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Hidden Cost of Soil Erosion: From Biophysical Cost to Institutional Economics of Agribusiness

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ABSTRACT

Agribusiness in tropical highland environments faces two interconnected challenges: persistent soil erosion and the absence of robust institutional systems to address it. This research addresses both biophysical and agronomic concerns, as well as governance shortcomings, by estimating the hidden economic costs of potato cultivation in Pangalengan, West Java, and suggesting alternative institutional arrangements to counter erosion. Primary data were obtained through a randomized field survey of 184 potato farmers, representing approximately 15% of a sampling frame of 1204 farmers. Secondary sources, including climate and environmental data, were also incorporated. Soil nutrient losses were estimated using the SCUAF model, and these estimates were integrated with a production function analysis to quantify the economic losses attributable to erosion. In addition, an institutional arrangement framework was developed, drawing on established concepts from institutional economics. The results indicate that the hidden costs associated with potato farming surpass the actual costs, yet overall profitability remains positive. These findings suggest opportunities for policy interventions that could promote sustainable farming in erosion-prone uplands. By integrating SCUAF-based biophysical modelling with economic loss estimation within an institutional economics framework, this study connects environmental degradation, financial implications, and governance gaps. It provides a practical case for upland potato production in *Pangalengan* and offers both academic

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contributions and actionable insights for developing sustainable and economically viable agribusiness models in highland settings.

Keywords: Hidden Costs; Upland Agriculture; Institutional Economics; Potato Cultivation; SCUAF; Soil Erosion

1. Introduction

Farming in tropical highland regions is confronted with a double challenge: ongoing soil erosion and weak institutional capacity to control it. Erosion directly affects the physical condition of the land, imposing financial burdens such as lower yields and higher input costs. However, these impacts are often underestimated by farmers and policymakers. As land degradation accumulates, the long-term sustainability of agribusiness in these areas is compromised.

Erosion is influenced by a combination of land cover, vegetation type, and management practices [1–3]. Different cropping systems and vegetative covers significantly alter erosion rates [4]. Globally, soil erosion is widely recognized as a threat to sustainable food production. For example, in the United States, annual soil loss has been estimated in the billions of tons, accompanied by substantial water loss, resulting in multimillion-dollar costs for nutrient and water replacement [5]. Erosion also modifies the soil's physical and chemical characteristics, ultimately reducing its productivity [6]. The severity and nature of these impacts vary depending on the local context and time frame.

One difficulty in addressing erosion is that many of its costs remain hidden, since they do not appear in farm financial records. Such costs, which involve the depletion of soil nutrients and reduced productivity, are not immediately visible. Pangalengan, a highland region characterized by sloping hills and valleys within the Citere catchment of the Citarum watershed, is a prime example. It supplies water to three large dams—Cirata, Saguling, and Jatiluhur—and plays a vital role in the water security of the *Bandung* region. However, extensive land-use change, particularly from forest to agriculture, has altered the ecological balance and could undermine long-term productivity if not managed carefully [7, 8].

High erosion risk is associated with steep gradients, sparse vegetation cover, and high rainfall [9, 10]. While the area is more naturally suited to tree crops, potatoes and cabbage dominate due to their profitability. The Andisol soils of *Pangalengan* are fertile and rich in organic matter, but their low structural stability and heavy rainfall make them highly vulnerable to erosion [11].

1.1. Research Gap

In Pangalengan, unsustainable farming practices have intensified the problem of soil erosion, causing significant nutrient losses that lower yields and reduce farmer income [12]. Beyond the farm gate, erosion contributes to sediment build-up in waterways, diminishes dam capacity, and raises maintenance costs for public infrastructure [3]. At the global scale, approximately 10 million hectares of arable land are lost annually due to erosion [13], further constraining food production capacity [14].

For this study, "hidden costs" refer specifically to two on-site impacts: the fraction of fertilizer that fails to benefit crops because it is washed away, and the unrealized income caused by nutrient depletion. Costs linked to off-site effects, such as siltation in reservoirs or downstream flooding, are excluded from the analysis.

A critical institutional gap exists between private control of farmland and the collective consequences of degradation. Farmers may own or control the land they cultivate, yet the resulting environmental harm—such as sedimentation, nutrient depletion across the region, and higher flood risks—is borne by society. This disconnect reduces the incentive to adopt conservation measures, especially in the absence of clear regulations or shared community norms.

From the perspective of institutional economics, this represents a governance failure within agribusiness systems. The inability to internalize environmental externalities stems from weak institutional frameworks and poor coordination among stakeholders. Addressing erosion, therefore, requires treating it not just as a technical or agronomic issue but also as an institutional challenge that demands collective solutions.

1.2. Research Objectives

This study aims (1) to measure the hidden cost of potato farming and analyze how erosion affects profitability in upland regions, and (2) to propose an institutional arrangement for agribusiness governance based on the Pangalengan case study. The novelty of this study lies in bridging biophysical assessment tools (e.g., SCUAF modeling and the replacement cost method) with institutional economics to evaluate hidden erosion costs in upland potato farming. Unlike earlier studies that treat biophysical and institutional dimensions separately, this work presents soil erosion as a failure of institutional arrangements, requiring public–private alignment. By doing so, it contributes to a transdisciplinary approach to sustainable agribusiness development in highland farming systems [15–17].

2. Materials and Methods

2.1. Analytical Framework

The term hidden cost refers to expenditures that are not captured in market transactions or standard accounting practices. It is costs not explicitly recorded in farm accounts or reflected in market prices, even though farmers may observe erosion and yield losses. These costs eventually manifest as reduced yields in financial records or as externalities in downstream areas. However, they remain "hidden" from farmers' short-term economic calculations because they are either deferred into the future or externalized to society. By using the term 'hidden cost' or, more explicitly, soil erosion cost (used interchangeably), we explicitly state that the scope of measurement is indeed at the farm level. Although no single economic work provides a universal definition, the concept is closely related to externalities [18], opportunity costs [19, 20], and indirect or unobserved losses [21]. Indirect or unobserved costs, although not attributed to a single theorist, have foundations in the welfare economics of Pigou, environmental economics [22–24], and institutional economics [25, 26]. These costs capture long-term impacts that remain invisible in immediate market transactions. From the standpoint of the short-term interest of farmers specifically, this cost is hidden.

The key implication is that costs excluded from market exchanges must nonetheless be incorporated into the calculation of actual economic costs. This process, known as the internalization of hidden costs, requires institutional mechanisms to ensure that markets account for such externalities and that economic decision-making reflects their broader social and environmental impacts...

This clarification has been added to the revised manuscript, including confirmation of the phrase "soil-erosion costs (hidden in farm accounting)." Furthermore, we emphasize that the costs of soil erosion, although often overlooked, must be addressed through solutions grounded in institutional economics, which can provide mechanisms to internalize these hidden costs for sustainable land management.

Soil Erosion

Erosion refers to the movement of soil by water or wind. The ability of soil to support agricultural productivity is influenced by cultivation and cropping activities [27]. Soil serves as both a nutrient source and a physical medium for crops; degradation of either function undermines productivity. While fertilizers can remedy nutrient decline, structural degradation is harder to reverse. One key cause of land degradation on slopes is erosion [6, 28].

This study employs the replacement cost approach to estimate the hidden costs of soil erosion associated with upland potato farming, as outlined by Barbier [29]. Soil is treated as a slowly renewable resource, where degradation reduces productive capacity. The framework connects physical erosion to economic loss through the depletion of nutrients, organic matter, and rooting depth, resulting in measurable yield declines.

These phenomena are illustrated in **Figure 1**. Erosion shifts nutrient availability from X_1 to X_0, decreasing farm revenue from the area A+B+C+D to only A+B. The hidden cost comprises both the cost of replacing nutrients (area D) and the profit lost due to lower yields (area C).

Insights from Nakhumwa and Hassan [30] complement the replacement cost approach, modeling rooting depth as an exhaustible resource that reflects the long-term impacts of erosion. Other studies often employ cost–benefit analysis[31, 32] or productivity-change approaches[33], but in this work, the focus is strictly on the on-site financial losses due to erosion.

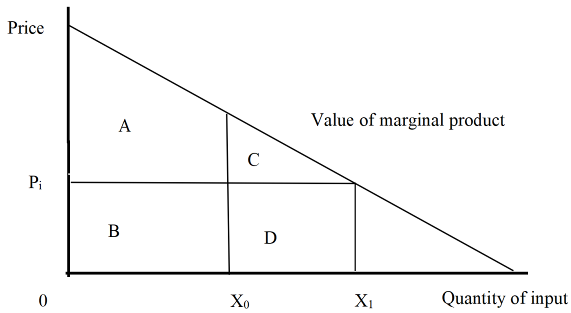

Figure 1. Application of the Replacement Cost Method to Assess Hidden Costs of Erosion in Upland Potato Farming, Pangalengan.

Note: Soil erosion shifts nutrient availability from X_1 (higher fertility) to X_0 (lower fertility). At X_1, farm revenue equals areas A + B + C + D; after erosion, revenue declines to A + B. The difference (C + D) represents the hidden cost of erosion. Component D reflects the nutrient replacement value—the cost of restoring lost nutrients and organic matter—while component C reflects the profit foregone due to lower yields when nutrients are not replaced. In practice, farmers experience either D (if they replace nutrients) or C (if they do not). Reporting C + D together provides a broader valuation of soil services, representing both the natural capital degraded and the associated economic impact on farm productivity.

2.2. Framework for Institutionalizing Public Bad

In upland agricultural landscapes, soil and water often function as shared resources that suffer degradation when management lacks clear and enforceable rules. Following Hardin's[34] "The Tragedy of the Commons", farmers may prioritize short-term yields over long-term sustainability, adopting erosion-prone practices such as slope-wise planting. Effective institutions are necessary to internalize these environmental costs and guide farming toward conservation-oriented behaviors. Without effective institutions, farmers tend to focus on short-term outcomes (higher yields, weaker agricultural practices). Incentives can enable a shift in these behaviors.

From the standpoint of collective action theory, Olson[35] notes that cooperation among resource users can fail when transaction costs are high, unless selective incentives are in place. Ostrom[36] further outlines governance principles—such as locally tailored rules and monitoring—that can overcome these barriers. Applying these principles in *Pangalengan* means creating institutional arrangements that reduce the cost and complexity of cooperation for soil conservation.

Secure and well-defined property rights, as highlighted by Schlager and Ostrom[37], are another crucial principle that supports land conservation efforts. They can encourage farmers to invest in long-term land stewardship, whereas uncertain tenure reduces motivation to conserve. Paavola[38] emphasizes that sustainable upland management often necessitates multi-level governance, which integrates local norms with formal state regulations. Khanna and Palepu's[39] concept of "institutional voids" is also relevant, as many highland farming areas lack essential market rules, extension services, or enforcement mechanisms.

In this study, institutional economics enriches the framework by emphasizing how property rights, transaction costs, principal–agent relations, collective action, and institutional voids shape land-use decisions. In the absence of effective institutions, farmers tend to prioritize short-term profitability and externalize the costs of soil erosion, ultimately leading to long-term soil degradation.

By recognizing erosion as a public bad—where private land-use decisions generate negative impacts for the wider community—this framework emphasizes the need for governance that balances private benefits with public environmental health. In this study, governance is treated as the third analytical pillar alongside biophysical and economic assessments.

2.3. Data Collection Methods

The research was conducted in *Pangalengan*, a highland region in *West Java*, renowned for its intensive potato cultivation. The survey was conducted under strict adherence to the ethical principles of survey research. We explicitly stated here that ethical clearance for this study was obtained from the Department of Agribusiness, Faculty of Economics and Management, IPB University, under the Annual Research Grant Initiative. We followed strict ethical practices. Responding farmers were entirely voluntary, and informed consent was obtained from all farmers prior to the interviews. Farmers were informed of the study's objectives, their right to withdraw at any time, and the confidentiality of their responses. No personal identifiers were collected, and all data were anonymized and presented in aggregate form only.

For the farm survey, three existing land preparation methods—slope-wise, contour-wise, and bench terrace—were compared in terms of their impact on erosion and productivity outcomes. Field surveys documented slope gradients, soil conditions, and land use, while structured interviews gathered data from 184 randomly selected potato farmers (out of 1,204 farmers registered in the office of extension services).

Pangalengan Sub-district comprises 13 villages. For each village, a list of farmers was obtained, from which those regularly engaged in potato cultivation were identified. The verification of potato farmers was carried out with the assistance of agricultural extension officers at the sub-district level. From these verified groups of potato farmers in each village, respondents were selected using a simple random sampling technique. The randomization process was conducted in a manner analogous to a lottery draw, ensuring fairness and equal opportunity for selection. **Table 1** presents the number of potato farmer respondents selected through simple random sampling in each village. The sampling frame—that is, the information on the total number of farmers—is also provided.

Table 1. Sampling Design for Pengalengan Survey.

Number	Number of Respondents of Potato Farmers per Village, as Results of 15% Simple Random Sampling		Per Village Sampling Frame (Persons)
	Village	Number of Sample Respondents (Persons)	
1	Lumajang	9	60
2	Warna Sari	20	134
3	Sukamanah	18	120
4	Marga Mekar	12	80
5	Marga Mukti	10	67
6	Pengalengan	20	134
7	Sukaluyu	11	74
8	Margaluyu	12	80
9	Tribakti Mulya	10	67
10	Pulosari	16	107
11	Margamulya	27	180
12	Banjar Sari	10	54
13	Wanasuka	9	47
Number of Farmer Respondents (persons)		184	
Sub-district Pengalengan Sampling Frame (persons)			1204

Data collection involved:

- Biophysical surveys—measuring slope with Abney levels and clinometers.
- Soil sampling—laboratory analysis of pH, texture, bulk density, organic matter, and nutrient content.
- Climate data—rainfall and other parameters obtained from the Pangalengan climate station.
- Farm performance—yields, input usage, and labour requirements obtained from farmer interviews.

These datasets were used to parameterize the SCUAF model and to estimate a Cobb–Douglas production function linking input use to potato yields.

2.4. Analytical Methods

In this study, hidden costs are quantified by translating the indirect impacts of farming practices into economic terms. Specifically, we estimate the costs associated with soil erosion and yield reduction that are not captured in conventional accounting records. Soil erosion costs are calculated by multiplying the estimated loss of topsoil per hectare by the replacement value of soil nutrients. Yield reduction costs are derived from the difference between potential and actual crop yields, valued at local market prices. This approach allows us to integrate biophysical data with economic analysis, providing a comprehensive measure of total production cost that includes both visible and hidden components."

To measure productivity effects, the study uses the Cobb–Douglas production function, expressed in a log-linear form that allows elasticity values to be read directly from the coefficients. Despite its simplifying assumptions—such as constant returns to scale—the model was selected for its tractability, data compatibility (mainly due to the relatively limited number of samples), and extensive use in agricultural economics. It is especially suited to situations with multiple inputs but limited data, enabling the estimation of marginal value products for each input. This, in turn, allows erosion-induced nutrient loss to be converted into a monetary value using prevailing market prices for potatoes.

The Cobb–Douglas production function was used to determine the impact of each component of soil nutrient loss on potato production. For estimation with the ordinary least squares (OLS) method, the function was converted into a log-linear form. To ensure predictive feasibility, the OLS classical assumptions were tested to diagnose the existence of multicollinearity and heteroscedasticity.

In *Pangalengan's* upland farms, potato cultivation typically follows one of three methods:

- Slope-wise beds—planting rows parallel to the slope's incline.
- Contour-wise beds—planting along contour lines.
- Bench terraces—cutting the slope into flat, step-like surfaces.

These systems vary considerably in both productivity and erosion potential. To simulate nutrient losses, the study utilized the SCUAF (Soil Changes Under Agroforestry) model, which estimates changes in nutrient stocks based on soil, land-use, and climate data. Input parameters were gathered from field surveys, laboratory analyses, and secondary datasets. Nutrient losses for nitrogen (N), phosphorus (P), and carbon (C) were then converted to equivalent fertilizer quantities and valued using market prices. The three land preparations — slope-wise, counter-wise, and bench terrace — are not treated as shifting variables, because in this study, they represent three distinct scenarios of production.

2.4.1. Measure Nutrient Loss

The SCUAF model, adapted from the Universal Soil Loss Equation (USLE) by Young et al.[40], was run for a 120-day potato cropping cycle. That is equivalent to one growing season for potatoes. In Pangalengan, potatoes are cultivated twice a year, but for consistency, we report results on a per-hectare, per-season basis (kg/ha/season, IDR/ha/season). Model inputs included slope percentage, rainfall, soil texture, organic matter, and management practices.

The model outputs nutrient losses for C, N, and P. Carbon losses were converted to equivalent humus quantities using the assumption that humus contains 58% C. The humus amount was then converted to organic fertilizer requirements using the average C/N ratio and nitrogen content of locally used manures (cow and chicken manure are most common in the region).

Tables revised to include:

For N, P, and K, nutrient losses were converted to market fertilizer equivalents based on the nutrient content of common fertilizers:

- Urea (46% N)
- SP36 (36% P_2O_5)
- Phonska (15% N, 15% P_2O_5, 15% K_2O, and 10% S)

Market prices were then applied to estimate the replacement cost for each nutrient.

While SCUAF quantified nutrient losses, actual yield impacts were modeled through an econometric Cobb–Douglas production function:

$$Q = f(N_{total}, P_{total}, K_{total}, F_{organic}, L_{total}, A_{total})$$

Where Q is potato yield (quintals), inputs include nutrient applications, labor, and cultivated area. Coefficients from the model provided elasticities for each input, enabling calculation of the value of the marginal product (VMP) for lost inputs. Multiplying these VMPs by the quantities of nutrient loss gave the monetary value of unrealized output.

To address multicollinearity, total labor was normalized by cultivated area (Ltotal/ha). Model robustness was assessed through classical OLS diagnostics (multicollinearity, heteroscedasticity) and significance tests (F-test and *t*-tests). **Table 2** presents the parameters used in the SCUAF model.

Table 2. Parameters Used in SCUAF Model and Corresponding Data Sources.

Variable	Description or Parameter Value	Source of Data
Location	Pangalengan (Ds. Margamulya)	Field survey
Land use system	Agriculture-Horticulture	Field survey
Soil class	Andisols	Field survey
Rainfall	2324 mm	Local climate station at Pangalengan
Slope	15% (moderate)	Field survey
Drainage	moderate	Field survey
Soil texture:		
Sand	24%	Field survey
Silt	37%	Field survey
Clay	39%	Field survey
pH	5.8	Field survey
Bulk density	0.58g/cc	Field survey
Soil pore total	78%/volume	Field survey
Soil permeability	11cm/hour	Field survey
C organic	2.37%	Soil and Agroclimate Research Center (2023)
N total	0.15	As above
C/N	15.8	As above
P2O5 HCl 25%	83mg/100g	As above
K2O HCl 25%	45mg/100g	As above
Kation Exchange Capacity	27.59	As above
Cover factors of the potato plant	0.40	Arsyad (2012) and Hardjowigeno (2003)
Value of preventing erosion:		
Slope wise	1	As above
Contour wise	0.75	As above
Bench terrace	0.04	As above
Soil erodibility	0.29	Rompas (1996)

2.4.2. Calculating Hidden Cost

The hidden cost per hectare is the sum of:

1. Nutrient replacement value – the market cost of replacing C, N, P, and K lost to erosion.
2. Profit foregone – the revenue gap between actual yields and the yields expected without nutrient depletion.

These were calculated for each cultivation method (slope-wise, contour-wise, bench terrace) to compare economic efficiency and erosion resilience.

Formally, the hidden cost calculation per hectare was calculated as:

$$HC = NRV + PFLHC = NRV + PFL$$

where

HC = hidden (erosion cost) cost (IDR/ha/season),

NRV = nutrient replacement value (IDR/ha/season), and

PFL = profit foregone (IDR/ha/season).

Profit foregone was derived from:

$$PFL = (\Delta Q \times P) - NRV$$

where

ΔQ = yield loss due to erosion (kg/ha),

PP = potato price (IDR/kg).

2.5. Institutional Arrangement Methods

This study proposes an institutional arrangement to address soil erosion, farming practices, and prevailing land-use patterns in Pangalengan's highlands. The concept is grounded in key principles: the tragedy of the commons, transaction costs of collective action, property rights and stewardship, environmental governance, and institutional voids in upland farming communities. These principles are adapted to local challenges and potentials to propose a tailored governance model for sustainable land management.

The design of institutional proposals drew on the conceptual framework described in Section 2.2. Local conditions—such as the strength of farmer organizations, access to extension services, and market linkages—were assessed to determine feasibility. Proposed arrangements emphasize:

- Formal agreements among farmers to adopt conservation techniques.
- Tiered incentive schemes linked to erosion-control compliance.
- Community-based soil monitoring.
- Incentive system.
- Village-level governance bodies for land management.
- Integration of conservation compliance into agribusiness supply contracts.

By merging quantitative loss estimates with governance analysis, the study presents a case for policy and institutional interventions that address both the causes and the costs of erosion. Our proposed governance mechanisms are conceptual and policy-oriented, based on institutional economics theory and comparative literature, and represent potential pathways for policy innovation. Therefore, it is understandable that further empirical validation is required.

3. Result

Using the parameters in **Table 1**, the SCUAF model estimated nutrient losses caused by potato cultivation in Pangalengan. Among the three cultivation systems, bench terraces showed the least soil loss, cutting erosion by around 60% compared to slope-wise planting and by about 46% compared to contour-wise planting. Seasonal soil loss ranged between 2.9 and 7.25 tons per hectare, as shown in **Table 3** column 2 (equivalent to 5.8–14.5 tons per hectare per year). These figures align with earlier findings by Sutono et al.[41], who reported annual erosion rates ranging from 5.7 to 16.5 tons per hectare for similar highland land uses.

SCUAF, based on the nutrient cycling approach of Nye and Greenland[42] and modified by Young et al.[29], generated estimates for carbon, nitrogen, and phosphorus losses. Potassium losses, not directly modelled by SCUAF, were taken from field trials by Banuwa[43] in the same region (**Table 2**).

Loss of topsoil components reduces the soil's ability to sustain crop production. Farmers can partially compensate for this depletion by applying more fertilizer, but this increases production costs per unit of output. Over time, continued erosion reduces farm income to below its potential levels and increases vulnerability to crop failure. One long-term drawback of conventional tillage is its adverse effect on soil quality, particularly through the decline in soil organic matter[44].

Carbon losses were converted into humus quantities using a factor of 58% carbon content. From there, the required amount of organic fertilizer was determined based on the average C/N ratio (18) and nitrogen content (0.13) of manures commonly used in the region. Nitrogen, phosphorus, and potassium losses were converted to equivalent quantities of market fertilizers (urea, SP36, and Phonska) using their respective nutrient compositions. **Table 3** (columns 3–6) summarizes the replacement value of these nutrient losses for each cultivation method, expressed as a percentage of total farming costs.

> Fertilizer losses per hectare as a percentage of total production costs (IDR/ha/season). Note: Average production costs were IDR 18,540,000/ha for slope-wise, IDR 16,200,000/ha for contour-wise, and IDR 14,750,000/ha for bench terraces. For example, a 10.55% loss in slope-wise farming equals approximately IDR 1,955,000/ha. Detailed information on the total cost, total revenue, and total profit will also be provided in a later section.

Cobb–Douglas production model was applied to quantify the impact of nutrient loss on potato yields. To avoid collinearity, total labor was adjusted to a per-hectare basis.

The results of the assumption test indicate that the initial model requires modification. The independent variable, total labor used in the initial production function, was converted into total labor used per hectare of cultivated area (Ltotal/ha) due to a high degree of collinearity between the variable total labor used (Ltot) and the variable area of land (Atot). To test the significance of the estimation model and the significance of individual model coefficients, the F-test and t-test were applied, respectively. The results of estimating the modified model are presented in **Table 4.** To find the value of the t-test, one needs to divide the coefficient (β) in **Table 4** by its standard error.

Diagnostic tests showed no significant multicollinearity or heteroscedasticity. The model's R^2 (0.710) and adjusted R^2 (0.699) values indicate that the Cobb-Douglas model effectively explains the variation in potato yield and possesses strong explanatory power (**Table 4)**. The F-test is highly significant, confirming the model's explanatory power. All variables have VIF values between 1.653 and 4.709, indicating no serious multicollinearity. The Glejser test revealed no heteroscedasticity, as none of the independent variables significantly affected the error term at the 0.05 level. Significance values ranged from 0.131 (total labour/ha) to 0.98 (Organic fertilizer).

Table 3. Losses of Soil and Key Nutrients (C, N, P, K) Due to Erosion During a Potato's Growing Season.

Method of Cultivation	Soil Losses (Ton Ha^{-1} $Season^{-1}$)	C Losses (Kg Ha^{-1} $Season^{-1}$)	N Losses (%) Farming Cost	P Losses (%) Farming Cost	K Losses (%) Farming Cost
Slope wise	7.25	285.62	18.58	2.85	14.31
Contour wise	5.42	216.05	14.05	2.13	6.56
Bench terrace	2.90	116.85	7.56	1.16	2.27

Table 4. Estimated Outputs of Potato Farming Using the Production Function in Pangalengan.

Model	Coefficient (β)	Standard Error	Significant
Constant	3.865	0.512	0.000
Ntotal	0.193	0.088	0.030
Ptotal	0.084	0.112	0.453
Ktotal	0.105	0.080	0.192
Forganic	0.244	0.050	0.000
Ltotal/ha	0.386	0.095	0.000
R^2 = 0.710; R^2 Adj.= 0.699; F test = 66.145 (sig. 0.000)			

Organic fertilizer and labor per hectare had the highest and most statistically significant effects on yield, with elasticities of 0.244 and 0.386, respectively. Labor per hectare showed the highest elasticity at 0.386 and was statistically significant, suggesting that increased labor substantially boosts yield. Pre-harvest labor, particularly for weeding and bed preparation, plays a crucial role in productivity.

The results show that organic fertilizer, nitrogen (N), phosphorus (P), and potassium (K) are essential inputs in potato production. While all had positive coefficients, not all were statistically significant. Their elasticities indicate that a 1% increase in organic fertilizer, N, P, and K leads to yield increases of 0.244%, 0.193%, 0.084%, and 0.105%, respectively.

By integrating SCUAF nutrient loss estimates **(Table 2**) with production elasticities (**Table 4**), the study calculated unrealized revenue from erosion (**Tables 5** and **6**). **Table 5** quantifies the hidden cost as the expenditure necessary to restore soil nutrient levels through fertilizer replacement, corresponding to area D in **Figure 1**. Conversely, **Table 6** illustrates the foregone profit attributable to the absence of soil conservation practices, represented by area C in **Figure 1**.

Table 5. Fertilizer Losses per Hectare per crop cycle (Season). In Various Potato Farming Practices, Percentage of Total Costs Represented.

Method of Cultivation	Organic Fertilizer (%)	Urea Fertilizer (%)	SP36 Fertilizer (%)	Phonska Fertilizer (%)	Total Percentage (%)
Slope wise	10.24	0.16	0.04	0.11	10.55
Contour wise	6.88	0.11	0.03	0.04	7.06
Bench terrace	3.87	0.06	0.01	0.02	3.96

Table 6. Soil Erosion Impact: Revenue and Profit Loss per Hectare Across Farming Methods (as Percentage of Total Revenue Loss and Profit Loss).

Method of Cultivation	Revenue Loss of C (%)	Revenue Loss of N (%)	Revenue Loss of P (%)	Revenue Loss of K (%)	Total Revenue Loss (%)	Potential Profit Loss (%)
Slope wise	8.41	2.26	0.28	1.06	12.01	14.35
Contour wise	6.73	1.78	0.22	0.50	9.23	15.93
Bench terrace	4.05	1.07	0.13	0.19	5.41	11.78

Slope-wise planting resulted in the most significant losses, whereas bench terraces minimized them. The potential revenue loss for bench terraces was about 39% of the loss observed for slope-wise planting. Profit-loss estimates, obtained by subtracting fertilizer replacement costs from total revenue loss, ranged between 11.8% and 14.4% of actual profits, depending on the cultivation method.

The conversion factor for N, P, and K nutrients is based on the ingredient list printed on each bag of fertilizer sold in the market and used by potato farmers. Urea and SP36 fertilizers are single-ingredient fertilizers. Urea contains 46% nitrogen (N), and SP36 contains 36% phosphorus pentoxide (P_2O_5). Phonska is a compound fertilizer containing N (15%), P (15%), K (15%), and S (10%). **Table 5** presents the results of converting C, N, P, and K components into the type of fertilizer available on the market, calculated by multiplying each market price by the corresponding nutrient and dividing by the total cost, expressed as a percentage of total cost.

Soil erosion reduces the soil's capacity to produce crops. The depletion of topsoil components can be mitigated by adding a larger quantity of fertilizers, which increases the cost per unit of output. Soil erosion reduces farmer income and increases the risk of farm failure. One primary negative impact of conventional long-term tillage is the reduction of soil organic matter, which damages soil quality [45].

The amount of C, N, P, and K lost due to potato cultivation can be converted into fertilizer quantities. Carbon content in humus is 58%, so the amount of humus required equals 100/58×100/58 \times100/58× the quantity of C loss [45]. To calculate the amount of organic fertilizer needed, the C/N ratio of manure is used. In this study, the C/N ratio in manure is 18, and the N content in manure used by potato farmers in *Pangalengan* is 0.13. Farmers primarily use organic fertilizers made from cow or chicken manure. Manure is readily available in Pangalengan, which is also known as a production center for milk cows in West Java.

The quantity of potatoes lost due to erosion was estimated by combining **Table 4** (Cobb-Douglas function) with **Table 2** (SCUAF model), providing the basis for calculating potential revenue loss by multiplying the quantity of potatoes produced by their market price. **Table 5** presents predicted revenue loss, expressed as a percentage of total revenue, from potato farming in upland *Pangalengan*.

Potential revenue losses were substantial. The most significant losses occurred with the slope-wise method, while bench terraces resulted in the least. Bench terraces resulted in 39% revenue loss compared to 100% for slope-wise farming. Subtracting total fertilizer loss (**Table 5**) from total revenue loss (**Table 6**) provides potential profit loss (**Table 6**, column 7). The predicted production losses in this study are lower than those estimated by Barbier and Bishop [46], who calculated land degradation in developing countries to be approximately 15% of gross national product. This study only considered on-site erosion costs; including off-site impacts would increase estimates. The findings exceed those of Aswafa et al. [17], who reported erosion-related losses of 1%–3% of Malawi's GDP.

To present the comparative performance of three existing potato planting systems in Pangandaran, farm performance is presented in monetary terms in **Table 7**, including slope-wise, contour-wise, and bench terraces.

Hidden cost can be conceptualized as the profit gap between observed short-term outcomes and sustainable long-term outcomes. Interpreting the observed data, farmers naturally prefer slope-wise planting (the highest observed profit). However, considering hidden costs, the actual long-term profit of slope-wise planting may be lower than that of contour or terrace systems. Thus, contour and terrace systems appear as "losers" in short-term financial data but "winners" in terms of long-term sustainability.

The productivity per hectare of contour-wise and bench terrace systems is relatively lower compared to slope-wise planting because the construction of terraces or contour ridges reduces the effective land area available for planting potatoes. Interviews indicated that the effective land area decreases to about 80% for bench terraces on 15% slopes. Naturally, the steeper the slope, the greater the reduction in plantable land.

Table 7. Farm Performance of Different Planting Systems. Units in volume (Ton) or money value (Indonesian Rupiah, IDR), per hectare (Ha) per season.

Planting System	Productivity (Ton Ha^{-1} $Season^{-1}$)	Revenue (IDR Ha^{-1} $Season^{-1}$)	Cost (IDR Ha^{-1} $Season^{-1}$)	Profit (IDR Ha^{-1} $Season^{-1}$)	R/C
Slope-wise (without conservation)	17.78	55,920,905	36,571,903	19,349,001	1.53
Contour Wise (with conservation)	16.75	53,676,299	41,183,380 *	12,492,920	1.30
Bench Terrace (with Conservation)	15.10	43,422,141	39 531 104*	8,698,830	1.22

*Note: Conservation costs included, representing the expenses for constructing ridges or bench terraces.

This finding introduces a third dimension of hidden costs in the Pangalengan highlands, referred to as the area reduction effect: part of the revenue decline is not due to erosion or input inefficiency, but rather from a loss of effective planting area. Farmers in conservation systems sacrifice productive land area for long-term soil protection. In terms of **Figure 1**, the "revenue forgone" includes not only C (profit loss from erosion) and D (replacement cost) but also the structural reduction in maximum revenue potential due to a smaller effective area.

Empirical findings confirm that.

- revenue declines as conservation intensity increases from slope to contour to bench.
- Costs rise with conservation due to higher labor, inputs, or maintenance.
- Profits shrink with conservation, despite lower erosion risks.
- R/C ratios confirm profitability drops with conservation.
- These results reveal a paradox: conservation systems, while environmentally superior, are economically less attractive to farmers in the short term.

4. Discussion

4.1. Institutional Implications for Sustainable Land Management

The findings confirm that soil erosion generates significant hidden costs in upland potato farming. Farmers practicing slope-wise planting achieve the highest short-term profits but externalize the costs of erosion, including nutrient depletion, declining yields, and off-site damage. By contrast, conservation systems partially internalize these costs—through higher labor and input requirements (such as contour planting) or reduced productive land area (bench terraces)—resulting in lower immediate profitability.

This creates an apparent paradox: conservation practices are environmentally sustainable but economically unattractive under current market and institutional conditions. In the absence of intervention, farmers will continue to plant slope-wise, despite its long-term unsustainability.

Institutional responses are therefore required, including:

- Payment for Ecosystem Services (PES): direct compensation to cover profit gaps for contour and terrace farmers.
- Targeted financial support: low-interest loans, subsidies, or grants to reduce the upfront cost of conservation.
- Collective action through cooperatives: pooling land and resources to lower infrastructure costs and transaction burdens.
- Regulations and enforcement: local bylaws mandating conservation on sloped land.
- Market-based incentives: certification or branding of "sustainable potatoes" with access to premium markets.

The Pangalengan highlands are ecologically strategic, demanding governance that balances private farming returns with public environmental health. Erosion represents a "public bad," producing external costs such as sedimentation in reservoirs and loss of ecosystem services. These costs cannot be managed effectively through individual farm-level decisions alone.

From an institutional economics perspective, reliance on private land rights, as assumed in neoclassical models, is insufficient. Erosion must be understood as a collective action problem requiring coordinated solutions. Mechanisms such as enforced planting regulations, designated fallow periods, and vegetative buffer zones can help internalize externalities, but are most effective when supported by community norms, monitoring, and enforcement.

Land regeneration is not merely a technical matter; it is also an institutional process. Sustainable governance, therefore, requires a mix of collective agreements, incentive structures, and local institutions that place soil conservation at the center of highland agribusiness development.

Conservation imposes a dual burden on farmers:

1. Higher costs (labor, inputs, and maintenance).
2. Reduced revenues due to smaller effective planting areas, especially under bench terraces.
3. Specific trade-offs: contour systems entail recurring labor costs to maintain ridges (high replacement costs, moderate land reduction), while bench terraces involve permanent land sacrifice (low replacement costs, high land reduction).

The hidden cost framework thus requires refinement. If institutions consider only replacement costs (D) and yield losses (C), they overlook the third hidden cost: land reduction. Policies must compensate for both added expenses and sacrificed land, while differentiating support by conservation method. Without such institutional backing, conservation lowers competitiveness and discourages adoption.

Key principles of institutional economics underpin conservation adoption:

- Property rights: secure tenure and soil service rights incentivize long-term investment.
- Transaction costs: coordinated conservation reduces costs and facilitates adoption.
- Principal–agent relations: adoption occurs when incentives align with private returns.
- Collective action: erosion is a common-pool resource issue requiring shared governance.
- Institutional voids: where markets fail to value soil services, institutions must intervene through payments, regulations, or joint investment.

By realigning incentives, reducing transaction costs, compensating land sacrifices, and strengthening collective action, institutions can make conservation both environmentally sustainable and economically viable.

4.2. Proposed Institutional Arrangement

The hidden cost framework should explicitly recognize three components:

- Replacement cost: expenditures on fertilizers and amendments required to restore depleted nutrients.
- Profit loss: yield decline when nutrients are not replenished.
- Land reduction cost: revenue forgone from smaller effective planting areas under conservation practices.

Policy priorities should therefore:

- Provide compensation for replacement costs and land lost under terrace systems.
- Tailor support to conservation method: labor-sharing and seasonal subsidies for contour planting; PES or tax relief for terraces.
- Address competitiveness gaps, since without institutional support, conservation reduces profitability and discourages adoption.

Mechanisms to embed environmental stewardship include:

- Collective Land Management Agreements: formalized commitments among farmers, facilitated by cooperatives and extension services.

- Tiered Incentives: fertilizer subsidies, market access, or small grants linked to low-erosion practices.
- Soil Quality Monitoring and Certification: farmer groups, trained by NGOs or universities, assess soil health and issue "Sustainable Highland Potato" certification.
- Village-Level Governance Bodies: multi-stakeholder committees responsible for land-use planning, training, and compliance oversight.
- Integration into Agribusiness Contracts: procurement agreements and certification schemes that reward compliance with conservation standards.

By explicitly incorporating the third hidden cost—loss of effective planting area—into institutional design, policies can avoid penalizing conservation farmers. Institutional arrangements grounded in property rights, transaction cost reduction, collective action, and incentive alignment offer a pathway to balance short-term profitability with long-term soil sustainability.

5. Conclusions and Recommendations

5.1. Conclusions

1. Soil erosion in upland potato farming imposes substantial hidden costs, with fertilizer replacement accounting for 4–11% of farm expenditure and profit losses for 12–16% of earnings. Bench terraces minimize these costs, while slope-wise planting accelerates nutrient depletion and financial losses.
2. Individual property rights alone are insufficient to manage erosion, which produces significant off-farm impacts. Erosion must therefore be addressed as a public concern through collective governance and compensation for the negative externalities it causes.
3. An institutional economics perspective highlights that conservation farmers face triple disadvantages—higher costs, reduced effective planting areas, and lower competitiveness—while non-conservation farmers capture short-term gains by externalizing erosion costs. Institutional interventions are required to realign private incentives with social sustainability.

5.2. Recommendations

1. Payment for Ecosystem Services (PES): compensate conservation farmers for both higher costs and land sacrifices.
2. Differentiated support: provide labor-sharing and seasonal subsidies for contour farming, and PES or tax relief for terrace systems.
3. Collective action: strengthen farmer groups to lower transaction costs and enhance bargaining power.
4. Market- and contract-based incentives: embed conservation compliance into procurement contracts and certification schemes.
5. Public investment and regulation: ensure upfront funding for terrace construction, enforce land-use rules, and expand extension services that emphasize long-term soil productivity.

Author Contributions

S.: Conceptualization, methodology, software application, formal analysis, investigation, resources, writing original draft. N.R.: software application, validation, visualization. R.K.: Conceptualization, methodology, investigation, resources, writing original draft. Y.R.W.: Writing review and editing, project administration, data curation. H.: Conceptualization, methodology, software application, formal analysis, investigation, resources, writing original draft, writing review editing, supervision. All authors have read and agreed to the published version of the manuscript." Authorship must be limited to those who have contributed substantially to the work reported.

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Institutional Review Board Statement

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Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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