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Sectoral Fallow Systems and the Management of Soil Fertility: The Rationality of Indigenous Knowledge in the High Andes of Bolivia

In the High Andes of Bolivia, sectoral fallow systems are a common form of land use. Fields in the study area (Japo, Department of Cochabamba) are cultivated for 3 years with potatoes as the first crop and then lie fallow for 9 years. Despite the low nutrient content of the soil and the high elevation of the area (between 4000 and 4500 m above sea level), farmers achieve relatively high yields. This is explained by traditional knowledge about soil fertility management. The study focuses on nutrient dynamics over a 12-year cycle. A participatory research approach was applied to obtain information about indigenous knowledge. Soil nutrient content, phytomass, and yields were measured in 72 fields together with the farmers. Subterranean phytomass was identified as the key factor in nutrient storage during the fallow period. A multiple linear regression model shows three main factors that determine potato yields on cultivated fields. Farmers know about the nutrient dynamics of the fields; hence, cultivation measures show an impressive rationality. New elements such as mineral fertilizer have been incorporated in the system in a sustainable way. Participatory research intensifies these processes, stimulating farmers to reflect about their own land use system.

Keywords: *fallow systems; soil fertility; High Andes; Bolivia; agro-ecological assessments; phytomass measurement; indigenous soil management.*

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Introduction

In the High Andes of Peru and Bolivia, at the upper limit of agriculture, the indigenous population practices an agricultural system whereby fields are sectorally cultivated for a few years and then lie fallow for several years or decades. The fallow fields spontaneously cover with vegetation and are used for cattle grazing (Zimmerer 1991; Morlon 1992).

This traditional farming method based on potatoes as the main crop produces comparatively high yields of 15,000 kg/ha under normal weather conditions, compared with the average Bolivian yield of 5,000 kg/ha (INE 1996). Fallow systems are widely practiced throughout the High Andes as well as in other mountainous regions (Andreae 1981; Orlove and Godoy 1986; Sarmiento et al 1993) and constitute a successful strategy for utilizing soil with low nutrient content. How can these comparatively high yields be explained? There are two main reasons.

1. All authors and farmers agree that fallowing is a successful way of restoring fertility to fields (Ruthsatz and Fisel 1984; Mahnke 1985; Hanagarth1987). However, only a handful of studies have been conducted to determine how this regeneration takes place (Hervé 1994; Sarmiento and Monasterio 1995; Schaad 1995), while the comparable slash-and-burn systems practiced in the humid tropics have been studied in depth (Pfund et al 1997). In both systems, plant biomass plays a key role as a source of nutrients.
2. By practicing special farming methods, farmers skillfully exploit ecological factors and convert them into high yields (Schulte 1996; Saravia 1997). Specific farming parameters such as choice of sector, fallow age, and exclusion period for grazing, as well as rituals, are collectively dictated by the land use system, while the concrete aspects of farming such as choice of crop, sowing date, quantity of fertilizer, etc., can be individually selected by each farmer. Both are rooted in a profound indigenous knowledge of the local ecology, acquired over the centuries by careful observation and through trial and error in working the fields.

This article uses a case study to examine the ecological principles and nutrient dynamics of a typical fallow system. The results are compared with concrete farming measures. How well are they adapted to ecological conditions?

New influences and changing conditions such as population increase, easier market access, and availability of artificial fertilizers are presenting new challenges to the farming community. How do farmers tackle these innovations? Can they integrate them effectively into the system? These questions are addressed at the end of the article.

The study area

The study area lies in the eastern cordillera of the Bolivian Andes (66° 46′W, 17° 41′S) in the Department of Cochabamba between 4000 and 4500 m above sea level (Figure 1). The highest lying fields examined were at 4500 m. The climate is typical of mountainous regions in the outer tropics, with a summer rainy season from November to March and a winter dry season from April to October. With barely 400 mm of annual precipitation, the region is on the threshold of the semiarid climate zone (Lauer 1986), with an annual average tem-

FIGURE 1 The study area lies in the eastern cordiller of the Bolivian Andes at altitudes between 4000 and 4500 m above sea level. (Photo by author)

perature of 6.6°C, as recorded by the climate measuring station in the community of Japo, for the period 1994–1997 (Pestalozzi 1999). The approximately 100 days of frost are normally limited to the dry season, although, depending on incline and altitude, acute night frosts can occur at ground level during the vegetation period with resultant damage to potato crops (Saravia 1997).

Fields are laid out primarily on Eutric Cambisols. The sand-lime texture, slightly acidic pH value, and a medium humus content of these soils favor the cultivation of potatoes, while the soil nutrient contents of P and K are low to very low (Table 1).

The vegetation is dominated by bunchgrasses interspersed with cushion plants and a large variety of hemicryptophytic herbs and grasses, all of which form an excellent root system (Pestalozzi and Torrez 1998).

Population and land use

The region is inhabited by an Aymara-speaking indigenous population. Population density is low, at 14 inhabi-

TABLE 1 Soil parameters of fields laid fallow for over 8 years.

n = 37	pH_{CaCl2}[a]	Conductivity[b] (µS/cm)	C[c] (%)	N_{tot}[d] (%)	P[e] (mg/kg)	K_{int}[f] (mval/100 g)
Mean	4.77	47.9	2.24	0.20	6.13	0.39
SD	±0.20	±23.0	±0.90	±0.07	±3.23	±0.21
Rating	Slightly acidic		Medium humus	Medium	Low to very low	Low

[a]0.01 M $CaCl_2$, soil : water = 1:2.
[b]Soil : water = 1:2.
[c]Humid oxidation (by Walkley–Black).
[d]Kjeldahl.
[e]Extraction with $NaHCO_3$ at pH 8.2 (by Olsen).
[f]Extraction with 0.5 M NH_4Ac at pH 7

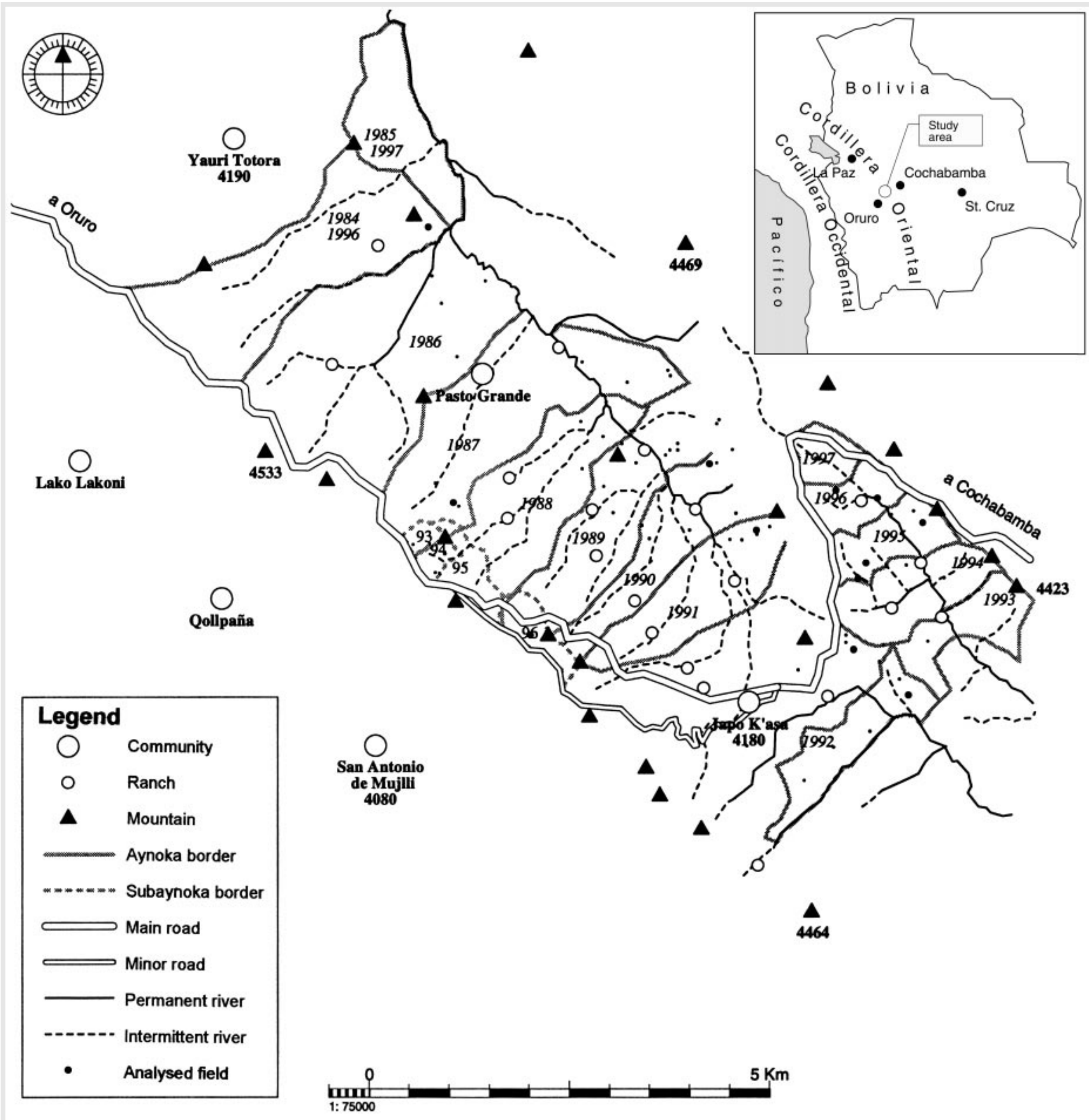


FIGURE 2 Map of the studied sectoral fallow system showing the boundaries of the sectors (Aynokas and Subaynokas) of the last cycle lasting 12 years. Every year a new sector is replowed and sowed with potato seed (indicated with date). Three adjacent sectors are farmed simultaneously, while the remaining sectors are laid fallow and used for grazing. The dots represent the studied fields.

tants/km^2. The most important economic base is agriculture, with a high level of self-sufficiency. The organizational forms show pre-Columbian traits. For instance, land ownership and the sectoral fallow system are collectively regulated.

The sectoral fallow system currently practiced is illustrated in Figure 2. The region is divided into different sectors (*Aynokas*). Every sector contains hundreds of fields separated by natural vegetation, but only the fields in three (usually adjacent) sectors are cultivated simultaneously. The fields in the other sectors are laid fallow. Every year, the cultivated zone moves on a sector. In addition to the main system, various subsystems (*subaynokas*) have arisen in recent years, which operate according to the same principle but substantially reduce the distance farmers need to travel (see map, Figure 2).

The fields in the new sector are tilled toward the end of the rainy season (Figure 3). The first crop, pota-

FIGURE 3 A farmer tilling his field toward the end of the rainy season. (Photo by author)

toes, is sown at the beginning of the next rainy season. Forty different varieties of potato from five botanical species are grown in the region (Saravia 1997). In the second farming year, barley, oats, or Quinua are sown, and in the third year, just barley is grown. The fields then lie fallow for 9 years. They spontaneously cover with vegetation and are used for cattle grazing (Figure 4). Fertilizer in the form of sheep dung or artificial fertilizers is spread only on the potatoes.

No cattle must be grazed in the cultivated sectors while the crops are growing, not even in the zones of natural vegetation between the fields. Two young men from the village (Jilakatas) monitor adherence to these rules.

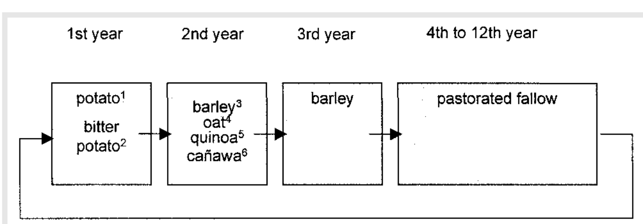


FIGURE 4 Crop sequence in the studied sectoral fallow system: (1) *Solanum tuberosum* spp *andigenum, Solanum ajanhuiri, Solanum stenotonum*; (2) *Solanum curtilobum, Solanum juzepczukii*; (3) *Hordeum vulgare*; (4) *Avena sativa*; (5) *Chenopodium quinoa*; (6) *Chenopodium palladicaule.*

The system described above offers the following advantages:

- Reduced workload: Instead of having to tend all the animals, only the (neighboring) fields need to be monitored (Zimmerer 1991).
- Pest control: The fallow time significantly reduces the incidence of soil-borne pests such as nematodes (Esprella et al 1994).
- Regeneration of grazing land and natural apothecary: The normally heavily grazed, natural vegetation between the fields can evolve and regenerate during the space of three vegetation periods in the absence of grazing pressure. These are also the zones where the residents gather medicinal herbs and other plant products (Genin et al 1994).
- Regeneration of soil fertility: Fertility is regenerated during the collectively observed fallow period (Sarmiento 1995).

It is worth explaining this last point in greater detail. According to our working hypothesis, mineralizing nutrients in the soil are absorbed during the fallow period by spontaneously growing vegetation and are stored as plant biomass until the fields are tilled. After the soil is tilled, the phytomass breaks down and provides the necessary nutrients for the cultivated plants. This hypothesis accords with the observations of the farmers. One of them explained the regeneration of fertility in the following way: "This straw and these roots, fertilizer is then!"

Methodology

The studies were conducted in 1996 and 1997 in close collaboration with the farming community of Japo and with the workers in the fields. The information on farming methods and indigenous knowledge was acquired through participatory field research methods such as semistructured interviews, field inspections, joint evaluation of aerial photographs, workshops, participation in social events, etc.

Seventy-two fields belonging to three farming families were analyzed for the agroecological studies. The fields cover all stages of use and are situated in varying microclimates. From an ecological standpoint, a random selection may be assumed. During the dry season in 1996 and 1997, a total of 116 soil samples were taken. Cultivated fields and young fallow fields were tested in both years. In addition, 22 samples were taken in the natural vegetation adjacent to the fields. One mixed sample per field was taken, consisting of eight cylindrical probes of 0–20 cm (2-inch diameter). The sample was then dried and sieved, and the fine soil was analyzed using standard chemical methods of soil analysis (Table 1). To obtain a rough phytomass measurement, the residual (>1.6 mm) was washed in water and the floating phytomass was collected, washed, dried, and weighed.

Detailed phytomass readings were taken on five ecologically comparable fields with different fallow ages: The above-ground phytomass was gathered on four randomly laid out square plots (1 m by 1 m), and the below-ground phytomass was then gathered using four cylindrical probes in each square and was then processed as described above.

To analyze the nutrient dynamics, seven fields were periodically examined between tilling of the fal-

FIGURE 5A The biomass shows a clear and significant correlation with the fallow age but with a considerable spread. The dotted line indicates the mean of 22 biomass analysis in natural vegetation. Hence, it takes more than 30 years for the biomass in the fields to reach the same level as the natural vegetation. The large dots represent the detailed biomass analysis.

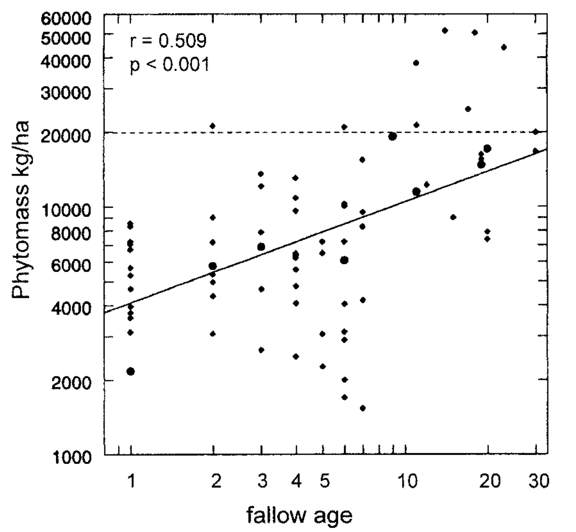
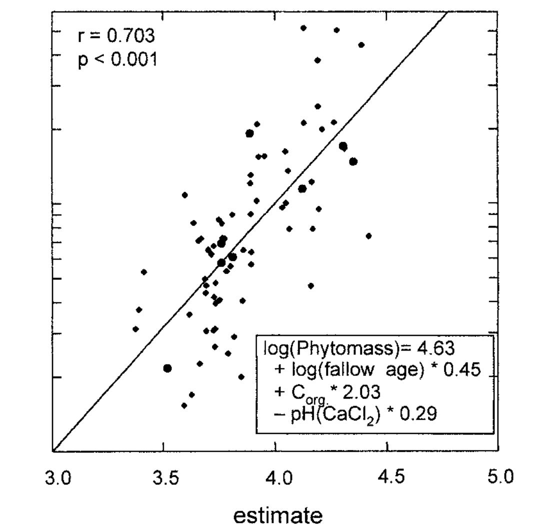


FIGURE 5B Multiple regression: In addition to the fallow age, organic C and pH ($CaCl_2$) values are incorporated in the model. The highest biomass values were registered in old fallow fields with a high level of organic C and a low pH value.



low vegetation and the potato harvest. Most of the fields had a fallow age of 19–20 years or were created with natural vegetation due to the sectors that had been cultivated by the farmers during the study period. Before tilling, a detailed phytomass reading was taken. At sowing time, the fertilizer and seed quantities were recorded, and at harvest time, the potato yields were measured (in three 5-m furrows). The total nutrient content (N and P) of the phytomass as well as the fertilizer, seed, and crops was determined. The farming methods used on the fields were selected by the farmers based on their experience, and, on four of the seven fields, control plots without fertilization were laid out.

Results

Key factor: phytomass

What happens in the ground during the fallow period? How does fertility regenerate in the soil? The first important finding is that soil nutrient contents and soil parameters hardly changed during the fallow period. No correlation with the fallow period could be established (Table 2). Similar results were achieved by Hervé (1994) and Sarmiento and Monasterio (1995).

TABLE 2 Pearson correlation of the fallow age with soil parameters and nutrient content of the fields. There is almost no relation between the fallow age and the nutrient content, so the regeneration of soil fertility during the fallow period cannot be explained by an increase of the extractable soil nutrients.

n = 82	pH_{CaCl_2}	Conductivity	C	N_{tot}	P	K_{int}
Correlation with fallow age *r*	0.143	0.033	0.163	0.126	–0.129	0.005

Only the biomass content, as anticipated, shows a clear increase during the fallow period. A linear relationship with significant correlation is obtained using the logarithm of biomass and fallow age ($r = 0.509$; Figure 5A). After 9 years lying fallow, the fields exhibit an average biomass of 10 tons/ha, while current data indicate that it can take over 30 years before the fields have built up the same level of biomass that is found in the natural vegetation adjacent to the fields (19.9 tons/ha, mean of 22 measurements).

However, the large spread of phytomass values in Figure 5A leads to the conclusion that other factors besides the fallow age influence phytomass production in fallow fields. A stepwise multiple regression using the key soil parameters shows that, in addition to fallow age, a high humus content and a relatively low pH ($CaCl_2$) value have a positive influence on the build-up of biomass in the fields (Figure 5B), conditions that mainly occur in troughs and in higher altitude locations in the region. Taking these factors into account, the correlation coefficient rises to $r = 0.703$. Further optimization of the model does not appear possible due to the limited accuracy of the phytomass measurement methods.

Where are these significant quantities of phytomass accumulated? The detailed biomass studies indicate that 90–95% of the plant biomass originates in the root area, as illustrated in Figure 6. A high proportion of belowground biomass is characteristic of grassland vegetation (Dormaar 1992). This is especially true of Andean grass

TABLE 3 Summary of the nutrient cycling data of seven fields, four of them with control plots without fertilizers.

Field number[a]	Fallow age[b]	Altitude (m asl)	Organic matter (%)	Conductivity (μS/cm)	Phytomass Dry matter (kg/ha)	Phytomass N (kg/ha)	Phytomass P (kg/ha)	Fertilizer[c] N (kg/ha)	Fertilizer[c] P (kg/ha)	Potato yield Total (kg/ha)	Potato yield N (kg/ha)	Potato yield P (kg/ha)
2	19	4200	2.7	78.7	14,867	113.3	14.4	112.8	31.1	20,856	80.4	9.8
2*	19	4200	2.7	78.7	14,867	113.3	14.4	—	—	6472	27.3	2.0
6	n. veg.	4250	3.5	40.0	15,871	174.6	17.5	22.8	25.5	18,693	81.5	5.4
3	20	4210	1.5	42.4	17,222	211.8	29.3	21.4	23.9	18,978	82.7	5.5
3*	20	4210	1.5	42.4	17,222	211.8	29.3	—	—	8475	36.9	2.4
1	9	4100	1.4	90.9	19,353	115.9	12.3	5.3	5.9	9200	35.6	2.9
5	n. veg.	4270	4.1	43.7	23,433	260.1	35.1	15.1	16.8	16,662	65.6	4.9
7	n. veg.	4360	3.2	156.0	26,142	119.9	31.0	12.2	13.6	14,087	79.8	7.6
7*	n. veg.	4360	3.2	156.0	26,142	119.9	31.0	—	—	8158	46.2	4.4
4	n. veg.	4270	3.5	232.0	32,731	383.6	46.4	8.1	9.1	21,350	90.1	11.2
4*	n. veg.	4270	3.5	232.0	32,731	383.6	46.4	—	—	17,070	72.1	8.9

[a]Numbers with *: control plots without fertilizer.
[b]n. veg., natural vegetation.
[c]Field 2, dried sheep dung; other fields, mineral fertilizer (18-46-0, N_2-P_2O_5-K).

meadows with a high proportion of plants with hemicryptophytic life forms (Weberbauer 1911, 1945). According to our own observations, the below-ground biomass consists mainly of fine roots. Thick roots and rhizomes make up only a small proportion. It is to be expected that the fine roots decompose rapidly once the fields have been tilled, providing nutrients for the potato crops.

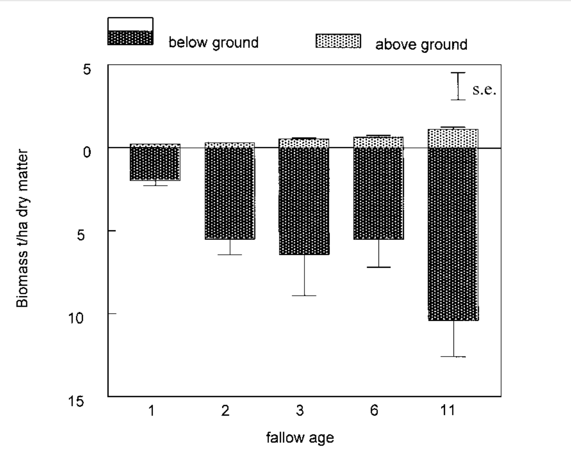
From phytomass to yield

Does a high phytomass content actually have a positive effect on the potato yield, as our initial hypothesis suggests? The results of the studies on nutrient dynamics are summarized in Table 3. It will be seen from the data that the phytomass initially measured in all studied fields contains more N and P than was extracted by the potato harvest. Fertilizing alone introduces far less nitrogen than is extracted later when the potatoes are harvested.

However, correlation of the phytomass initially present in the fields with subsequent potato yields produces only a very weak, insignificant dependency ($r = 0.224$), whereas the unfertilized control plots exhibit a greater dependency ($r = 0.853$). Fertilization of the fields therefore has a highly modifying effect on yield. Field 2 was fertilized using dry sheep dung, while all other fields were spread with artificial fertilizer (18-46-0; N_2-P_2O_5-K). What strikes one here is that the farmers applied large quantities of additional nutrients in the case of low phytomass contents but were very sparing with fertilization in the case of fields with high phytomass contents (Figure 7). The increase in yield for fertilized fields compared with the control plots is proportional to the phosphorus quantity, which therefore represents a key element in the system as a whole.

Which nutrients contribute to yield and to what extent? The nutrient levels introduced by phytomass and fertilizer were subjected to stepwise testing in the multiple regression model together with several soil parameters. A very good correlation was obtained when incorporating nitrogen in the phytomass, phosphorus in the fertilizer, and the electrical conductivity of the soil (Figure 8). As already indicated, the phytomass supplies the major proportion of nitrogen to the potato plants. However, this nitrogen can only be optimally exploited

FIGURE 6 Above- and below-ground biomass in fields with different fallow age. The below-ground biomass accounts for 90–95% of the entire biomass.



if sufficient phosphorus is introduced with the fertilizer. These two key nutritional factors are modified by the electrical conductivity of the soil, which serves as a general measure for nutrient concentration in the soil and can be used in the region as a parameter for soil fertility.

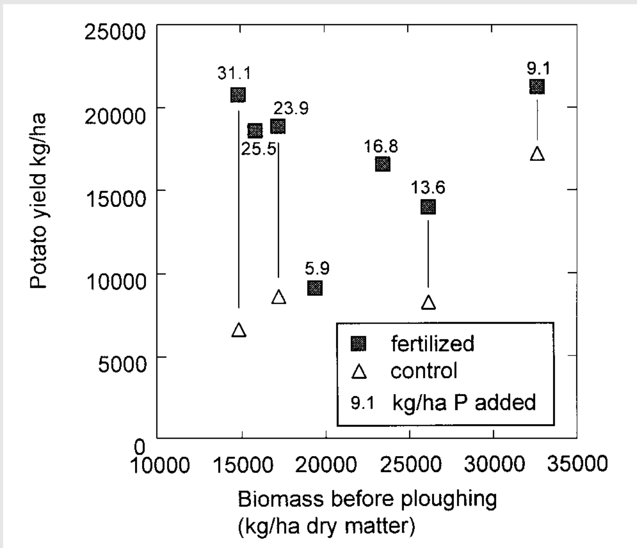


FIGURE 7 Potato yield of seven fields in relation to the available biomass prior to tilling. Only the unfertilized control plots show a correlation with the biomass ($r = 0.853$). The yield of the field is heavily modified by fertilization. Farmers spread more phosphorus-based fertilizer on fields with low phytomass content.

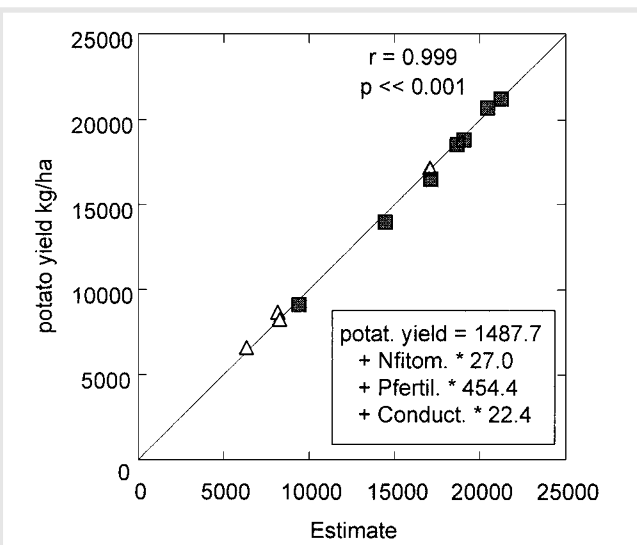


FIGURE 8 Multiple regression: The potato yields of the fields examined by the study depend on phytomass, nitrogen, fertilizer, phosphorus and the electrical conductivity of the soil. The model, based on the yields of the 7 fields, predicts the yields of the 4 unfertilized control plots very accurately.

Discussion

How rational is indigenous knowledge?

What conclusions about the rationality of indigenous knowledge can be drawn from the results? In the *Aynoka* system studied, the fields normally lie fallow for 9 years. After this period, 10 tons/ha biomass with approximately 91 kg N and 12.5 kg P can be determined in an average field. These nutrient levels are clearly above the requirements of an average potato yield. If one also takes into account the fact that the accumulation of biomass represents a logarithmic function of the fallow age, ie, per unit of time, the accumulated phytomass decreases as the fallow age increases, the fallow age collectively practiced by the farming system appears to be optimally attuned to the ecology and, in terms of nutrient balance, can be regarded as sustainable.

For the less fertile fields, the farmers use a special name, *Lullu Laq'a,* according to their own soil classification system. This refers to fields with sparse vegetation cover and hence low biomass levels. These fields are not tilled when their 9-year fallow period has expired but are kept fallow for another cycle. The farmers know from experience that these fields will not yield a good crop. Any shortening of the fallow period would lead to more fields of this type, which is why this measure is never proposed in the region.

If a field is laid fallow for two cycles (= 21 years), it is called *Samata* and is regarded as just as fertile as natural vegetation that has never been tilled (*Puruma*). The results of the phytomass analysis (Figure 5A) confirm these estimates.

In recent years, fertile fields in troughs and usually in the vicinity of settlements have increasingly been fenced off with stone walls and hence have been effectively excluded from the collective cultivation cycle. Hence, the number of fallow years can be defined on an individual basis. The results of this study show that phytomass grows much faster in locations rich in humus and that shortening the fallow period of these fields leads to better exploitation of resources. The abundance of dung available in settlements intensifies this effect.

Surprising observations were made in terms of the correlation between the quantity of fertilizer spread and the available biomass in the field. Naturally fertile fields with high levels of phytomass were treated with only small amounts of additional fertilizer, while large quantities of fertilizer were spread on fields with low natural fertility. Although artificial fertilizer has only been used in the region for the past 10 years or so, the farmers use it rationally and sparingly in order to enhance exploitation of the nutrients in the biomass.

The dynamics of indigenous knowledge

Many elements of the farming system studied are very old and ideally adapted to the ecological conditions of the region. But the system is flexible, and new elements such as the use of artificial fertilizer, fencing off, or the installation of *Subaynokas* were integrated in an ecologically sustainable way. This seems to be characteristic of indigenous knowledge systems: Founded on a wealth of experience, they are in a state of continual change and are constantly being further developed and adjusted. This is what ensures their ability to survive.

New challenges are facing the system in this region. In recent years, a large part of the remaining arable natural vegetation has been tilled. The farmers profited from the high phytomass content of these fields. In future, potatoes must be cultivated almost exclusively on 9-year fallow fields. The farmers are aware of this problem. To solve it, they are planning to increase fertilization based on a combination of abundantly available sheep dung and artificial fertilizer. One unsolved problem with this approach is the potato blight (*Synchytrium endobioticum*) transmitted by sheep dung.

A participatory research approach as was used here involves farmers in research as partners with valuable knowledge of the ecosystem. Not only does this stimulate research, the findings of which demonstrate the ecological principles of traditional farming methods and make them available to a broader public, it also encourages participating farmers to reflect on their own farming system. The aim of the approach is to preserve and promote the above-mentioned dynamics of indigenous knowledge in order to tackle new challenges sustainably and in accordance with indigenous values.

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