US$ 1.8 billion a year to farmers and landowners to plant long-term ground cover to prevent soil erosion (Robinson et al 2014). At the European level, the European Union common agricultural policy (CAP) contains mechanisms that provide PES.

b. Primary valuation options (for both exchange values and welfare values) including discussion of assumed counterfactuals or baselines required for valuation

What is valued?

The economic value of soil retention services is broken to use and non-use values, the sum of the two, providing total economic value. When assessing the economic value of soil retention services, valuation options are based on preference based approaches relying either on revealed or stated preferences for the benefits derived from retaining the soil. In both cases, valuation is based first on the biophysical assessment of the service, and then on willingness to pay (WTP) for the service by each beneficiary. Table 5 gives an overview over the services protected by soil retention ecosystem services. To prevent double-counting, either the value of supporting services is assessed or the value of the services that fall into the three remaining categories; cultural, regulating and provisioning ecosystem services are valued (see Table 5).

Table 5: Use and non-use values of ecosystem services protected by soil retention ecosystem services (from Robinson et al 2014).

	Goods or Services	**Use value**				**Non-use value**
		Consumptive	**Non consumptive**	**Indirect**	**Option value**	
Provisioning services	**Topsoil**	X				
	Subsoil	X				
	Peat	X				
	Sand/Clay minerals	X				
	Soil organisms, earthworms	X				

	Biomedical resources, antibiotics & new organisms used in medicine	X				
	Provision of physical support	X				
	Provision of food wood and fibre	x				
Regulating services	**Waste processing** · Detoxification · Nutrient recycling			X X	X X	X X
	Filtering of Nutrients and contaminants · Water filtration			X	X	X
	Hydrological regulation · River flows mitigation/water levels · Flood peak regulation			X X	X X	X X
	Climate regulation · Carbon storage · Soil moisture buffering of heat and cold waves · Greenhouse gases mitigation			X X X	X X X	X X X
	Hazard regulation · Structural support shrink swell · Dust emissions ·Liquefaction ·Landsliding and slumping			X X X X	X X X X	X X X X
	Pests and Disease regulation · Human and animal pathogens · Disease transmission and vector control		X X		X X	X X

Cultural services	**Burial ground**	X				X
	Scenery		X		X	X
	Recreation		X		X	X
	Preservation of artefacts			X	X	

How is it valued?

The economic value of soil retention services can be derived either as i) the avoided expenditures associated with: mitigating actions, actions to repair damage such as by soil reclamation or replacement of soil retention services or ii) the indirect cascading cost associated with losing soil retention as measured through the negative impact on other soil ecosystem services (see Table 5).

Overall the associated economic values in either case are classified into exchange-based or welfare-based estimates (see examples in Table 6).

Welfare-based values reflect the value of soil retention to society, often illustrated by what would happen if we would lose the ecosystem service in question. These values are in most cases higher than the values classified as exchange values.

Exchange values reflect the price at which ecosystem services would be exchanged between a buyer and seller in an actual or hypothetical market. Exchange values are normally assessed as use or non-use values.

Table 6: Examples of direct and indirect ecosystem service values and related welfare and exchange values.

Ecosystem service	**Welfare value**	**Exchange value**
Direct value Soil retention	Social cost of soil erosion	Avoided expenditures of mitigating soil erosion
Indirect value Soil retention – air quality	Social damage of PM related air quality	Avoided expenditures on air filtration devices
Indirect value Soil retention – Hydrological control	Social damage of reduced water quality	Avoided expenditures associated with dredging waterways
Indirect value Soil retention – Climate regulation	Social damage of climate change	Avoided expenditures on actions to sequester carbon in soils

Use values: In general, the following three types of use value can be distinguished: (i) direct use value; (ii) indirect use value and (iii) option/bequest value.

i) Direct use value arises from the direct utilization of soil retention ecosystem services and can be consumptive or non-consumptive. Consumptive values are applied when assessing provisioning services and rely on direct market exchange. Examples are the market value of topsoil, or the value of various agricultural products (biomass) where soil is a key input factor. Non-consumptive values include the values linked to recreation and aesthetic experiences that are part of cultural services. The value of soil retention services thus can be assessed via for instance the negative impact (cost) soil erosion has on recreational value, which is observed through a hypothetical market. All provisioning services, and some cultural services (such as recreation), have direct use value.

(ii) Indirect use values are either based on the cost of mitigation actions conducted to provide soil retention or on the impact soil retention (or the loss thereof) has on the indirect use of soil ecosystem services. These services normally are not directly exchanged in markets, and thus do not have a market price. As a result, hypothetical markets and demand curves for these services need to be derived. Examples include: climate regulation (carbon sequestration) and hydrological control. The value of these services commonly are assessed by the cost associated with avoiding the negative consequences of losing these services, the damages incurred due to the loss of these services or the cost of replacing these services.

iii) Option and bequest value relates to risk and refer to the willingness to pay for retaining the possibility of using the service in the future, where option value refers to current generations and bequest value to future generations. Examples of option values includes the potential to use soil biodiversity or soil raw materials in the future.

Non-use values, are values that are not associated with use of the service but are inherent in the ecosystem service itself. This includes for example existence value that people place on knowing that healthy soils exist, even if they do not retain any benefits from them and thus are willing to pay for actions that will retain and conserve our soils.

Valuation methods

Numerous economic valuation tools have been developed and are categorized according to whether they rely on actual consumer behaviour (revealed preferences) or stated consumer behaviour (stated preferences). Revealed preference methods rely on observed consumer behaviour and usually are used to assess use values. These methods thus look at actual decisions people make in reaction to specific ecosystem services such as soil retention or to changes in environmental quality due to e.g. soil erosion. Stated preference methods elicit values by constructing a hypothetical market that is captured through surveys. Such methods have been used to assess the value of e.g. soil conservation programmes. As stated preference methods are not compatible with SEEA guidelines, they are not further discussed.

Revealed preference methods, when used in the context of assessing the use value of soil retention, are linked to direct and indirect payments made in relation to the benefits derived from the services maintained by soil retention. However, since many of the derived services are not exchanged in markets, and thus do not have a market price, their value is derived from the value of associated products assessed using a diverse array of methods. The most common valuation methods are: market prices, net factor method, cost-based methods, travel cost and hedonic pricing.

Market prices: The market pricing method estimates the economic value of ecosystem goods or services that are sold in markets. Most often this is used to obtain the value of provisioning services, since commodities provided by them are often sold in markets, for example agricultural commodities. Examples include the value of topsoil, which can be derived from the market value of soil sold in gardening stores or the farm-gate value of agricultural products that are derived from soils.

Cost-based values: Cost-based methods rely on actual expenditures associated with mitigative or avertive expenditures, damage cost avoided or replacement cost. That is, these methods involve estimating the value of the soil ecosystem service based on avoiding: i) the costs of mitigative or avertive actions to prevent loss in soil retention , ii) the cost incurred due to damages to the ecosystem service, for instance the clean-up cost to enhance water quality due to soil erosion (loss in soil retention), or iii) the cost of replacing the ecosystem service by providing man made substitute services, for instance carbon sequestration in the soil to be replaced by man-made carbon capture and storage (CCS) approaches.

These methods do not provide strict measures of economic value, which are based on people’s willingness to pay. Instead, they assume that the costs of mitigation, avoiding repairing damages or replacing services provide useful estimates of the willingness to pay for the service in question. As stated before, the direct use value of soil retention services in most cases is assessed using avoided cost methods.

Net factor income (FI): Net factor income is based on the value of soil retention derived from the value of soil services to for example agricultural yields with less use of added inputs, increasing the income of farmers. Another example could be the impact of soil retention on water quality and thus indirectly on the productivity of river systems in terms of fishery or the costs of purifying municipal drinking water in the case of water utilities. Thus, the indirect economic benefits of soil retention services could be captured from the economic benefits of improved water quality as measured by the increased revenues from a bigger spawning stock of salmon or the decreased costs of providing clean drinking water.

Travel Cost (TC): The travel cost method is based on using travel expenses as a proxy for the willingness to pay for visiting recreational sites. The underlying rationale is that travel is a complementary good to recreation. Soil erosion can reduce the demand for traveling to the place in question, illustrating the indirect value of soil retention.

Hedonic Pricing (HP): The hedonic pricing method seeks to explain the value of a commodity as a bundle of valuable characteristics with one of them linked to environmental quality such as air quality. A classic example of such a commodity is real estate as the price of real estate depends on size, location, as well as various environmental amenities such as air quality. For example, housing prices where there is lower air quality due to particulate matter pollution may be lower compared to areas where air quality is better, illustrating the indirect value of soil retention ecosystem services.

c. Summary of main data requirements and techniques (including benefit transfer)

When summarizing main data requirements and evaluation techniques it is useful to distinguish between assessing the direct value of soil retention services through the avoided cost associated with soil retention, and the indirect value of soil retention services as valued through the cascading negative impact of a loss in soil retention (thus soil erosion) on soil ecosystem services. The assessment of the indirect value assumes that a causal relationship can be derived from soil retention or alternatively soil erosion to each soil ecosystem service.

Direct value of soil retention services

The assessment of the direct value of soil retention services relies on the cost of retaining soils measured either in \$/ha or \$/ton based on mitigation, damage or replacement cost approach. In all three cases the value of soil retention services is measured through the **avoided cost** of mitigation, damage or replacement.

Mitigation cost approach. The mitigation cost approach relies on assessing the expenditures associated with investing in mitigation actions designed to prevent the loss of soil retention services. This could include various soil restoration and management actions. The assessment requires three steps. First, assess the magnitude of the loss in benefits that is to be mitigated, including an assessment of who the beneficiaries are. Second, identify appropriate mitigation actions that could be used to mitigate the loss in benefits. Third, assess the cost of selected mitigation actions, measured in \$/ha or \$/ton.

Damage cost approach. The avoided damage cost approach relies on assessing the avoided expenditures of repairing the damages incurred due to the loss of soil retention services. This could include e.g. dredging of waterways to enhance water quality. The assessment requires three steps. First assess the magnitude of the damage to be repaired and identifying the beneficiaries. Second, identify appropriate actions that could be used to repair the damage caused by the loss in soil retention. Third, assess the cost of the appropriate reparation actions measured e.g. in \$/ton.

Replacement cost approach. The replacement cost approach relies on an assessment of the expenditures of a man-made replacement for soil retention. The assessment includes three steps. First the benefits associated with soil retention are evaluated in terms of how the benefits are used and by whom, in addition to the magnitude of the benefits that are to be replaced. Second, the most likely alternative source of the benefit is identified (that is the replacement) that would provide the same benefits as soil retention provides. Third, assess the costs associated with replacing soil retention with the replacement. The main weakness of this approach is the difficulty of identifying “perfect replacements” or perfect substitutes for soil retention.

Benefit transfer methods could also be applied, where results on avoided costs obtained in another context or location would be applied. Benefit transfer methods should only be applied in similar contexts as the case in question.

Indirect value of soil retention services

Supporting soil ecosystem services (this section is based on Jonsson and Davidsdottir 2017).

Soil formation: Includes the chemical, physical and biological activities that lead to the formation of soil over time by weathering of rocks and minerals. The value of soil formation has been assessed based on the price of topsoil, using market prices.

Nutrient cycling: Nutrient cycling maintains soil fertility and is a process whereby chemical elements are moved through the biotic and abiotic parts of the soil. Microorganisms are key moderators of this service. When assessing the value of nutrient cycling, most authors have used replacement cost, relying on the market price of restoring lost nutrients such as through the use of fertilizers.

Biodiversity pool: Soils are one of the most species-rich habitats of terrestrial ecosystems providing habitat to millions of species, enabling them to function and develop. The value of soils as biodiversity pools has been assessed using stated preference surveys.

Water cycling (storing, filtering and transformation): Includes the physical processes enabling water to enter soils, to be stored and to be released. The value of the water cycling function has been assessed based on the replacement cost of irrigation.

Regulating soil ecosystem services

Biological control of pest and diseases: A healthy soil community keeps pests and harmful disease vectors at bay through competition, predation and parasitism. The value of biological control normally is based on the replacement cost of artificial pest control.

Hydrological control (regulating, buffering, and filtering): The physical processes enabling water to enter soils, be stored and released, thereby regulating water runoff and thus lessening the impact of flood, drought and erosion events are considered as hydrological control. This ability allows soils also to "control" water quality, by absorbing and retaining solutes and 'contaminants', therefore avoiding their release in water bodies such as groundwater, lakes and rivers. The economic value of hydrological control has been evaluated based on replacement cost of topsoil, avoided cost of flood prevention or the avoided cost of dredging waterways.

Climate and GHG regulation: This service includes the production and sequestration of greenhouse gases as well as the regulation of atmospheric chemical composition such as CO2/O2 balance, O3 for UVB protection and SOx levels. The methods used to assess the economic value of climate regulation services are based on the mitigation or replacement cost of providing carbon sequestration in various contexts or the market price of carbon quotas.

Provisioning ecosystem services

Biomass production: Soils provide nutrients, water and physical environment for terrestrial biomass production. The value of biomass production is in most cases based on market values or producers/farm gate prices of the type of biomass produced or the raw materials in question.

Clean water provision: The soil services of buffering and filtering are crucial for establishing the quality and quantity of our subterranean and surface water reserves. The value of clean water provision is in most cases based on the avoided cost of cleaning the water and making it fit for consumption.

Raw materials: Primary soil products such as topsoil, subsoil, peat, and turfgrass are examples of raw materials from soil. Economic values are normally based on the market price of raw materials per ton and vary widely based on the raw material in question.

Cultural ecosystem services

The cultural value of soil ecosystem services has rarely been measured, apart from the recreational value.

Recreation services: Soils provide a platform for recreational activities such as ecotourism and different types of sports. Recreational value is in most cases assessed using the travel cost method. However, studies of soil recreational services are largely missing with the exception of Eastwood et al. (2000) who assessed the reduction in recreational value due to soil erosion and found it to be 1 % of the operation cost for National conservation estates in New Zealand.

In summary, the value of soil retention (regulating) ecosystem services can thus be assessed through i) the direct value of soil retention based on the avoided costs associated with mitigating loss, correcting damage or replacing soil retention, or ii) the indirect value through the exchange value of various soil ecosystem services maintained by soil retention or the welfare values associated with soil retention based on the negative welfare implications of soil erosion.

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