https://doi.org/10.17221/281/2023-AGRICECON

Indirect use value of improved soil health as natural capital that supports essential ecosystem services: A case study of cacao agroforestry

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Citation: Kristanto Y., Tarigan S., June T., Sulistyantara B., Wijayanti P. (2024): Indirect use value of improved soil health as natural capital that supports essential ecosystem services: A case study of cacao agroforestry. Agric. Econ. – Czech, 70: 137–154.

Abstract: Multifunctional landscapes, such as agroforestry, that improve soil health are essential in sustaining terrestrial life by supporting various ecosystem services (ESs). However, decision-making often requires more attention to soil health because its parameters have no market value. In this study, we aim to evaluate soil health parameters in cacao agroforestry and monoculture and their degradation due to erosion and to estimate their indirect use value (IUV). We develop a soil health economic valuation approach bridged by ESs because the economic valuation of ESs tends to be better studied. We estimated the IUVs of the eight soil health parameters by using the direct proxy revealed prevalence valuation method on the basis of the valuation of the four ESs they support: water regulation, climate regulation, nutrient retention and biodiversity. The total IUVs for cacao agroforestry were USD 633 with Endoaquepts and USD 723 with Dystrudepts and for cacao monoculture were USD 415 with Endoaquepts and USD 575 with Dystrudepts. Soil carbon has the highest contribution to IUV, followed by soil nitrogen. Agroforestry not only increases IUV but also minimises its decrease due to erosion. Despite economic valuations being subject to uncertainty, these results encourage the internalisation of soil health values in sustainable land management design.

Keywords: biodiversity services; multifunctional landscape; regulation services; revealed preference; soil indirect use value

Supported by PMDSU (Program Pendidikan Magister Menuju Doktor untuk Sarjana Unggul) scholarship from Ministry of Education, Culture, Research, and Technology, Republic of Indonesia and The Economics of Ecosystem and Biodiversity for Agriculture and Food Initiative in Indonesia (TEEB Agrifood) collaborating with Institut Pertanian Bogor (IPB), The Ministry of National Development Planning, Republic of Indonesia (Bappenas), and United Nation of Environmental Programme (UNEP).

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Ecosystem services (ESs) and sustainable development are integrally interrelated, with soil health at the core (MA 2005; Schreefel et al. 2022). By definition, soil health is the sustainable capacity of soils as natural capital to sustain humans, plants and animals within ecosystem and land-use boundaries (Doran and Zeiss 2000). In the healthy condition, soil plays an essential role in sustaining terrestrial life by supporting the ESs, both provisioning and regulating cultural and habitat services that contribute direct and indirect benefits to human well-being (TEEB 2018). The direct benefits of the soil include providing various resources to meet human needs, such as provisioning food, fibre, fuel, fodder and fertiliser (Pozza and Field 2020). However, the nutrients, water and climate regulation and the provision of habitat for life above and below the soil are among the indirect benefits provided by soil (Dominati et al. 2014a; Jónsson and Davíðsdóttir 2016; Pereira et al. 2018). These indirect benefits play an essential role in the resilience of direct benefits in the long term because of uncertainties caused by external disturbances such as climate change (Nouri et al. 2021).

ESs supported by soils significantly improve communities' and ecosystems' health and vitality, reduce poverty and mitigate climate change (Kihara et al. 2020). Healthy soil can optimally provide benefits in the form of ESs, such as climate regulation through soil carbon storage, water regulation through soil porosity and nutrient retention by the soil matrices (Pereira et al. 2018). Conversely, these benefits will become suboptimal in unhealthy or degraded soil. Soil health degradation is mainly caused by the intensive land management that has increased since the beginning of the green revolution (John and Babu 2021), which has led to soil compaction and erosion (Kristanto et al. 2022). If this trend continues, it could lead to irreversible soil degradation. Because soil is a natural capital that cannot be renewed, its degradation poses a threat to the food security of future generations (Kopittke et al. 2019).

Given the importance of the ESs supported by soils, soil health must be maintained through sustainable management. However, soil health is often overlooked and rarely appreciated. Regenerative agriculture can be achieved only by respecting soil health and the ESs it supports (Schreefel et al. 2022). Recently, policymakers have become interested in soil functions besides increasing agricultural productivity (Keesstra et al. 2018). One method of sustainable soil management is implementing multifunctional landscapes or integrated landscape management (i.e. agroforestry). Agroforestry is a land-use management system that combines crops with multipurpose tree species (MPTS) to restore the soil's multifunctionality (Nair et al. 2021). The crops cultivated in agroforestry maintain provisioning services, and MPTS maintain regulation and habitat services (Kristanto et al. 2022).

Besides its function for crop production, soil economic value is rarely considered, and farmers rarely prioritise soil health in investment (Carlisle 2016). Maintaining soil health through agroforestry increases farming costs and reduces income in the initial stages, so farmers adopt agroforestry when financially incentivised to do so (Garen et al. 2009). However, various soil health parameters do not have market prices. To promote soil health in decision-making, we need a valuation method to estimate the indirect use value (IUV) and internalise it into a cost-and-benefit analysis (Kiran and Malhi 2011). Monetising the soil health's IUV is a practical approach accessible for stakeholders to understand.

In this study, we aim to evaluate soil health parameters in cacao agroforestry and monoculture and their degradation due to erosion and to estimate their IUVs. Soil health includes eight parameters, and the IUV estimation is bridged by the economic valuation of ESs. The ES economic value has been studied previously (e.g. Alam et al. 2014; Dominati et al. 2014b), and a renewed interest in the economic value of soil-supported ESs has developed (Dominati et al. 2010; Pascual et al. 2015). However, the economic valuation of soil health is not as well developed. Filling this gap requires establishing methods for valuing soil health bridged by an economic valuation of ESs. Thus, that framework is assumed to be applicable to link soil health with ES valuation methods, and the results can be used to design a payment for soil health (PSH) as a development of payments for ESs (PESs).

MATERIAL AND METHODS

Study site

We applied an integrated framework for the assessment and valuation of soil health to the Rongkong watersheds in North Luwu, South Sulawesi, Indonesia, a tropical landscape dominated by cacao plantations. The Rongkong watershed is located at 2°21.72'–2°51.96'S and 119°52.92'–120°21.54'E and has an area approximately of 1 240 km^2. We determined the study area purposively – that is, we determined it with certain considerations tailored to achieving the research objectives. In addition, TEEBAgriFood Indonesia supported this research.

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The downstream area of the watershed is tropical lowlands with very flat topography, whereas the upstream area of the watershed is hilly with very steep topography. The soil types in the upstream and downstream areas are homogeneous, with the soil type in the upstream area being Cambisols (Dystrudepts) and in the downstream area being Gleysols (Endoaquepts). Paddy fields, rural settlement and cacao plantations are the dominant use of agricultural land in the downstream region. In contrast, the upstream region is dominated by natural forest, with few cacao and mixed plantations. This area is interesting to study because cocoa agroforestry tends to be neglected and require maintenance in the future (Figure 1).

Sampling and data collection

We based soil sampling locations on a survey approach or conducting systematic exploration to get a comprehensive picture of the data collection location. We took soil samples at topsoil (0–15 cm) to identify the soil health parameters. We chose topsoil as the analysis boundary because it is the primary area of rooting and tillage activity, so at that depth, the noninert soil properties tend to change (Gregory et al. 2016).

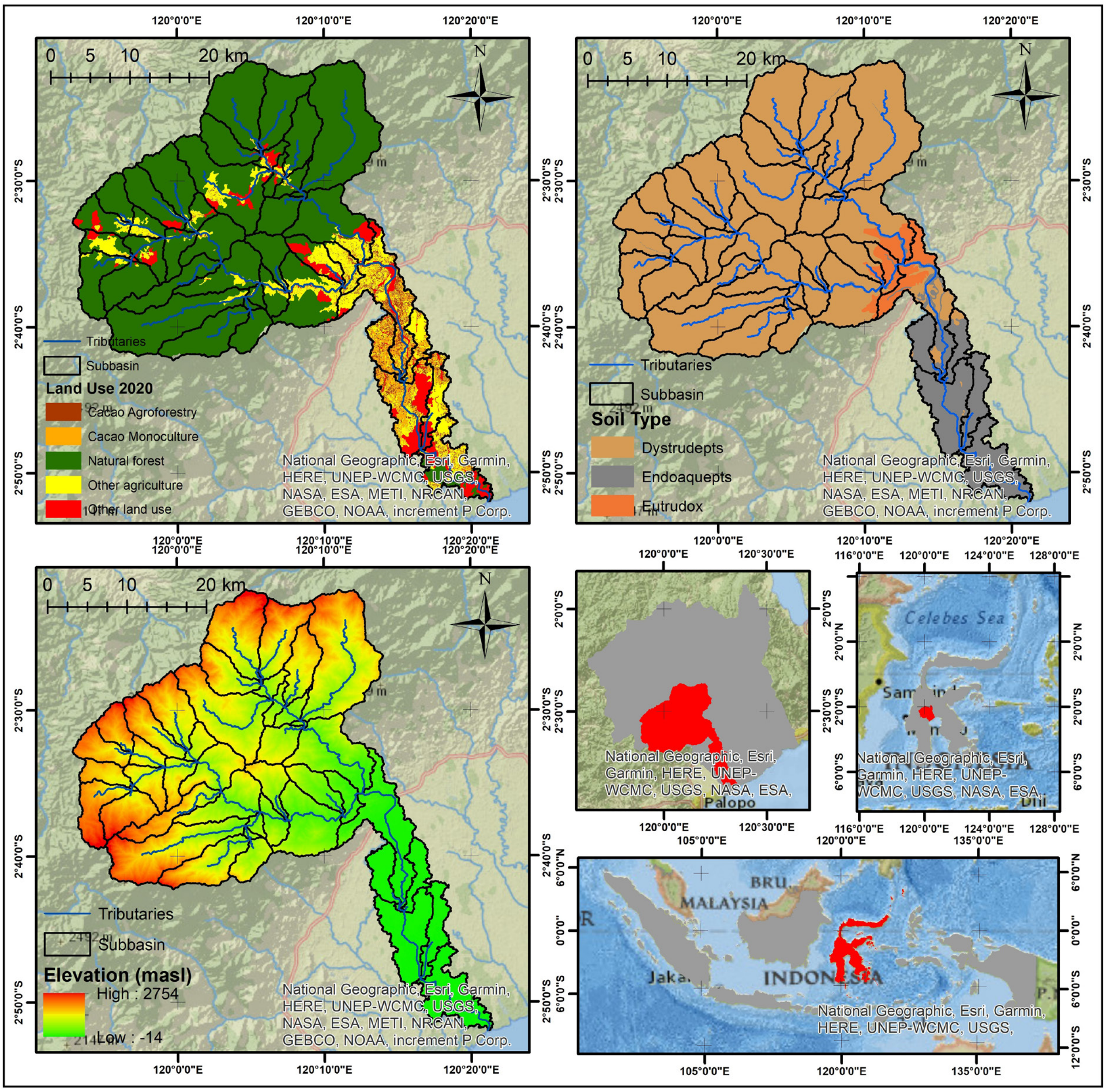

Figure 1. The study area is in North Luwu Regency, South Sulawesi, Indonesia

Source: Authors' own processing

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On the basis of a stratified purposive sampling design, we took 40 undisturbed and composite soil samples with details of two types of management (agroforestry and monoculture), two types of soil (Dystrudepts and Endoaquepts), five locations per management and two samples per location. Because the soil types are different, the assumption we used is that different soil types will have different soil health conditions under the same management.

In addition to using soil samples, we used various forms of data in this research. These include secondary data such as daily rainfall, soil type maps, digital elevation models and biophysical tables of vegetation and land management factors. We used these secondary data to calculate soil erosion. The research also involved using interviews to collect data on prices of substitute goods from local markets. We used these prices to calculate the replacement cost of soil health in IUV calculations.

Data analysis using economic valuation of soil health framework

In this study, we present a soil health economic valuation method based on the relationship between soil health parameters and the ESs they support. This research consisted of four stages. First, we identified differences in soil health parameters in cacao agroforestry and monoculture. Second, we estimated the soil health degradation due to erosion which then led to the degradation of the ESs. Third, we identified the ESs associated with each soil health parameter; after consulting with experts and conducting literature studies, we evaluated four ESs related to eight soil health parameters. Fourth, we estimated the soil health *IUV* by using the direct proxy revealed preference valuation method (Figure 2).

i) Analysis of soil health. Bulk density, porosity, invertebrates, total nitrogen (N-total), available phosphorus (P-available), microbes, fungi and soil organic carbon (*SOC*) are essential parameters that have been evaluated for their significant implication for various ESs (Dominati et al. 2010; Jónsson et al. 2017). Bulk density and porosity are related to water regulation; *SOC* is related to climate regulation; N-total and P-available are related to nutrient retention; and total microbes, fungi and micro-invertebrates are related to biodiversity services. We analysed bulk density, porosity and micro-invertebrates from undisturbed soil samples, and we analysed N-total, P-available, total microbes, total fungi and *SOC* from composite samples.

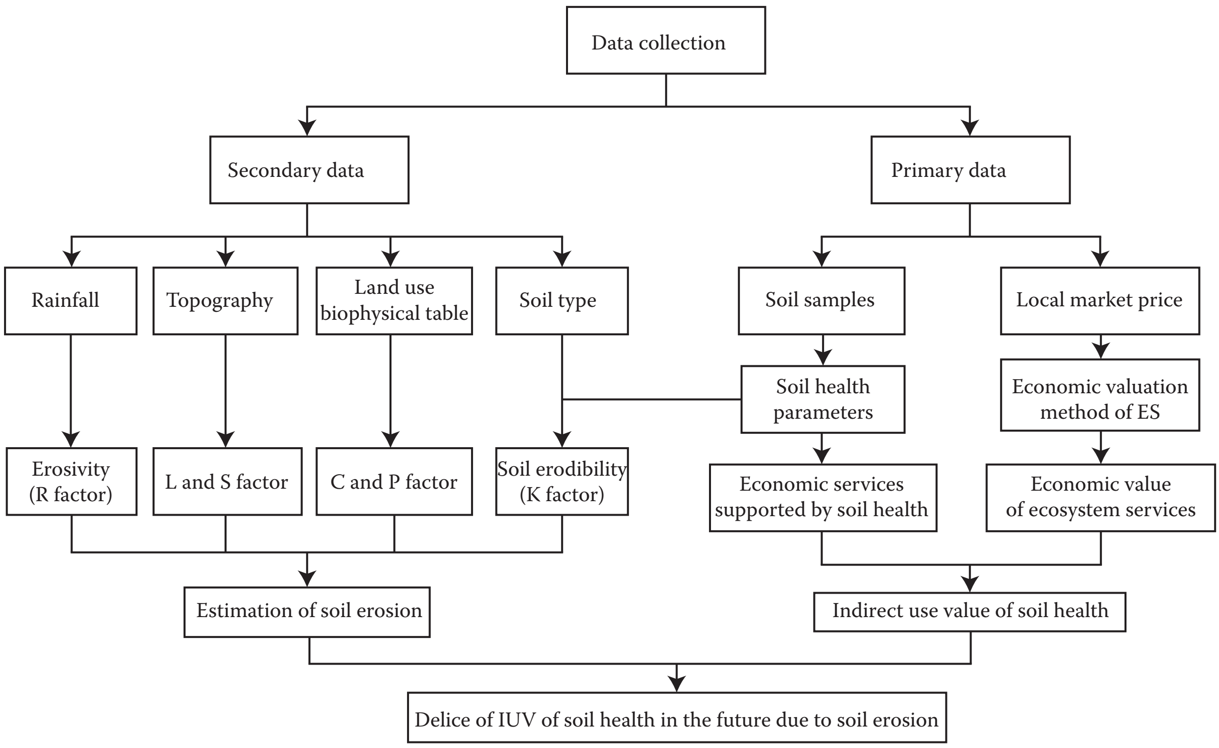

Figure 2. Flow chart of data analysis

Source: Authors' own elaboration

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Other soil health parameters such as micronutrients, pH, base saturation and cation exchange capacity can be measured and evaluated; however, some have autocorrelation with other parameters, and others have less significant implications for ESs. We used descriptive statistics – histograms and analysis of variance – to examine differences in soil parameters between cacao agroforestry and monoculture. If analysis of variance showed a significant difference ($P \leq 0.05$), then we performed a post hoc test by using Duncan's multiple range test.

***ii*) Analysis of soil degradation due to erosion.** Erosion is the main factor causing soil degradation and directly affects on-farm and off-farm ecosystems. Erosion reduces crop production on the on-farm scale by leaching nutrients and organisms bound by the soil matrix and reducing topsoil depth (Boardman et al. 2009; Bashagaluke et al. 2018). On the off-farm scale, erosion can cause siltation and eutrophication of water bodies (Issaka and Ashraf 2017). The general equation used to calculate soil erosion is the Universal Soil Loss Equation (Neitsch et al. 2011).

$$E = 1\,292 \times R \times K \times LS \times C \times P \quad (1)$$

where: 1 292 – unit conversion constant; E – soil erosion (kg/ha per year); R – rainfall erosivity (m metric ton cm/m^2 per hour); K – soil erodibility (metric ton m^2 hr/m^3 metric ton cm); C – vegetation factor; P – management factor; LS – length and slope factor.

We set the value of R at 4 023 m metric ton cm/m^2 per hour on the basis of average annual rainfall in the study area from 2001 to 2022. We set the LS value at 1.17 as an implication of the average slope in the downstream area and 1.68 for the upstream area. We set the C value at 0.05 for agroforestry and 0.2 for monoculture, and we set the P value at 0.5 for cacao planted in slopes of 2% to 7% and 0.9 for cacao planted in slopes of 18% to 24%. Unlike the constant R, LS, C, and P values, the K values vary according to the soil properties. Some soils erode more quickly than others, even when all other factors are equal. We estimated soil erodibility by using the Wischmeier et al. (1971) nomograph, which uses soil texture, soil organic matter (SOM), soil structure and permeability.

iii) ESs supported by soil health. ES is inseparable from soil health but is provided by soil through a combination of climatic, topographic and anthropogenic factors (Diaz et al. 2015). On the basis of this fact, this research is limited to evaluating soil health as a support for ESs, not the final value of ESs. The final value of ESs may be greater than the value estimated using soil health factors alone.

Figure 3 shows the Dominati et al. (2010) conceptual framework, and we used it to assess the contribution of soil health to support ESs (Table 1). The evaluated ESs are limited to regulation and habitat services. In contrast to provisioning services, these services do not have market value, so they are under consideration in the research objectives. The benefits of these

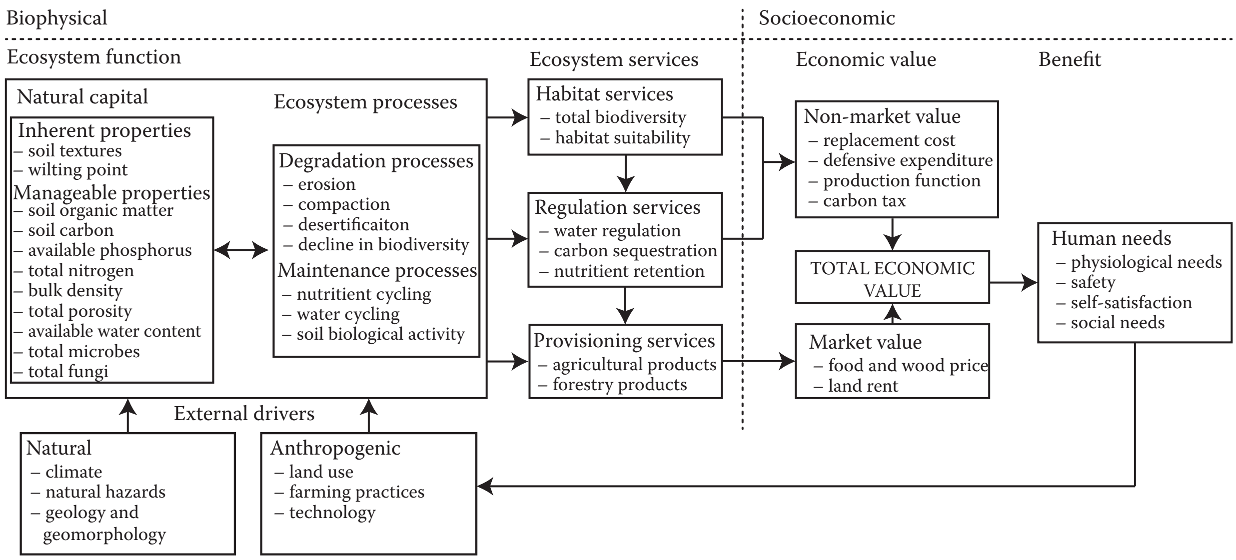

Figure 3. The framework for valuation of soil health based on the ecosystem service it supports

Source: Dominati et al. (2010); author's own elaboration

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Table 1. Soil parameters, the ES that supported by each soil parameter, and the economic valuation method

No.	Soil parameters and units	Supported ES	Economic valuation	Equation (USD/ha)
1	soil carbon organic (*SOC*) (%)	climate regulation	cost based: carbon incentive	$EV_{SOC} = SOC \times W \times \frac{Mr_{CO_2}}{Mr_C} \times CI$
2	total nitrogen or N-total (*TN*) (%)	nutrient retention	cost based: replacement cost	$EV_{TN} = TN \times W \times 46\%\ N \times FP_{Urea}$
3	available phosphorus or P-available (*AP*) (%)			$EV_{AP} = AP \times W \times 46\%\ P \times FP_{TSP}$
4	gravitational water (*GW*) (%)	water regulation	production function	$EV_{GW} = GW \times V \times WP$
5	available water content (*AWC*) (%)			$EV_{AWC} = AWC \times V \times CWU \times DBP$
6	total microbes (*TM*) (cfu/ha)	soil biodiversity	production function	Equation (5)
7	total fungi (*TF*) (cfu/ha)			
8	total invertebrates (*TI*) (ind/ha)			

ES – ecosystem services; EV – economic value; W – soil weight (kg/ha); Mr_{CO2} – relative molecular mass of carbon dioxide; Mr_C – relative molecular mass of carbon; CI – carbon incentive (USD/kg CO_{2eq}); 46% N – nitrogen content in urea; FP_{Urea} – urea price (USD/kg); 46% P – phosphorus content in TSP; FP_{TSP} – TSP price (USD/kg); V – soil volume (m^3/ha); WP – water utilization price (USD/m^3); CWU – crop water usage (kg/m^3); DBP – cocoa dry bean price (USD/kg); TSP – triple super phosphate

Source: Authors' own elaboration

ESs often go unnoticed and tend to be degraded over time. We excluded cultural services from this study because the quantification requires different techniques because of their nonbiophysical characteristics. However, the IUVs of cultural services must be added to other studies for a more complete analysis. A crucial dimension of the value of soil health is the distributional benefits expected from the various ESs it supports. These benefits can simultaneously be private and public benefits that become externalities (Bennet et al. 2010).

iv) Economic valuation method. Investment decisions can affect the health of soil, either positively or negatively. Thus, through the logic of neoclassical economics, soil health can be considered as a natural capital, and the ESs it supports are the returns obtained from those capitals. Quantitative relationships linking soil health with ES are needed to estimate the economic value of soil health as natural capital. Through this relationship, the economic value of soil health can be approached using the ES valuation method.

This research is limited to estimating the *IUV*. Suppose the overall value of ES is the total economic value. *IUV* is associated with regulation, cultural and habitat services, whereas direct use value is associated with provisioning services (Pascual et al. 2015). Calculating *IUV* is more challenging than calculating direct use value (Stuip and van Dam 2018). In one case, various methods can be used in calculating the *IUV*; in other cases, there are no reliable *IUV* methods. *IUV* (USD/ha) can be grouped into private (*PIV*) and social (*SIV*). The main difference is who obtains and controls the ESs (Bennet et al. 2010).

$$IUV = SIV + PIV = \sum_{i}^{I} \sum EV_i \qquad (2)$$

where: IUV – indirect use value; PIV – private indirect use value; SIV – social indirect use value; EV_i – economic value of soil health parameter i obtained from Table 1 (USD/ha); I – number of analysed soil health parameters.

Changes in the time series *IUV* because of erosion, along with *IUV*'s present value (*PV*), can be calculated as follows:

$$IUV_t = IUV_0 - \sum_{i}^{I} \sum REV_i \qquad (3)$$

$$PV_t = \frac{IUV_t}{(1+r)^t} \qquad (4)$$

where: IUV_t – IUV at time t (USD/ha); PV_t – PV for IUV_t (USD/ha); IUV_0 – initial IUV (USD/ha); REV_i – reduction of the economic value of each soil parameter owing to erosion (USD/ha); r – discount rate.

We used the direct proxy revealed preference valuation method to calculate the *IUV*. This method is grouped into the cost approach and the production function.

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– The cost approach is a valuation method related to a relevant market for ESs that do not have a market price (Selivanov and Hlaváčková 2021).

– The production function is a valuation method of ESs that do not have market prices but act as input for the supply of other ESs that already have market prices (Faber et al. 2021).

The production function can be a pedotransfer function (PTF), the empirical model proposed to predict unobserved soil properties on the basis of the observed soil properties (van Looy et al. 2017). In this study, we used PTF to estimate the IUV of soil biodiversity (total microbes, fungi and micro-invertebrates). Various kinds of literature explain soil biodiversity affected by pH, N-total, P-available and SOM (Manzoni et al. 2012; van Looy et al. 2017). According to Pascual et al. (2015), the formulation of the ecological relationship between changes in soil parameters and changes in soil biodiversity quantitatively is a suitable method for the economic assessment of soil biodiversity. The logic used is similar to that of econometric equations. If other soil parameters can approximate soil biodiversity, then the economic value of biodiversity can also be approximated by the economic value of the soil parameters that influence it. In this study, we constructed the PTF by using stepwise regression.

$$SB = \beta_0 + \beta_1 SOM + \beta_2 TN + \beta_3 AP + \beta_4 pH \quad (5)$$

where: *SB* – soil biodiversity, which is total microbes (CFU), total fungi (CFU) and total invertebrates (individuals); *SOM* – soil organic matter (kg); *TN* – N-total (kg); *AP* – P-available (kg); *pH* – soil acidity.

Details of the soil health parameters analysed, the ESs supported and the valuation method for each soil health parameter are presented in Table 1.

RESULTS AND DISCUSSION

Soil health parameters

We developed a broader scope of the concept of soil health in which soil, apart from functioning for agricultural production also functions to support environmental sustainability through the maintenance of various ESs (Kihara et al. 2020). Soil is healthy if the physical, chemical and biological parameters optimally support all soil functions and processes to enhance ESs. Physical parameters are parameters related to the structure of soil particles, where chemical parameters are related to the composition of chemical elements in the soil ecosystem and biological parameters are related to the abundance and diversity of organic matter and soil organisms.

Table 2 presents the soil health parameters in cacao agroforestry and monoculture on the basis of soil sampling and laboratory analysis. Cacao agroforestry with both Dystrudepts and Endoaquepts improves the overall soil physical, chemical and biological parameters, indicating that these systems have healthier soil than does cacao monoculture. This fact is evidenced by the *SOC*, N-total, P-available, porosity, total microbes, total fungi and total invertebrates, which were significantly higher ($P \leq 0.05$), and the bulk density, which was also significant and was lower in agroforestry systems. One of the reasons for the increase in soil health was the higher *SOM* from litter produced by MPTS in agroforestry.

SOM is a crucial parameter because it significantly affects the overall soil health parameters (Craswell and Lefroy 2001). Nutrient balance is often found in soils with high *SOM*, creating optimal conditions for plant growth (Akoto et al. 2022). High *SOM* also directly affects increasing soil porosity by improving soil structure and supporting higher soil organism diversity (Garratt et al. 2018). *SOM* is an alternative feed source for invertebrates, microbes and fungi that play a role in decomposition processes, pest control and nutrient cycling. The relationship between *SOM* and soil biodiversity forms a positive reinforcing loop to improve soil health (Laban et al. 2018).

SOM also plays a role in minimising erosion by decreasing *K* (Wischmeier et al. 1971), evidenced by the lower level of *K* in agroforestry than in monoculture (Table 1). In addition, the lower erosion in cacao agroforestry is caused by a decrease in *C* because of the presence of MPTS. Although the *K* value for Endoaquepts was higher than that for Dystrudepts, the erosion rate for Dystrudepts was higher than that for Endoaquepts, both in agroforestry and monoculture. Dystrudepts had a higher *LS* because they dominate a hilly landscape with steep slopes. These findings imply that efforts to control erosion through agroforestry must be emphasised on plantations with higher erosion potential to reduce *K* and *C* values (Sun et al. 2021). Reducing the value of *K* by adding *SOM* in soil with steep slopes, assuming the identical *R*, *C*, and *P*, will reduce erosion more significantly than will intervention on flat slopes.

Economic value of soil health

Soil health improvement in cacao agroforestry has been hypothesised to increase the ESs and *IUV*s. We describe the implicit role of each soil health param-

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Table 2. Soil health parameters on cacao agroforestry and monoculture

No.	Soil health parameter	Dystru–AF	Dystru–Mono	Endo–AF	Endo–Mono
Observed (mean ± SD)					
1	*SOC* (%)**	2.17 ± 0.38[a]	1.70 ± 0.35[b]	1.54 ± 0.33[b]	1.05 ± 0.26[c]
2	N-total (%)**	0.178 ± 0.022[a]	0.150 ± 0.027[b]	0.139 ± 0.026[b]	0.103 ± 0.018[c]
3	P-available (ppm)**	51.66 ± 20.66[ab]	26.12 ± 17.62[b]	80.14 ± 57.99[a]	28.13 ± 13.14[b]
4	bulk density (kg/m^3)**	1.06 ± 0.06[bc]	1.11 ± 0.08[c]	0.98 ± 0.07[a]	1.03 ± 0.07[ab]
5	total pores (%)**	0.524 ± 0.021[b]	0.514 ± 0.033[b]	0.577 ± 0.023[a]	0.566 ± 0.023[a]
6	*TM* (cfu/g)**	(9.6 ± 5.8) × 10^5[a]	(5.0 ± 4.2) × 10^5[b]	(8.9 ± 4.3) × 10^5[a]	(4.1 ± 2.0) × 10^5[b]
7	*TF* (cfu/g)**	306 ± 154[b]	182 ± 118[b]	540 ± 227[a]	239 ± 146[b]
8	*TI* (ind/ring[1])**	13 ± 3[b]	8 ± 2[b]	54 ± 25[a]	14 ± 7[b]
Derived (mean)					
1	field capacity (%)	34.2	33.5	40.2	39.4
2	permanent wilting point (%)	15.9	15.5	15.5	15.3
3	*AWC* (%)	18.3	18.0	24.6	24.2
4	*GW* (%)	18.3	17.9	17.5	17.2
5	soil erodibility (tonne m^2 hr/m^3 tonne cm)	0.36	0.39	0.39	0.43
Derived erosion rate (mean)					
1	soil loss (tonne/ha/yr)	11.34	49.78	4.81	21.00
2	volume loss (m^3/yr)	10.71	45.05	4.95	20.45
3	solum loss (cm/yr)	0.11	0.45	0.05	0.20

** significant on 95% confidence level; [1] ring sample with diameter 15 cm and height 15 cm; [abc] numbers followed by the same letter are not significantly different; AF – agroforestry; Mono – monoculture; *SOC* – soil organic carbon; *TM* – total microbes; *TF* – total fungi; *TI* – total invertebrates; *AWC* – available water content; *GW* – gravitational water

Source: Authors' own processing

eter in supporting ESs and the estimation of the *IUV*s more clearly in the following points.

SOC. Healthy soil stores *SOC* to reduce atmospheric carbon concentrations. Soils store carbon three to four times more than does the atmosphere (Lal 2004; Laban et al. 2018), so increasing *SOC* efficiently mitigates climate change. Cacao monoculture contains 1.05% *SOC* with Endoaquepts and 1.70% with Dystrudepts, which equals 16.3 tonneC per ha (59.8 tonneCO_2e/ha) and 28.4 tonneC per ha (104.3 tonneCO_2e/ha), respectively. In cacao agroforestry, SOC increased to 1.54% with Endoaquepts and 2.17% with Dystrudepts, which equals 22.7 tonC per ha (83.1 tonneCO_2e/ha) and 34.2 tonneC per ha (125.4 tonCO_2e/ha), respectively. The amount of litter and the population of decomposers can explain differences in *SOC* (Tate et al. 2005). Inadequate organic inputs, both through litter decomposition or adding organic fertilisers, reduces SOC in monoculture. In contrast, agroforestry retains higher *SOC* through litter decomposition even without organic fertilisation (Figure 4).

The valuation of SOC can be approached with a carbon incentive for those who sequester carbon. The Indonesian government set a carbon incentive for 2022 of USD 2 per tonCO_{2e}. On the basis of this approach, the *IUV*s of Endoaquepts *SOC* for cacao agroforestry and monoculture were USD 166.28 per ha and USD 119.66 per ha, respectively, with erosion-induced depletion of USD 0.54 per ha per year and USD 1.60 per ha per year, respectively. However, the *IUV*s of Dystrudepts *SOC* for cacao agroforestry and monoculture were USD 250.74 per ha and USD 208.56 per ha, respectively, with depletion due to erosion of USD 1.78 per ha per year and USD 6.12 per ha per year, respectively. The results show that, from a carbon perspective, agroforestry is preferable to monoculture in terms of economic value. The *IUV* of soil carbon is considered an SIV and is actualised through PES because it is not used by farmers but by the broader community in climate change mitigation efforts (Ovando et al. 2019).

Soil porosity. Soil distributes rainfall into surface runoff, groundwater recharge and soil water storage.

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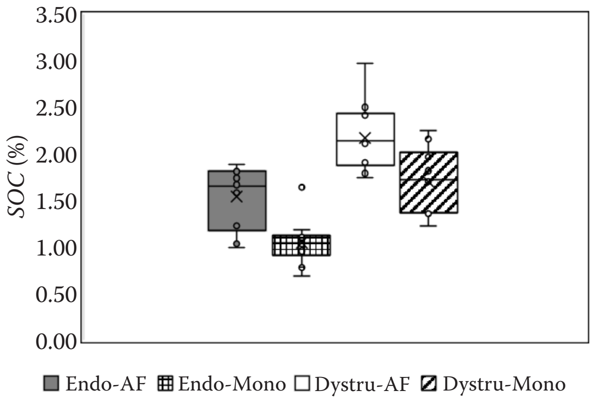

Figure 4. Histogram of soil organic carbon

SOC – soil organic carbon; Endo – Endoaquepts; Dystru – Dystrudepts; AF – agroforestry; Mono – monoculture
Source: Authors' own processing

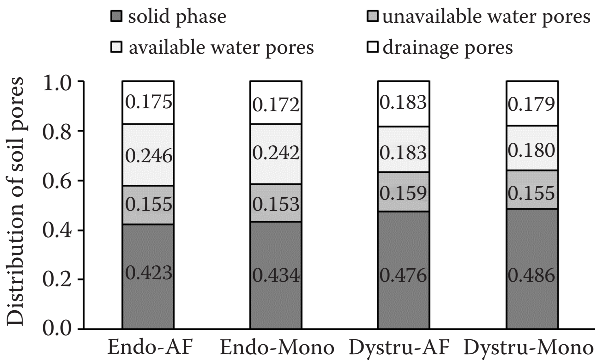

Figure 5. Distribution of soil pores

Endo – Endoaquepts; Dystru – Dystrudepts; AF – agroforestry; Mono – monoculture
Source: Authors' own processing

Groundwater recharge is related to the drainage pores, whereas soil water storage is related to the available water pores (Kristanto et al. 2022). Drainage pores for cacao agroforestry with Endoaquepts was 17.5% and for monoculture was 17.2%. However, drainage pores for agroforestry with Dystrudepts was 18.3% and for monoculture was 17.9%. Gravitational water is water that occupies the drainage pores, where this water moves freely owing to gravity to fill the groundwater. Thus, the higher the drainage pore, the more gravitational water can be accommodated by the soil volume so that the groundwater recharge also becomes higher (Figure 5).

Cacao agroforestry with Endoaquepts held a volume of gravitational water of 263 m^3, with a depletion rate of 0.87 m^3 per year, whereas monoculture held 258 m^3, with a depletion rate of 3.53 m^3 per year. However, agroforestry and monoculture with Dystrudepts held 274 m^3 and 269 m^3 of gravitational water, respectively, with depletion of 1.96 m^3 per year and 8.11 m^3 per year, respectively. Because groundwater is used as a raw water source, the *IUV* can be estimated using water public utility prices. On the basis of the local groundwater use price that applies to the lowest user level, USD 0.2 per m^3, the *IUV* of gravitational water for agroforestry was USD 52.61 per ha with Endoaquepts and USD 54.83 per ha with Dystrudepts, with depletion rates, respectively, of USD 0.17 and USD 0.39. The *IUV* of gravitational water for monoculture was USD 51.64 with Endoaquepts and USD 53.77 with Dystrudepts, with depletion rates, respectively, of USD 0.71 and USD 1.62. The *IUV* of gravitational water is also an SIV and can be actualised through PES.

Plant roots absorb available water content (*AWC*) to form biomass, so the higher the *AWC*, the higher the biomass produced. The *AWC* values for agroforestry and monoculture with Endoaquepts were 24.6% and 24.2%, and those with Dystrudepts were 18.3% and 18.0%. The *AWC* values of the Endoaquepts were equivalent to water volumes of 369 m^3 and 362 m^3, respectively, with depletion rates of 1.22 m^3 per year and 1.96 m^3 per year, respectively, and the *AWC* values of the Dystrudepts were equivalent to 275 m^3 and 269 m^3, respectively, with depletion rates of 4.96 m^3 per year and 8.12 m^3 per year, respectively. According to Ortiz-Rodriguez et al. (2015), 1 m^3 of *AWC* is needed for cocoa to produce 0.059 kg of dry beans. With use of a production function with a dry bean price of USD 2.13, the *IUV* of *AWC* for agroforestry was USD 46.66 per ha with Endoaquepts and USD 34.56 per ha with Dystrudepts. However, the *IUV* of *AWC* for monoculture was USD 45.62 per ha with Endoaquepts and USD 33.89 per ha with Dystrudepts. In contrast to gravitational water, the *IUV* of *AWC* is classified as a PIV because it directly influences crop production. Thus, this value can be internalised into premium selling prices or land rental prices.

Soil nutrients. N-total and P-available are both soil health and fertility parameters. These nutrients are bounded by the soil matrix, so the depletion of these nutrients occurs primarily owing to erosion and leaching (Dominati et al. 2014b). The N-total for Endoaquepts was 0.14% (2 039 kg/ha) for agroforestry, with a depletion rate of 6.62 kg per ha per year, and

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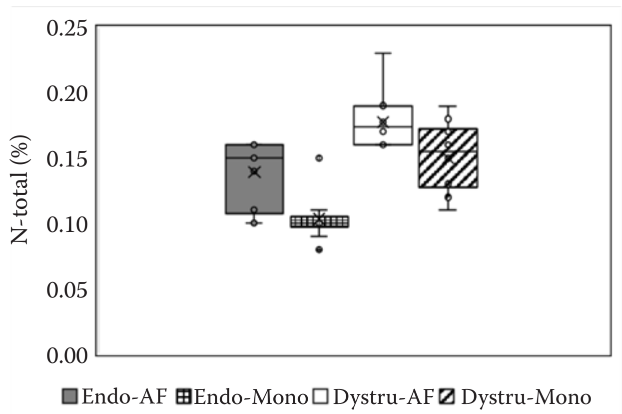
0.10% (1 601 kg/ha) for monoculture, with a depletion rate of 21.54 kg per ha per year. The N-total for Dystrudepts was 0.18% (2 802 kg/ha) for agroforestry, with a depletion rate of 19.92 kg per ha per year, and 0.15% (2 508 kg/ha) for monoculture, with a depletion rate of 73.78 kg per ha per year. However, the P-available for Endoaquepts was 80.14 ppm (119.53 kg/ha) for agroforestry, with a depletion rate of 0.38 kg per ha per year, and 28.13 ppm (43.02 kg/ha) for monoculture, with a depletion rate of 0.59 kg per ha per year. The P-available for Dystrudepts was 51.66 ppm (82.38 kg/ha) for agroforestry, with a depletion rate of 0.59 kg per ha per year, and 26.12 ppm (41.83 kg/ha) for monoculture, with a depletion rate of 1.31 kg per ha per year. On the basis of these results, the N-total for Dystrudepts was generally higher and the P-available lower than those in in Endoaquepts (Figure 6).

Decreasing levels of nitrogen and phosphorus in the soil lead to a decrease in soil fertility. In such cases, fertilisation becomes necessary to maintain the soil's productivity. Thus, the soil nutrient can be approximated using the replacement cost and the price of urea fertiliser for nitrogen and triple super phosphate (TSP) fertiliser for phosphorus. Based on the current urea price of USD 0.15 per kg, the valuation of N-total for Endoaquepts was estimated at USD 140.67 per ha for agroforestry and USD 110.46 per ha for monoculture, whereas the valuation of N-total for Dystrudepts was estimated at USD 193.36 per ha for agroforestry and USD 173.02 per ha for monoculture. Based on the current TSP fertiliser price of USD 1.2 per kg, the P-available valuation for Endoaquepts was estimated at USD 65.98 per ha agroforestry and USD 23.75 per ha for monoculture. The P-available value for Dystrudepts was estimated at USD 45.48 per ha for agroforestry and USD 23.09 per ha for monoculture. The *IUV*s of N-total and P-available were classified as a PIV. The *IUV*s of N-total and P-available provide benefits in reducing the additional costs for fertilisation when internalised into the feasibility analysis.

Soil organisms. Soil organisms are engineers in soil processes, including mineralisation, nutrient cycling and decomposition (Lavelle et al. 2016). High and diverse soil organism populations in cacao agroforestry indicate that these systems have higher soil functional diversity (van Looy et al. 2017). This diversity was shown by the populations of invertebrates, microbes and fungi with the Endoaquepts of 54 individual/ring samples soil (ind/ring), 8.9×10^5 CFU/g and 540 CFU/g, respectively. This value was higher than the invertebrate, microbe and fungi populations in the cacao monoculture of 14 ind/ring, 4.1×10^5 CFU/g and 239 CFU/g, respectively. We also found similar conditions with Dystrudepts agroforestry with populations of 13 ind/ring, 9.6×10^5 CFU/g and 306 CFU/g, higher than those for monoculture with populations of 8 ind/ring, 5.0×10^5 CFU/g and 182 CFU/g. The composition of invertebrates was dominated by Collembola, Acari and Hymenoptera and some Opiliones, Geophilomorpha, Coleoptera, Dermaptera, Diplura, Psocoptera and Symphyla (Figure 7).

Investigators in various studies have used experimental designs to examine the effect of soil organisms on agricultural production, so we can assume that the production function can approximate the *IUV* of soil



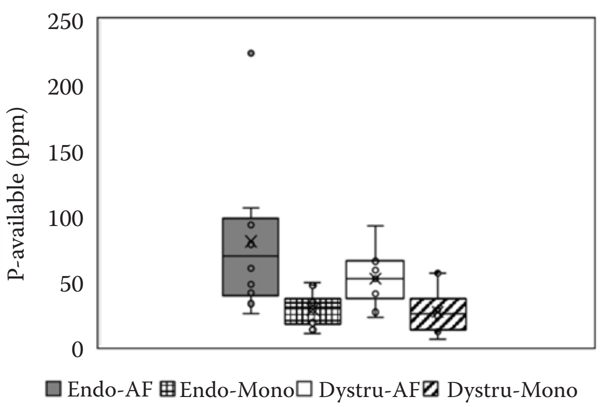


Figure 6. Histogram of soil total- N and P-available

Endo – Endoaquepts; Dystru – Dystrudepts; AF – agroforestry; Mono – monoculture
Source: Authors' own processing

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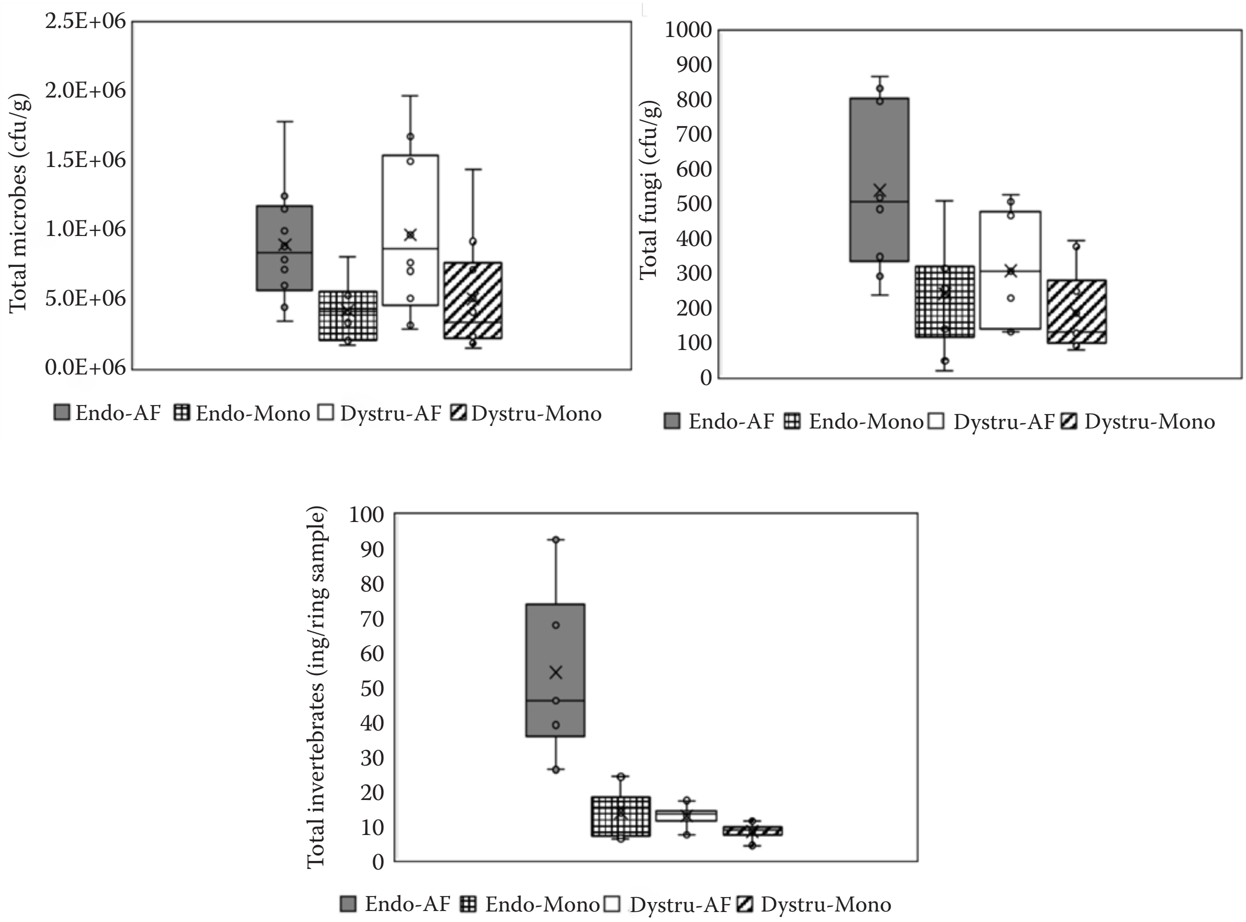

Figure 7. Histogram of soil total microbes, total fungi, and total invertebrate

Endo – Endoaquepts; Dystru – Dystrudepts; AF – agroforestry; Mono – monoculture
Source: Authors' own processing

organisms (Daniels et al. 2018). However, our study did not have an experimental design, making the production function unsuitable. For this reason, a more suitable economic valuation is using the PTF. Alam et al. (2014), who assessed the economics of earthworms, also used this method. On the basis of the PTF, as shown in Table 3 and Figure 8, we found that P-available influenced invertebrates but that SOC affected microbes and fungi. Thus, the IUVs of these soil organisms can be estimated from the IUVs of the soil properties that affect them.

The estimated *IUV*s of the invertebrates from the PTF were USD 2.1 per 10^{-6} invertebrates for Endoaquepts and USD 7.7 per 10^{-6} invertebrates for Dystrudepts. With use of a different PTF, even with the same dependent variable input, the *IUV*s of soil microbes were USD 0.04 per 10^{-12} CFU for Endoaquepts and USD 0.03 per 10^{-12} CFU for Dystrudepts. The *IUV*s of soil fungi were USD 0.06 per 10^{-9} CFU for Endoaquepts and USD 0.09 per 10^{-9} CFU for Dystrudepts. Based on these proxies, the *IUV*s of invertebrates for agroforestry Endoaquepts and Dystrudepts were USD 63.27 per ha and USD 53.34 per ha, respectively; the *IUV*s of microbes were USD 51.62 per ha and USD 42.15 per ha, respectively; and the *IUV*s of fungi were USD 45.60 per ha and USD 48.06 per ha, respectively. However, the *IUV*s of invertebrates for monoculture Endoaquepts and Dystrudepts were USD 15.80 per ha and USD 35.14 per ha, respectively; the *IUV*s of microbes were USD 25.67 per ha and USD 20.38 per ha, respectively; and the *IUV*s of fungi were USD 21.97 per ha and USD 26.78 per ha, respectively.

Total *IUV*

Cacao agroforestry has improved soil health and increased total *IUV*. Two-thirds of the *IUV*s are PIVs, and the remaining are SIVs. The parameters contributing to SIV are gravitational water and *SOC*, whereas the rest

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Table 3. PTF for estimating soil organism based on other soil properties

No.	Soil type and biodiversity	PTF*	R^2
1	Endo-*TI*	$4.58 - 1\,883.11\,\beta_{TN} + 141.85\,\beta_{SOC} + 6.48\,\beta_{pH} + \mathbf{0.71}\,\boldsymbol{\beta}_{\mathbf{AP}}$	0.96
2	Dystru-*TI*	$-22.22 + 148.54\,\beta_{TN} - 13.94\,\beta_{SOC} + 5.05\,\beta_{pH} + \mathbf{0.21}\,\boldsymbol{\beta}_{\mathbf{AP}}$	0.95
3	Endo-*TM*	$-82\,505.7 - 4\,781.67\,\beta_{pH} - (1.5\times10^7)\beta_{TN} + 2\,299.4\beta_{\mathrm{AP}} + \mathbf{1\,888\,358}\,\boldsymbol{\beta}_{\mathbf{SOC}}$	0.91
4	Dystru-*TM*	$205\,727.6 - 175\,561\beta_{pH} - (2.4\times10^7)\beta_{\mathrm{TN}} - 3747.04\,\beta_{AP} + \mathbf{2\,860\,439}\,\boldsymbol{\beta}_{\mathbf{SOC}}$	0.93
5	Endo-*TF*	$69.07 - 43.45\,\beta_{pH} - 9\,216.38\beta_{\mathrm{TN}} + 0.22\beta_{AP} + \mathbf{1\,282.97}\boldsymbol{\beta}_{\mathbf{SOC}}$	0.95
6	Dystru-*TF*	$90.24 - 38.84\beta_{pH} - 6\,909.69\beta_{\mathrm{TN}} - 1.05\beta_{AP} + \mathbf{793.37}\boldsymbol{\beta}_{\mathbf{SOC}}$	0.93

* the bold coefficients have the highest significance in influencing the dependent variable, the italicized coefficients do not significantly affect the dependent variable, while the coefficients written normally are significant but not the highest significance; PTF – pedotransfer function; TI – total invertebrates; TM – total microbes; TF – total fungi; TN – total nitrogen; *SOC* – soil organic carbon; AP – available phosphorus

Source: Authors' own processing

contribute to PIV. *SOC* is the parameter with the highest *IUV*, followed by N-total. Table 4 summarises the total *IUV* in agroforestry and monoculture. Furthermore, Figure 9A shows the decrease in *IUV* because of erosion. Using the Indonesia social discount rate, which is 4.75%, the *PV* value of soil health for 25 years (Figure 9B) or the average cacao rotation time can be estimated.

Improving the soil health of cacao agroforestry for Endoaquepts resulted in a total *IUV* 1.53 times higher than that for cacao monoculture. After 15 years, the total *IUV* of Endoaquepts agroforestry is estimated to be 1.82 times higher than that of monoculture. The agroforestry *IUV* will be USD 601.99 per ha or *PV* of USD 300.11 per ha, and the monoculture *IUV* will be USD 331.05 per ha or *PV* of USD 165.04 per ha. Furthermore, the total *IUV* of Dystrudepts agroforestry was 1.26 times higher than that of monoculture. The existing Dystrudepts *IUV* ratio tended to be lower than that of Endoaquepts. However, after 15 years, the total *IUV* of Dystrudepts agroforestry is estimated to be much higher than that of monoculture, which is 2.03 times higher. At that time, the *IUV* for cacao agroforestry with Dystrudepts was estimated to be USD 646.41 per ha or a *PV* of USD 322.26 per ha, and with monoculture was USD 318.52 per ha or a *PV* of USD 158.79 per ha because of massive erosion rates.

Implications for policy-making

Agroforestry must be implemented in cacao plantations because shade trees are required to reduce excessive sun radiation (Sueréz Salazar et al. 2018). Cacao can be combined with MPTS with high economic and ecological values, such as durian, avocado or other woody plants. Even so, agroforestry tends to be abandoned because it cannot generate maximum crop production. From an economic view, agroforestry is often associated with loss of income owing to reduced area for cacao as the main crop, but agroforestry also has been recognised as an example of regenerative and climate-smart agriculture (Muschler 2016; Elevitch et al. 2018). Benefits from the agroforestry system are supported by improved soil health, which we evaluated here.

Economic valuation is a framework for appreciating the long-term contribution of soil health to human well-being to encourage the preservation of cacao agroforestry. Adopting agroforestry will be desirable when the benefits are monetised. Estimating the economic value of soil health is challenging because *IUV* dominates it. There has been little research that links soil health to economic valuation. Besides this link being difficult to measure quantitatively, uncertainties and assumptions accompany it (Ludwig 2000). Optimising soil health from an economic perspective will highlight its potential for socio-economic development through developing new PES schemes.

The economic assessment of soil health in cacao agroforestry is a case study so that policies can be implemented to capture and inform these values in the cacao landscape community. In addition to reviewing case studies, we aim with this research to bridge soil science and ecological economics through the perspective of ESs. We put forward a simple conceptual approach to explain the relationship between soil health and ESs, which we then used to calculate the economic value of soil health. We used the concept of *IUV* as a part of the total economic value to estimate the monetary value of soil health from the point of view of ES valuation. However, apply-

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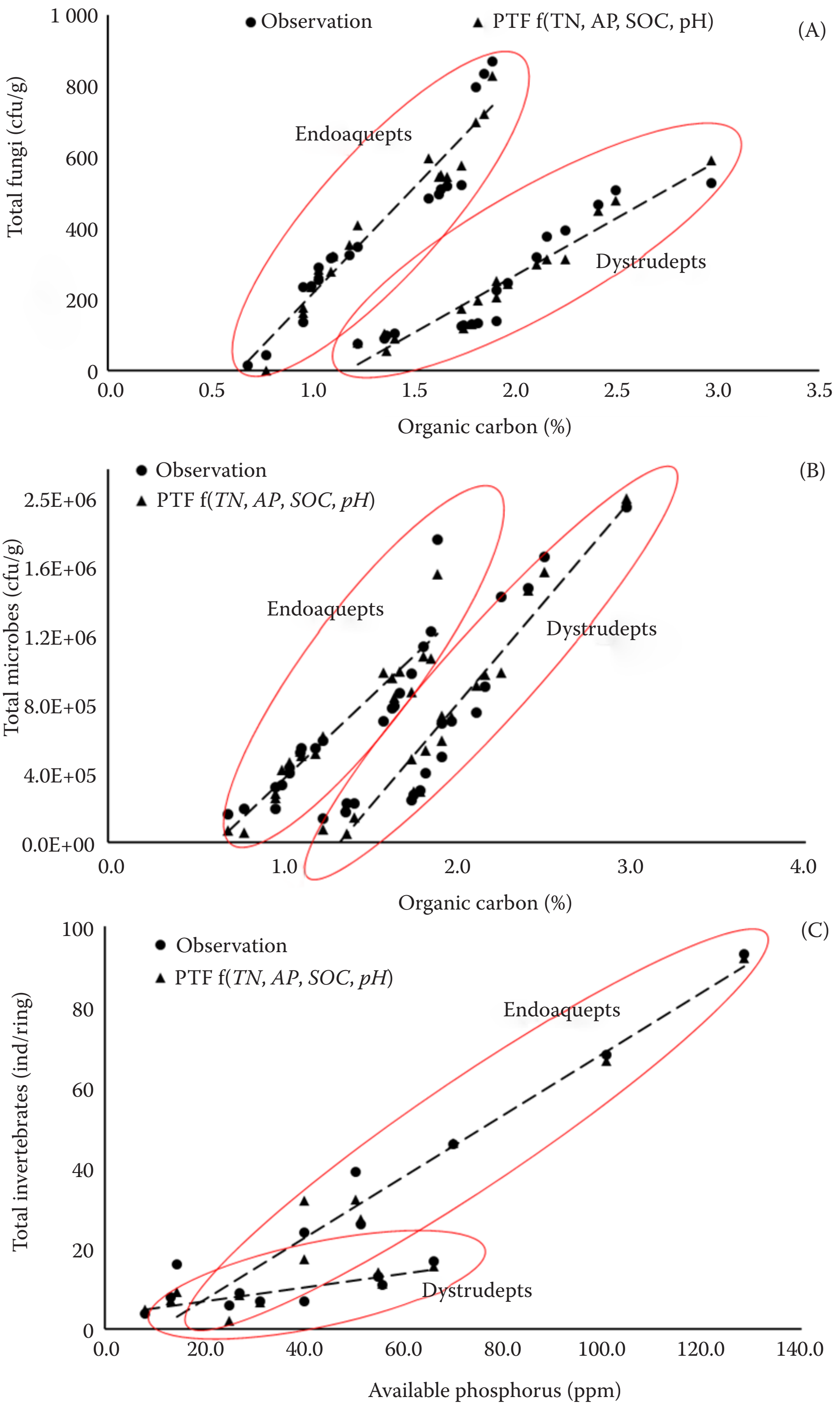

Figure 8. Comparison of soil biodiversity from observations and results of PTF, (A) total fungi, (B) total microbes, and (C) total invertebrates

PTF – pedotransfer function; TN – total nitrogen; AP – available phosphorus; SOC – soil organic carbon

Source: Authors' own processing

ing the valuation concept requires attention to the following matters that have the potential to provide different *IUV* values that lead to different policy interventions.

First, the soil health parameters and the ESs they support must be carefully mapped to avoid double counting (Boyd and Banzhaf 2007; Fisher et al. 2009). A single soil parameter can support multiple ESs, so its

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Table 4. Recapitulation of *IUV* in cacao agroforestry and monoculture

No.	Soil health parameter	Endo-AF	Endo-Mono	Dystru-AF	Dystru-Mono
1	*SOC* (USD/ha)	166.28	119.66	250.74	208.56
2	*GW* (USD/ha)	52.61	51.64	54.83	53.77
–	***SIV* (USD/ha)**	218.89	171.30	305.57	262.33
1	*TN* (USD/ha)	140.67	110.46	193.36	173.02
2	*AP* (USD/ha)	65.98	23.75	45.48	23.09
3	*AWC* (USD/ha)	46.66	45.62	34.56	33.89
4	*TM* (USD/ha)	51.62	25.67	42.15	20.38
5	*TF* (USD/ha)	45.60	21.97	48.06	26.78
6	*TI* (USD/ha)	63.27	15.80	53.34	35.14
–	***PIV* (USD/ha)**	413.80	243.27	416.96	312.30
Total *IUV* (USD/ha)	–	632.69	414.57	722.53	574.63

SOC – soil organic carbon; *GW* – gravitational water; *SIV* – social indirect value; *TN* – total nitrogen; *AP* – available phosphorus; *AWC* – available water content; *TM* – total microbes; *TF* – total fungi; *TI* – total invertebrates; *PIV* – private indirect value; *IUV* – indirect use value

Source: Authors' own processing

economic valuation can be approached in several ways. For example, *SOC* can support climate regulation (Lal 2004), erosion control (Wischmeier et al. 1971) and water regulation (Rawls et al. 2003). Thus, *SOC* can be valued according to carbon incentive, defensive expenditure and production functions (Dominati et al. 2010). Second, various methods of economic valuation can be applied to the same ESs so that they also have the potential to provide different *IUV*s. For example, nutrient retention can be assessed using replacement costs and production functions. The challenge is to choose the causal relationships among soil health, ESs and the valuation methods that best fit the research context and data availability. Third, soil health provides PIV and SIV simultaneously, which differences will affect incentive schemes. Lastly, applying economic valuation to policy implies that 'soil health value' tends to be anthropocentric because it relates only to human benefits (Rea and Munns 2017).

Soil health incentives will change the economic equation by introducing other income sources. Apart from agricultural products, some ESs may already have local to global markets, but the rest tend to be undervalued. An example is carbon, a commonly marketed ES, for which transactions on global carbon markets are known to have reached USD 1 billion per year. Through a more in-depth soil health valuation, other market schemes that have the potential to be developed are eutrophication and sedimentation taxes related to water quality. Furthermore, the community can consider the soil health IUV as part of the land selling or renting price. Of course, it must lead to support and dissemination of policies for the community, considering that without this support, coupled with the lack of public awareness of soil health, it can be an obstacle to realising incentive schemes for PSH.

Limitations of the study

There are certain limitations to the application of the soil health valuation framework in this study. First, we evaluated only eight parameters that have significantly supported ESs. Using more parameters makes future studies more attractive in estimating the total *IUV*. Second, in this study, we extrapolated the sample units to units per hectare. Although specific parameters were spread evenly in one area, others might have been spread unevenly. Third, in this study, we had the limits imposed by evaluating soil health bridged by ESs, which must be emphasised to avoid incentive policy problems because factors other than soil are essential in affecting ESs. Healthy soil supports an increase in ESs but does not necessarily produce a high final value owing to other limiting factors.

The weakness of using the revealed preference is that the soil *IUV* will depend heavily on substitutes and price volatility (Dominati et al. 2014a). Caution must be exercised when comparing soil health values between regions and over time because the spatiotemporal dynamics of market prices significantly affect these values. For example, soils containing more *SOC* can have a lower *IUV* because of a low carbon price, which

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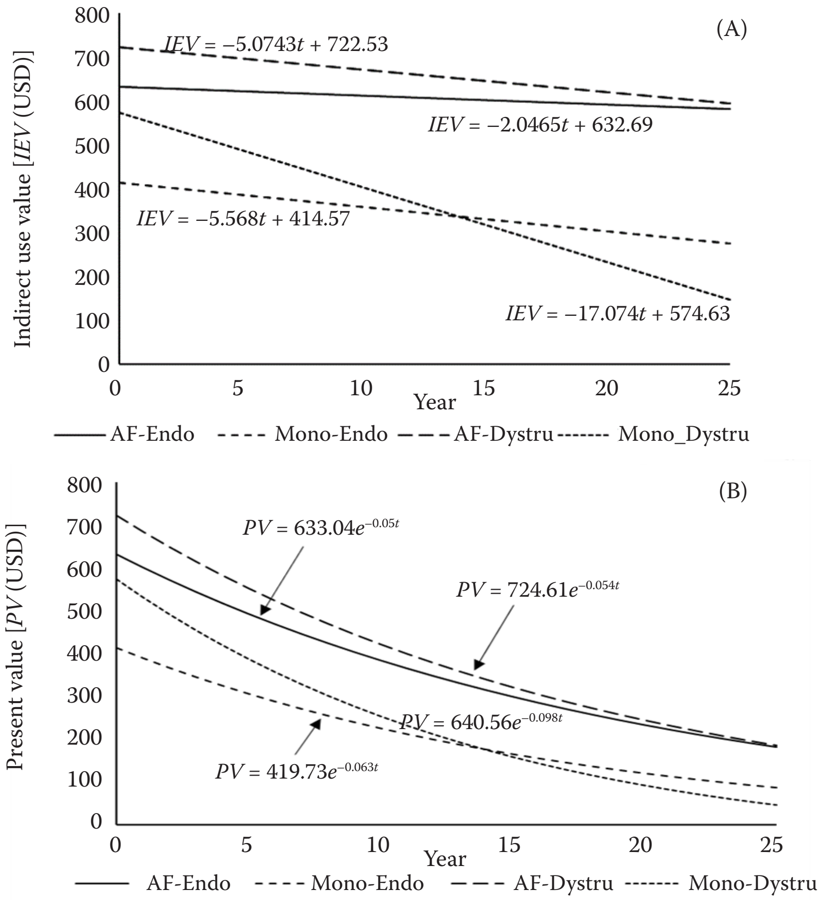

Figure 9. Time series soil health (A) *EV* and (B) *PV*

EV – economic value; *PV* – present value; *IEV* – indirect economic value; *t* – time

Source: Authors' own processing

can also happen with other ESs, such as a decrease in fertiliser prices leading to a decrease in the nutrient retention *IUV*. Other options can involve using stated preference methods to estimate willingness to pay or to accept. The more approaches that are tried, the richer the understanding of the soil health value will be.

Despite these limitations, the soil health *IUV* provides a good understanding of the synergy between economic and ecological functions in soil management. This framework holistically highlights the indirect economic benefits of soil health, as well as the unintended costs of soil degradation. When the soil is degraded, social costs exist to reduce environmental effects, and private costs exist to increase land productivity. To the extent that soil health benefits, the soil ecosystem must be valued and managed with a long-term perspective so that it does not become just an externality. Rewards for soil health can take the form of premium prices for PIV and PSHs for SIV. These incentives are given to farmers to maintain healthy soil functions to provide sustainable public ESs while securing cacao production in the future.

CONCLUSION

In this study, we present an economic valuation framework for improving soil health in cacao agroforestry which can be applied to other case studies. So far, improvements in soil health by agroforestry farmers have yet to be addressed because they reduce farmers' income. However, soil health supports various essential ESs with high *IUV*s as evidenced by an increase in soil porosity (water regulation), *SOC* (climate regulation), soil organisms (biodiversity) and soil nutrients (nutrient retention). Increasing soil health contributes to SIV and PIV so that they will cause externalities when not internalised into the market mechanism.

Economic valuation provides a framework for understanding the long-term benefits of soil health for human well-being, thus encouraging the preservation of cacao agroforestry. Monetising agroforestry benefits could incentivise its adoption. Optimising soil health for economic gain can lead to socio-economic development through PES or PSH schemes. Smallholder farmers' livelihoods generally depend on agricultural

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production; thus, soil health incentives will change the economic equation by introducing other income sources. However, the soil health valuation framework in this study is still in its early stages and is ongoing because it provides a reasonably rough result given price volatility. Despite these limitations, results from this study are expected to be able to provide a reasonable estimation of the IUV of soil health for community welfare. Further research is expected to enhance and develop this framework to understand the economic benefits of soil health better and help formulate soil health incentive schemes. When understanding the benefit of soil health holistically from an economic, ecological and social perspective, decision-makers can evaluate the effectiveness of regenerative agriculture programmes such as agroforestry.

Acknowledgement: This research was supported by cacao farmer in Luwu Utara in form of access to the study site and soil sampling.

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Received: August 24, 2023
Accepted: February 21, 2024
Published online: March 14, 2024