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Evaluación del índice de calidad del suelo bajo labranza convencional y reducida para el cultivo de maíz en la Estación Experimental Tunshi

Evaluation of the Soil Quality Index Under Conventional and Reduced Tillage for Corn Cultivation at the Tunshi Experimental Station

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Resumen: La degradación del suelo limita la productividad del maíz (*Zea mays* L.) en la Sierra ecuatoriana. Este estudio evaluó el Índice de Calidad del Suelo (ICS) bajo labranza convencional (LC) y labranza reducida (LR) en dos niveles altitudinales de la Estación Experimental Tunshi, Escuela Superior Politécnica de Chimborazo, Ecuador. Se aplicó un diseño de parcelas divididas con cuatro repeticiones; la altitud fue la parcela principal y el sistema de labranza, la subparcela. Se analizaron dieciséis indicadores físicos, químicos y biológicos en muestras compuestas recolectadas a 0–30 cm antes y después de la labranza. El ICS se calculó mediante normalización y ponderación aditiva, con pesos derivados del análisis de componentes principales. La LR aumentó la humedad del suelo (34,8 %), la profundidad efectiva de labranza (41,3 %) y la abundancia de lombrices (200 %) respecto de la LC. El ICS integrado fue 0,49, correspondiente a calidad moderada, limitada por la baja materia orgánica (1,73 %) y el nitrógeno (11,6 kg ha^{-1}). La labranza reducida favorece la conservación del suelo y la regulación hídrica en sistemas andinos de maíz.

Palabras clave: *índice de calidad del suelo, labranza convencional, labranza reducida.*

Abstract: Soil degradation limits maize (*Zea mays* L.) productivity in the Ecuadorian highlands. This study evaluated the Soil Quality Index (SQI) under conventional tillage (CT) and reduced tillage (RT) at two altitudinal levels of the Tunshi Experimental Station, Polytechnic School of Chimborazo, Ecuador. A split-plot design with four replications was used; altitude was the main plot and tillage system the subplot. Sixteen physical, chemical, and biological indicators were assessed in composite samples collected at 0–30 cm before and after tillage. The SQI was calculated through indicator normalization and additive weighting, with weights derived from principal component analysis. Compared with CT, RT increased soil moisture by 34.8 %, effective tillage depth by 41.3 %, and earthworm abundance by 200 %. The integrated SQI was 0.49, corresponding to moderate quality and mainly constrained by low organic matter (1.73 %) and nitrogen (11.6 kg ha^{-1}). Reduced tillage therefore offers advantages for soil conservation and hydrological regulation in Andean maize systems.

Keywords: *Soil Quality Index, Conventional Tillage, Reduced Tillage.*

INTRODUCTION

Soil degradation represents one of the main constraints limiting maize (*Zea mays* L.) production in the Ecuadorian highlands, where average grain yields remain low (1.63 t ha^{-1}) because of inadequate tillage practices and declining soil fertility (Caviedes & Espinoza-López, 2021; INIAP, 2021). Conventional tillage systems, widely adopted in the central Andean region, involve repeated soil inversion using plows and disc harrows. Although these operations temporarily control weeds and incorporate crop residues, they substantially disturb soil structure, accelerate organic matter mineralization, and increase susceptibility to erosion (Valverde, 2004; Hasang-Morán & Pérez, 2021; Jaramillo, 2017).

In sloping Andean landscapes, soil erosion under conventional tillage may exceed 80 t ha^{-1} $year^{-1}$, while organic matter losses range between 15 % and 20 % (Hasang-Morán & Pérez, 2021). High fuel consumption and soil compaction, with bulk density values above 1.5 g cm^{-3}, also compromise economic efficiency and environmental sustainability (Jaramillo, 2017).

Indicators used to determine soil quality should be related to physical, chemical, and biological properties and provide measurable information about changes over time (Cantú et al., 2007). These indicators should also reflect the soil's capacity to sustain the production of a specific crop (Doran & Zeiss, 2000; Barrera, 2020).

The transition toward reduced tillage in Ecuador's central highlands depends on socioeconomic and technical factors. Resistance to change is associated with limited access to specialized machinery and insufficient knowledge and training (Zambrano, 2023). Conventional tillage generally requires several passes of implements over the same plot. A disc plow cuts and inverts the soil, exposing it to erosion; a double-action disc harrow then refines the soil and mixes crop residues into the surface layer, and furrowing completes the sequence. The minimum use of three implements increases costs and time and raises the risk of degradation, particularly on Andean slopes greater than 12 % (Burba, 1985).

For reduced tillage, the use of a chisel plow is recommended because it works without lateral soil displacement and is suitable for erosion-sensitive areas. It improves drainage and aeration without inverting the upper horizons; subsequent furrowing facilitates later hilling operations (Burba, 1985). Reduced tillage systems based on minimum soil disturbance and residue retention are therefore viable alternatives for soil conservation in erosion-prone environments (Zambrano, 2023). However, their effects on integrated soil quality under high-altitude maize systems remain insufficiently quantified.

Accordingly, this study aimed to evaluate the Soil Quality Index (SQI) under conventional and reduced tillage systems for maize cultivation at the Tunshi Experimental Station in the Ecuadorian highlands.

MATERIALS AND METHODS

The research was conducted at the Tunshi Experimental Station of the Polytechnic School of Chimborazo, Riobamba canton, Chimborazo Province, Ecuador, at 1°44′47″ S and 78°37′41″ W, 2747 m above sea level. The site has an average temperature of 13.5 °C, annual rainfall of approximately 500 mm, and an Entisol with sandy loam texture. A randomized complete block design with split plots and four replications was used. Factor A was altitude and Factor B was tillage system. Each plot covered 222 m^2, for a total experimental area of 3552 m^2. Sixteen composite soil samples were obtained from eight subsamples per plot at a depth of 30 cm before and after tillage. Sampling was carried out 15 days before tillage and 30 days afterward, allowing stabilization of physical soil conditions.

Soil quality indicators were normalized using optimal threshold values for maize derived from INIAP guidelines and internationally accepted standards (INIAP, 2021; Cantú et al., 2007; Doran & Zeiss, 2000). Physical indicators included texture by the Bouyoucos method, bulk density by the cylinder method, porosity, infiltration using a double-ring infiltrometer, moisture, and shear strength measured with a penetrometer. Chemical indicators included pH, electrical conductivity, organic matter, nitrogen, phosphorus, potassium, calcium, and magnesium. The biological indicator was earthworm abundance per square meter.

The Cantú methodology was used to calculate the SQI. Indicators were normalized on a scale from 0 to 1, where 1 represents the maximum value and 0 the minimum value:

$$V_n = \frac{I_m - I_{\text{mín}}}{I_{\text{máx}} - I_{\text{mín}}},$$

where I_m is the measured value, $I_{\text{mín}}$ is the minimum index, and $I_{\text{máx}}$ is the maximum index according to optimal thresholds for maize. The integrated index was calculated as:

$$\text{SQI} = \sum_i V_{n,i} w_i.$$

Indicator weights were assigned using Principal Component Analysis (PCA): organic carbon 25 %, aggregate stability 20 %, basal respiration 15 %, and the remaining indicators 40 %. Three components with eigenvalues greater than one were retained and explained 72.4 % of the total variance. Organic carbon, aggregate stability, and basal respiration were identified as the most influential indicators. Statistical analyses included analysis of variance (ANOVA) and Tukey's test ($p < 0{,}05$) in SAS 9.4. Geospatial mapping was performed in ArcGIS Pro.

RESULTS

The soil had a sandy loam texture and a loose structure; consequently, ANOVA was not required for texture. Soil color, determined using the Munsell chart, corresponded to dark brown and dark grayish brown, and no ANOVA was required for this parameter.

Table 1

Analysis of variance for soil moisture before and after tillage

Source of variation	df	Moisture before tillage				Moisture after tillage			
		MS	F	p-value	Sig.	MS	F	p-value	Sig.
Replications	3	7.61	2.33	0.1742	ns	1.25	0.80	0.5776	ns
Altitude	1	4.87	1.49	0.2679	ns	2.21	1.41	0.2794	ns
Replication × altitude	3	3.52	1.08	0.4274	ns	3.89	2.48	0.1580	ns
Tillage system	1	2.92	0.89	0.3815	ns	33.79	21.58	0.0035	**
Altitude × tillage	1	0.04	0.01	0.9187	ns	0.39	0.25	0.9618	ns
Error	6	3.27	–	–	–	1.57	–	–	–
Total	15	–	–	–	–	–	–	–	–
CV (%)	–	16.51				4.75			

*Note: ns = not significant ($p > 0{,}05$); * = significant ($0{,}01 < p < 0{,}05$); ** = highly significant ($p < 0{,}01$).*

Before tillage, soil moisture showed no significant differences for any source of variation, with a coefficient of variation of 16.51 %. After tillage, Factor B (tillage system) showed a highly significant difference, whereas altitude and the altitude-by-tillage interaction were not significant. The coefficient of variation after tillage was 4.75 % (Table 1).

After tillage, highly significant differences were also observed in effective tillage depth, infiltration rate, soil shear strength, bulk density, true density, and porosity. Chemical properties such as pH, organic matter, nitrogen, phosphorus, potassium, calcium, magnesium, C/N, and Ca/Mg showed no significant differences before or after tillage.

3.1 Impact of Tillage Systems

Table 2

Soil properties under conventional tillage (CT) and reduced tillage (RT)

Indicator	CT	RT	Δ % (RT vs. CT)	p-value
Moisture (%)	9.20	12.40	+34.8 %	0.003
Tillage depth (cm)	42.69	60.38	+41.3 %	$< 0{,}001$
Infiltration (mm h^{-1})	32.39	23.43	-27.7 %	0.012
Earthworms (individuals m^{-2})	1	3	+200 %	$< 0{,}001$
Bulk density (g cm^{-3})	1.18	1.32	+11.9 %	0.004

Note: Values reconstructed from the table supplied in the original manuscript.

3.2 Altitudinal Gradients

Electrical conductivity (EC) was higher at 2740 m above sea level (322.5 μS cm^{-1}) than at 2747 m (169.28 μS cm^{-1}; $p < 0{,}001$), indicating altitudinal saline stratification. No significant altitude-by-tillage interaction was detected ($p > 0{,}05$).

3.3 Soil Quality Index (SQI)

Table 3

SQI indicators and normalization

Parameter	Value	Optimum range	V_n
pH	7.26	5.5–7.6	0.84
Organic matter (%)	1.73	3–5	0.00
N (kg ha^{-1})	11.60	60–120	0.00
P (kg ha^{-1})	938.89	40–80	1.00
Porosity (%)	53.09	50–70	0.15
Integrated SQI	**0.49**	–	–

Note: Indicator values and optimum ranges were taken from the original manuscript.

Table 4

Interpretation scale for the Soil Quality Index

Soil quality level	Scale	Class
Very high quality	0.80–1.00	1
High quality	0.60–0.79	2
Moderate quality	0.40–0.59	3
Low quality	0.20–0.39	4
Very low quality	0.00–0.19	5

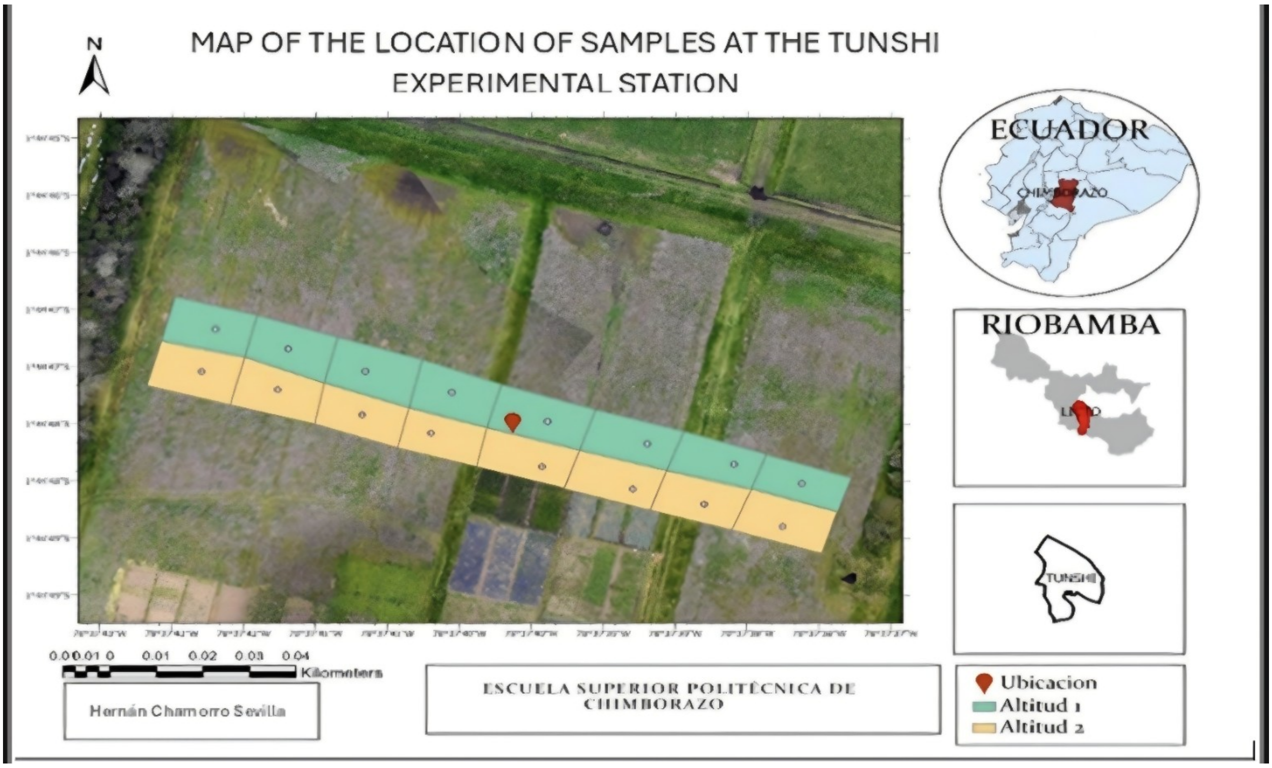
Source: Adapted from Cantú et al. (2007, pp. 173–178). Obvious interval typographical errors in the source table were normalized editorially.

The integrated SQI value of 0.49 classified the soils as having moderate quality (Class 3: 0.40–0.59), mainly limited by low organic matter and nitrogen.

3.4 Geospatial Mapping of Soil Quality

Georeferenced sampling points revealed spatial heterogeneity. Areas of lower quality were associated with historical compaction and debris removal (Figure 1).

Figure 1
Map of the sampling sites at the Tunshi Experimental Station



DISCUSSION

4.1 Effects of Tillage Systems on Soil Physical Properties

Soil texture at the study site was classified as sandy loam, a condition that generally favors root penetration and aeration but limits water retention. Under these conditions, tillage management plays a decisive role in regulating soil-water dynamics. Reduced tillage significantly increased soil moisture and effective tillage depth compared with conventional tillage, reflecting lower disturbance and greater preservation of soil aggregates. Similar responses have been reported in Andean agroecosystems, where reduced soil inversion promotes pore continuity and limits surface sealing.

Although conventional tillage exhibited higher infiltration rates, this response should be interpreted cautiously. In sandy loam soils under semi-arid conditions (approximately 500 mm annual rainfall), excessive infiltration may cause rapid percolation beyond the root zone and reduce water availability for maize. On slopes greater than 12 %, high infiltration combined with soil inversion may also increase susceptibility to water erosion. Reduced tillage therefore offers a more favorable balance between water retention and erosion control under the prevailing environmental conditions.

4.2 Biological Indicators and Soil Functionality

The significantly greater earthworm abundance under reduced tillage reflects improved habitat stability and residue availability. Earthworms contribute to nutrient cycling, aggregate formation, and porosity regulation, thereby enhancing soil functionality. The low abundance recorded under conventional tillage is consistent with repeated mechanical disturbance and organic matter depletion, which negatively affect soil biota.

4.3 Chemical Constraints: Organic Matter and Nitrogen Dynamics

Despite improvements in physical and biological indicators under reduced tillage, organic matter and nitrogen remained critically low under both systems. This condition may reflect long-term residue removal, accelerated mineralization under conventional tillage, limited organic inputs, and low biological nitrogen fixation in high-altitude Entisols. Reduced tillage alone is insufficient to restore fertility without complementary organic amendments. Applying compost at 8–10 t ha^{-1} every two cropping cycles and incorporating green manures could improve nutrient availability and raise the SQI beyond the moderate threshold.

4.4 Altitudinal Influence and Electrical Conductivity

Electrical conductivity varied significantly with altitude, probably because microclimatic differences affect evapotranspiration and salt accumulation. Lower elevations exhibited higher EC values, potentially associated with upward capillary movement and historical fertilizer use. However, the absence of a significant altitude-by-tillage interaction indicates that tillage effects on salinity were consistent across elevations.

4.5 Implications for Sustainable Corn Production

The moderate SQI value (0.49) reflects imbalances among physical, chemical, and biological properties. Comparable values have been reported in maize systems of central Mexico under similar management constraints (García-Oliva et al., 2019). Combining reduced tillage, residue retention, and organic nutrient management is essential to improve soil quality, productivity, and resilience in Andean maize systems.

Maize adapts to several textural classes, with preference for silt loam and silty clay loam soils (Montoro & Ruiz, 2017). At Tunshi, annual rainfall is approximately 500 mm, while maize may require around 700 mm during the crop cycle (Benítez & Hernández, 2022). The sandy texture and low water-retention capacity can therefore limit crop performance. Reduced tillage improved moisture retention by 34.8 % and tillage depth by 41.3 %, while earthworm abundance increased to three individuals m^{-2}. Conventional tillage showed higher infiltration, which can improve aeration but may increase erosion risk on steep slopes. The severe deficits in organic matter (1.73 % versus an optimum of 3–5 %) and nitrogen (11.6 versus 60–120 kg ha^{-1}) reveal an ongoing degradation risk. Supplemental irrigation and organic amendments are consequently needed to meet crop water and nutrient requirements.

CONCLUSIONS

Reduced tillage outperformed conventional tillage in biological conservation, with a 200 % increase in earthworm abundance, and in hydrological functioning, with a 34.8 % increase in soil moisture. These improvements are important for the resilience of Andean maize systems.

Soil quality was moderate (SQI = 0.49) and was mainly limited by low organic matter and nitrogen. Integrating reduced tillage with residue retention, compost, and green manures could raise the SQI above 0.60.

Geospatial tools effectively delineated management zones and can support precise interventions. Soil-conservation programs in Ecuador's central highlands should incorporate SQI thresholds and align their actions with Sustainable Development Goals 2 and 15.

RECOMMENDATIONS

Adopt reduced tillage with residue retention to enhance soil biota and moisture. Apply compost and green manure to increase organic matter above 3 %. Conventional tillage may be used selectively in soils with compacted layers above 1.4 g cm^{-3}, but reduced tillage should be prioritized on erosion-prone slopes.

ABBREVIATIONS

SQI: Soil Quality Index; CT: Conventional Tillage; RT: Reduced Tillage; EC: Electrical Conductivity; PCA: Principal Component Analysis.

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CONFLICTO DE INTERESES

The authors declare no conflicts of interest.

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