Water Balance and Soil Loss Under Long Fallow Agriculture in the Venezuelan Andes

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Water Balance and Soil Loss Under Long Fallow Agriculture in the Venezuelan Andes

In the páramo ecological belt of the Venezuelan Andes, a long fallow agricultural system is used to produce potatoes and cereals. Total rainfall, surface runoff, soil moisture, drainage, and soil loss were measured in this system during two consecutive years on 10 plots cropped with potatoes and on two successional plots with fallow periods of 1 and 15 years. Total rainfall (1129 mm on average) is characterized by many low-intensity events. The low rainfall intensity and high soil infiltration capacity partly explain the very low runoff (only 1.7% of the rainfall) and the low rates of soil loss (0.58 t/ha/y) on the cultivated plots. The main water outputs were by evapotranspiration (61%) and drainage (37%). The greatest runoff and soil losses were observed at the beginning of the fallow period when the ground cover was scarce; however, after a few months of fallow, both processes decreased below the rates measured on the cultivated plots. Because soil loss was not significant on all study plots, it is suggested that traditional fallow agriculture does not have a negative environmental impact at a local scale.

Keywords: *Water balance; runoff; drainage; soil moisture; soil loss; páramo; potato; Andes; Venezuela.*

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Introduction

In the upper belt of the Northeast Andes (3000–4800 m), the characteristic ecosystem is the *páramo,* a high-altitude tropical grassland dominated physiognomically by giant caulescent rosettes and shrubs. *Páramo* plays an important role in the regional water balance, largely controlling the availability of water in the lowlands. The Venezuelan *páramos* were not cultivated during the pre-Columbian period (Wagner 1978). Only during the colonial period did they begin to be utilized for extensive grazing and more recently for the cultivation of cereals and tubers. Today, agricultural pressure on the *páramo* is increasing because of the population increase. In spite of the great importance of the *páramo* belt as a water-collecting zone and the headwaters of major rivers, little is known about water balance in this ecosystem and the possible impacts of agricultural expansion.

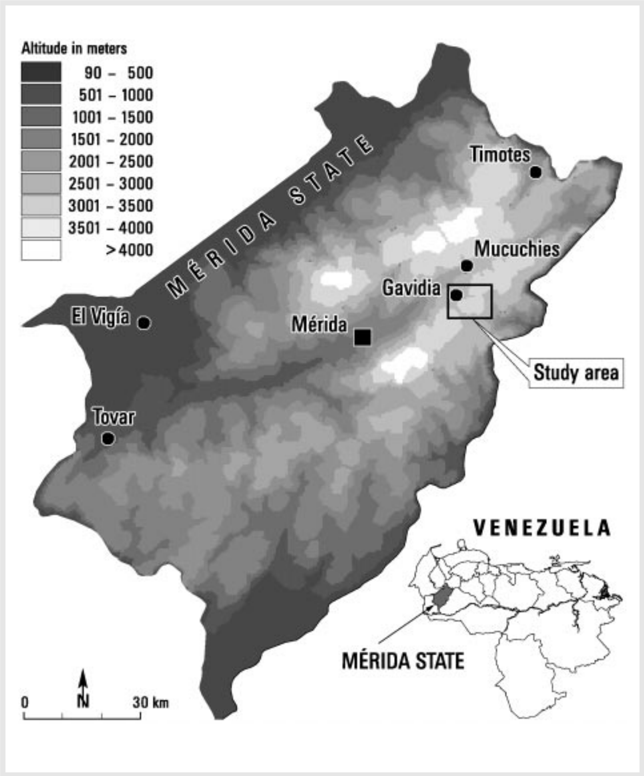
Water balance is especially important in mountain areas because it not only has a direct influence on the functioning of ecosystems but it also regulates water availability in the lowlands. The Mountain Agenda (1998) highlights the importance of mountains in global freshwater supply and emphasizes that the lack of data from mountain regions is a major limitation in designing concrete measures to promote sustainable management of mountain water resources. The present work is an attempt to study the hydrology of long fallow Andean agriculture, a system widely practiced in Venezuela and Colombia as well as in the central Andes. Fallow agriculture is characterized by a short period of cultivation (2–3 years), with potatoes as the main crop, followed by a long fallow period that may be prolonged for 5 to more than 10 years. It is important to analyze the water balance in this agricultural system during the cultivation interval as well as during the subsequent fallow period, and to assess the effect of eliminating or reducing fallow duration by an intensive use of mineral fertilizers, which is the current trend (Sarmiento et al 1993). Mishra and Ramakrishnan (1983), studying similar systems of potato crop in the mountains of northeastern India, found significant runoff and soil losses during the period of cultivation, which decreased as the fallow period progressed. These authors concluded that a fallow period lasting less than 5 years did not permit sustainable agriculture under the conditions of their study. In the Venezuelan *páramos,* evaluation of the effects on the water balance caused by the expansion of the agricultural frontier and reduction in the fallow period is an important priority.

The aims of the study included quantification of soil loss and the main processes involved in the water balance of a potato agroecosystem, as potatoes are currently and have historically been widespread across the Andes. A second objective was to compare the functioning of cultivated and fallow plots in order to analyze the different situations that characterize fallow agriculture and to assess the possible impacts of this agricultural system on local hydrology and soils.

Study area

The study was carried out at Páramo de Gavidia, located between 8°35' and 8°45'N and 70°52' and 70°57'W, 10 km from the town of Mucuchies in the state of Mérida, Venezuela (Figure 1). This area consists of several small and narrow glacial valleys with altitudes between 3200 and more than 4000 m asl. The vegetation is dominated by giant rosettes of the genus *Espeletia* and shrubs of the genus *Hypericum*, *Baccharis*, *Hesperomeles*, *Stevia,* and *Acaena.* Soils are well-drained inceptisols (*Ustic Humitropept*) of sandy-loam texture, very stony and acidic (pH 4.5–5.5), with topsoil 30–40 cm deep that is very rich in organic matter (20%). In this area, agriculture is practiced up to approximately 3800 m on alluvial

FIGURE 1 Map of the study area in the Venezuelan Andes.



and colluvial deposits, on small terraces and debris fans, and also on the steep slopes. The population of the Páramo de Gavidia is approximately 500 inhabitants, whose ancestors established the settlement at the beginning of the century (Smith 1995). Livelihoods are based on commercial cultivation of potatoes using long fallow agriculture, and on cattle raising.

Methods

Experimental design

Two fields in opposite phases of the agricultural cycle were utilized. One had been cultivated for 3 consecutive years and was in its first fallow year (depleted field), while the other had been fallow for 15 years (restored field). The fields were adjacent, located on a small fluvial fan, with a medium slope of 22% and similar exposition, stoniness, and soil type (Figure 2). The depleted field had scarce plant cover at the beginning of the experiment, with the herbs *Rumex acetosella* and *Lachemilla moritziana* as the dominant species. The physiognomy of the restored field was similar to that of the

FIGURE 2 Panoramic view of the study area (Páramo de Gavidia, 3400 m, Mérida, Venezuela). In the middle of the photo, the two adjacent fields, with 1 and 15 years of fallow, and within each field the five 10- × 10-m cultivated plots can be observed.

natural *páramo,* dominated by rosettes of *Espeletia schultzii* and shrubs that included *Baccharis prunifolia* and *Hypericum laricoides.* In each field, five 10- × 10-m plots were cultivated with potatoes and an area of approximately 500 m^2 was left uncultivated.

Water variables (rainfall, runoff, drainage, and soil moisture) were measured for 26 months (November 1990– February 1993), including two cycles of potato crops, separated by a short fallow of 7 months during the dry season. Soil loss was measured only during 1991.

Total precipitation was measured 1.50 m above the ground using six pluviometers 15 cm in diameter. A pluviograph with a continuous register was also installed in order to analyze other characteristics of precipitation such as magnitude and intensity, but for technical reasons, this instrument did not operate during the entire study period.

Runoff and soil loss were measured on all plots using 2- × 3-m subplots (Roose 1981; Acevedo and Sarmiento 1990). Lateral entry of water and sediments was avoided by closing the upper as well as the two lateral borders of the subplot. A water and sediment collection trough was located at the base of the subplot and was sampled for total water and sediment at each measurement interval.

Soil moisture was measured between 0 and 20 cm in a composite soil sample on each plot, obtained by mixing 10 individual samples. The permanent wilting and the field capacity points were estimated from a soil composite sample on each field.

Drainage was measured using three monolithic lysimeters 1800 cm^2 in area and 35 cm deep in each plot. A 5-cm layer of thick sand was placed at the bottom of each lysimeter, which was later filled with soil and stones reflecting natural proportions. The upper border of the lysimeter was buried several centimeters below the soil surface in order not to interfere with the runoff. A potato plant was sown within each lysimeter. Measurements of drainage were only carried out on the cultivated plots. This methodology was not appropriate on the uncultivated plots since the soil and vegetation would have been disturbed by the installation of the lysimeters.

Evapotranspiration was estimated as the difference between the input from precipitation and the outputs of runoff and drainage.

Agronomic practices

The methods of cultivation implemented were the same as those employed by the farmers in the study area. A first plowing was carried out in November 1991, when the successional vegetation was buried as green manure. Later, during the dry season (December–March), the plots were left fallow. They were plowed again at the beginning of the rainy season and were immediately sowed and fertilized according to the treatment. The potato variety used belongs to the subspecies *Solanum tuberosum andigenum* and is known locally as *papa negra arbolona.* It was sown in parallel furrows perpendicular to the slope, with a distance of 20 cm between tubers and 90 cm between furrows. Plant hilling was carried out in May and the harvest was in September, 7 months after sowing. The plots were then left fallow until April 1992, when they were sown again. During this second year of cultivation, plant hilling was carried out in May and harvesting was done in October.

The agronomic treatments on each field were 1 t/ha/y of NPK 16-16-08 on three plots (+F), with no fertilization on two plots (−F).

Crop leaf area index

The crop leaf area index (LAI) was determined periodically during the two cultivation cycles. The point quadrat method (Greig-Smith 1983) was used for nondestructive estimation of the biovolume (BIO), and the LAI was calculated using the equation LAI = 1.041 × BIO, estimated for this variety of potato by Sarmiento (1995).

Results and discussion

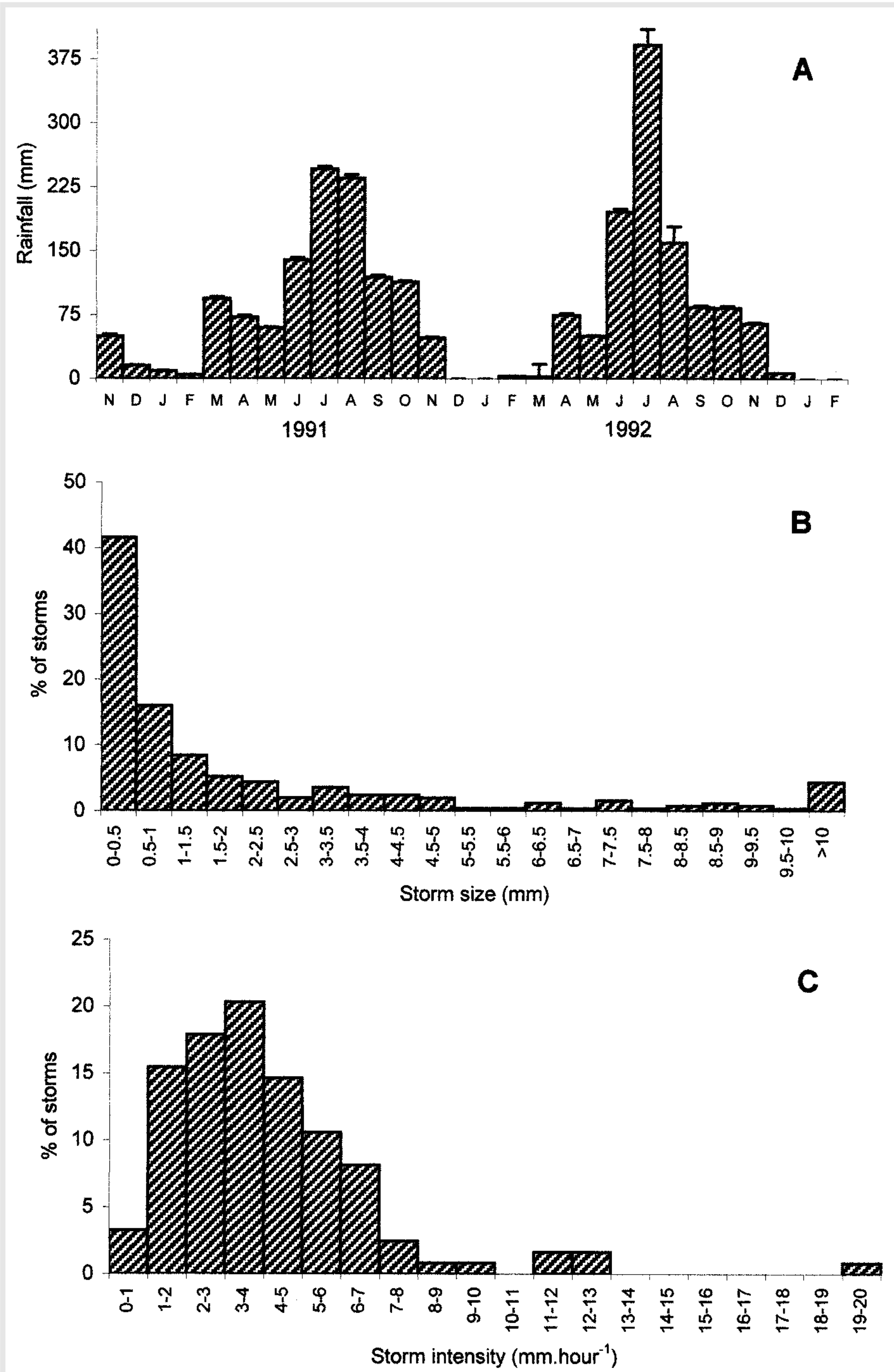
Rainfall

The annual rainfall measured was 1141 mm in 1991 and 1117 mm in 1992. The distribution was seasonal, with a unimodal pattern (Figure 3a). The dry season lasts from December to March. November, April, and May are interseasonal months. The peak rainfall occurs

TABLE 1 Mean annual runoff, drainage, soil moisture, and soil loss for all the cultivated plots, for the restored and depleted cultivated plots, and for the unfertilized and fertilized cultivated plots. Different letters indicate significant differences within treatments for each year.

	Annual runoff (mm)		Average soil moisture (%)		Annual drainage (mm)		Annual soil loss (t/ha)
Treatment	**1991**	**1992**	**1991**	**1992**	**1991**	**1992**	**1991**
All cultivated plots	17.2	21.5	37.4	34.5	409.1	418.9	58.3
Restored plots	14.9[a]	21.8[a]	38.1[a]	35.1[a]	419[a]	335[a]	53.1[a]
Depleted plots	19.5[a]	21.2[a]	36.8[a]	34.0[a]	399[a]	503[a]	63.4[a]
Unfertilized plots	17.5[a]	15.9[a]	37.1[a]	34.4[a]	344[a]	333[a]	56.2[a]
Fertilized plots	17.0[a]	23.1[a]	37.8[a]	34.6[a]	474[b]	456[b]	60.4[a]

FIGURE 3 (a) Monthly rainfall during the study period (mean ± standard error), (b) frequency distribution of storm size, and (c) storm intensity (percent of total number of storms).



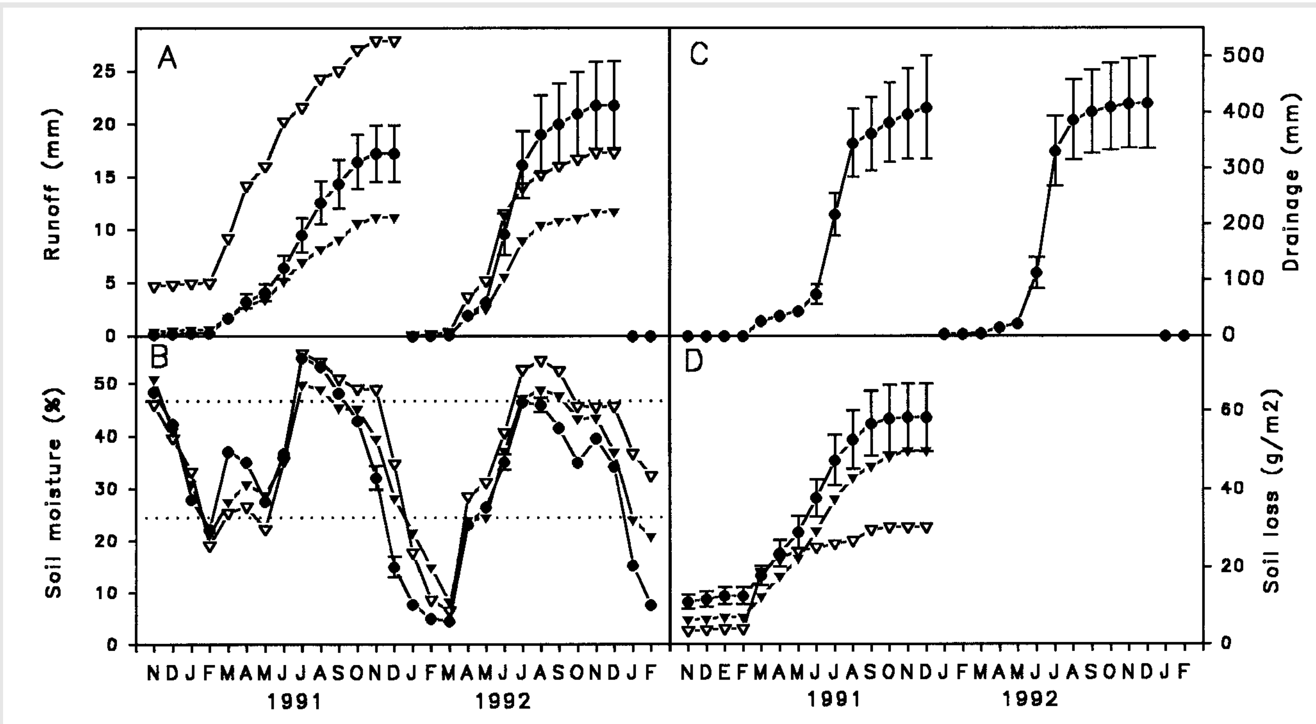
between June and September. The rainiest month during the study period was July 1992, with 392 mm. This unimodal rainfall pattern is characteristic in areas of the Venezuelan Andes that are under the influence of the Llanos climate, as opposed to those areas under the influence of Lake Maracaibo, which have a bimodal rainfall pattern (Monasterio and Reyes 1980).

The pluviographic registrations were carried out on 268 days in 1992. During this period, 250 rainfall events were registered, with a mean magnitude of 2.3 ± 3.9 mm and a mean intensity of 4.4 ± 3.5 mm/h (the events were considered to be different if they were separated by an interval of at least 1 hour without rain). Rainfall in more than 40% of the storms was less than 0.5 mm and less than 1 mm in 60%; it was greater than 10 mm in only 5% (Figure 3b). The greatest rainfall event registered was 29 mm. The intensity of most of the storms varied between 1 and 6 mm/h (Figure 3c). Only 6% of the events were of greater intensity than 10 mm/h. These data suggest that the region is characterized by many rainfall events of low magnitude, low intensity, and, consequently, low erosive power.

Runoff

Surface runoff represented a small percentage of the total precipitation. The average for all the cultivated plots was 17.2 mm in 1991 and 21.5 mm in 1992 (Table 1). No significant difference was observed between plots cultivated with or without a previous fallow period (Table 1). Fertilization also had no influence on the runoff rates. In comparing the cultivated and fallow plots (Figure 4a), it could be observed that the cumulative runoff during 1991 was greatest on the young fallow plot, moderate on the cultivated plots, and lowest on the old fallow plot. The highest rates of runoff were measured during the first months of the fallow period, when the plant cover was scarce. Runoff decreased after several months of fallow, when the cover of *Rumex acetosella* became more important. During 1992, runoff on young fallow decreased below the level of the cultivated plots, while the old fallow continued to present the lowest values.

FIGURE 4 Cumulative values of runoff, drainage, and soil loss and monthly values of soil moisture for the cultivated plots (filled circles), the 1-year fallow plot (hollow triangles) and the 15-year fallow plot (filled triangles) (mean ± standard error).



The rates of runoff obtained in this study are of the same order of magnitude as those reported in other agroecosystems in the Venezuelan Andes. Ataroff and Sanchez (1999) measured runoff of 1.8% of the rainfall for a potato crop at 2250 m on a slope of 76%. On coffee plantations, Ataroff and Monasterio (1997) measured runoff between 5 and 7% of the total precipitation. All these rates are very low considering the high to moderate slopes on which they were measured and can be partly explained by the high infiltration capacity and porosity that characterize the soils of the humid Venezuelan Andes.

Soil moisture

Soil moisture on all the cultivated plots was similar, independent of previous fallow time or fertilization treatment (Table 1). Soil moisture was greater on the fallow plots than on the cultivated plots (difference significant with $P < 0.01$ using a *t*-test for coupled data) (Figure 4b) with the exception of the first months of the study period, when the soil water content was lower on the young fallow. This tendency can be explained by scarce plant cover at the beginning of the fallow period, which favored direct evaporation from the soil.

During the dry season, the soil water decreased below the wilting point, while there were long periods with excess water during the rainy season. A water deficit occurred only during the first months of crop development (April–May).

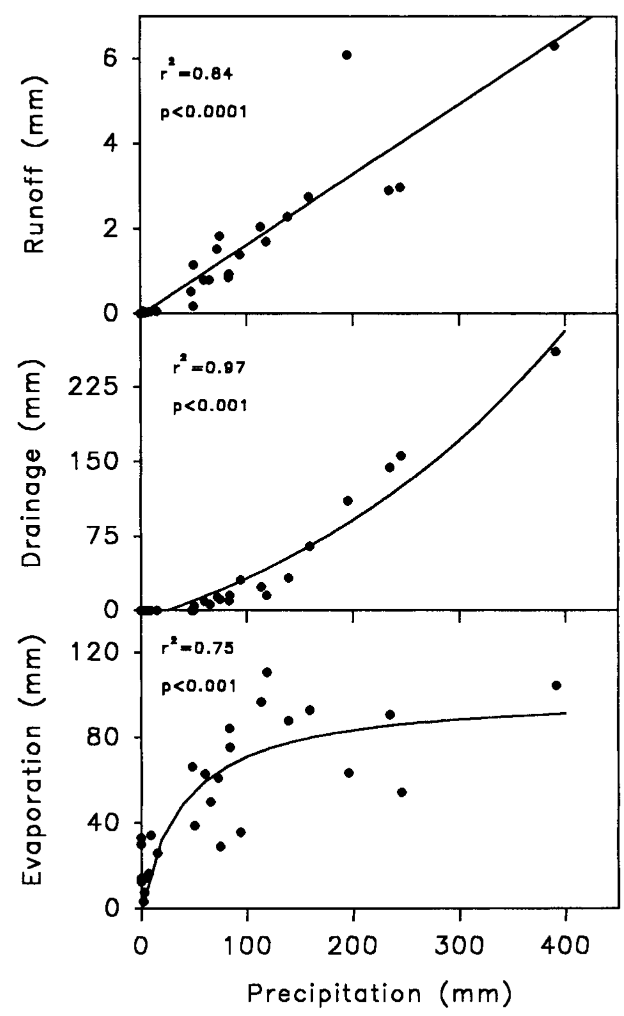
Drainage

Drainage constituted an important loss of water, representing an average annual output of 37% of the rainfall on all the cultivated plots. The process began after the soil was already saturated, 2 months after the start of the rains (Figure 4c). There were no differences due to the previous fallow time of the plots (Table 1). Fertilized plots had significantly higher drainage than unfertilized plots. This phenomenon is probably a consequence of the protective effect of the more abundant crop cover on the fertilized plots, which reduces direct evaporation. Supporting this hypothesis, positive significant correlations were found between the water lost to drainage and the leaf area index on different dates (r^2 between 0.37 and 0.77, data not shown). This suggests that losses through direct evaporation were more important than losses resulting from plant transpiration.

Comparative dynamics of water flows

Different types of relationships exist between monthly precipitation and other hydrological processes (Figure 5). Runoff fitted well to a linear equation ($r^2 = 0.83$, $n = 26$), being a constant proportion of the monthly precipitation. Drainage showed an exponential relationship with precipitation ($r^2 = 0.95$, $n = 26$), starting slowly and rising after about 100 mm of monthly rainfall. Evapotranspiration gradually increased to about 150 mm of rainfall per month and then leveled off, fitting well to a

FIGURE 5 Runoff, drainage, and evapotranspiration as a function of rainfall in the cultivated plots. Regression lines fitted to these data are $y = a + bx$, $y = yo + ab^x$, and $y = ax/b + x$, where y is the monthly runoff, drainage, or evaporation respectively, and x the monthly rainfall.



hyperbola ($r^2 = 0.75$, $n = 26$). Likens and Bormann (1995) obtained similar relationships in their classic experiment at Hubbard Brook. As a consequence, the relative importance of the different water flows varied throughout the year (Table 2). While only 10% of the annual precipitation fell during the 5 months of the dry season (November–March), 20% of the transpiration and only 4% of the drainage took place in the same period. During the two rainiest months of the year, 46% of the precipitation fell, 74% of the drainage occurred, and only 24% of the evapotranspiration took place. Runoff followed precipitation dynamics more closely.

Water balance

Figure 6 shows the annual dynamics of the different hydric processes and Figure 7 the annual water balance for the 2 years of the study on the cultivated plots. It can be observed that the soil water retention was relatively insignificant compared with the great importance of the input and output flows. Evaporation was very important throughout the year, representing the principal output of water from the agroecosystem, that is, 67% of the rainfall in 1991 and 56% in 1992; this was the only output of water from the soil during the dry season. The second most important output was drainage, which represented 36 and 38% of the precipitation during the 2 study years, respectively. Runoff represented less than 2% of the outputs. Few differences could be observed between the 2 study years.

The potential evapotranspiration, calculated by the Thornthwaite (1948) method using the mean monthly temperatures of 1992 (the only available data), was 575 mm—slightly less than the evaporation calculated by using the water balance equation (642 mm on the cultivated plots). However, real evaporation exceeded potential evaporation during the entire wet season, which raises questions about the accuracy of the Thornthwaite method for estimating potential evaporation in the *páramo* climate.

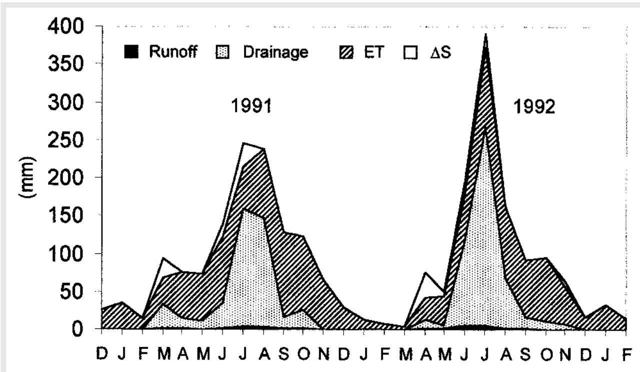
Soil loss

Insignificant soil losses were recorded on all plots. No effects of the previous fallow time or of the fertilization treatment were detected (Table 1). Comparing the cultivated and fallow plots (Figure 4d), it can be observed that soil loss was higher during the first months of the fallow period, corresponding to the beginning of the rainy season. During this period, the plant cover was scarce. After a few months of fallow, however, soil loss decreased below that on the other plots, suggesting that a cover of *Rumex acetosella* is apparently more efficient in preventing soil loss than the restored mature ecosystem. The average cumulative annual soil loss was 0.58 ± 25.8 t/ha/y on the cultivated plots, 0.50 t/ha/y on the 15-year fallow plot, and 0.30 t/ha/y on the 1-year fallow plot. These low values indicate that soil

Period in 1991–1992	Rainfall (%)	Runoff (%)	Drainage (%)	Evapotranspiration (%)
Dry months (Dec, Jan, Feb, Mar)	10.3	8.3	4.3	19.6
Interseasonal periods (Nov, Apr)	15.2	17.5	6.6	20.0
Two rainiest months	45.8	48.0	73.6	23.7
Remainder of the rainy season	28.7	26.2	15.5	36.7

TABLE 2 Percent of rainfall, runoff, drainage and evaporation during different periods of the year for the cultivated plots. The values are the average for the two years of study.

FIGURE 6 Dynamics of the different water flows during the study period for the cultivated plots. ET = evapotranspiration, S = variation in the soil stored water.



loss was insignificant and does not appear to represent a serious problem in these high altitude ecosystems. A simple calculation indicates that 1 cm of soil would be lost in 86 years and the complete plow layer in 1700 years (first 20 cm of the profile). This consideration excludes the simultaneous processes of soil formation by weathering of the parental rock and incorporation of plant residues.

On coffee plantations in the Venezuelan Andes with a slope of 31°, Ataroff and Monasterio (1997) measured soil loss rates that varied between 0.4 and 3.5 t/ha/y, depending on the plantation age and the existence of shade trees. Sanchez and Ataroff (1997) quantified soil losses in areas covered by four types of vegetation in the Venezuelan Andes, at 2250 m, with slopes between 50 and 90%. These authors obtained soil loss rates between 0.30 and 22 t/ha/y, of which the lowest corresponds to the natural forest and the highest was measured on the steepest slope with horticultural crops (potatoes and carrots). All these soil loss rates can be considered low, with the exception of the one for horticultural crops on a very steep slope. Possible reasons for these low rates of soil loss could be related to high infiltration rates, the sandy soil texture, high organic matter content, great stoniness, and the low intensity of the rainfall.

By contrast, Mishra and Ramakrishnan (1983) obtained a total soil loss of 50 t/ha/y for a similar fallow system with a potato crop in India, a value 100 times greater than the value obtained in the Páramo de Gavidia. The main difference between these two agroecosystems is the proportion of water loss by runoff, that is, 30% in the mountains of India and less than 2% in the *páramo*. The large loss by runoff reported by Mishra and Ramakrishnan was probably due to a lower level of soil organic matter (2% compared with 20%), the use of fire for field preparation, and the great intensity of rainfall that characterizes the Himalayan monsoon climate.

Conclusions

The results of this study suggest that the low rates of runoff are the most important aspect of the water balance in these Andean *páramos,* despite the region's steep slopes. This low runoff results in little soil loss, which is of major importance in terms of soil conservation and sustainability. The low runoff can be attributed to the high infiltration capacity of the soil, influenced by its physical characteristics and the low intensity of precipitation. On the cultivated plots, the presence of furrows perpendicular to the slope and surface roughness also facilitate infiltration. Plant cover appears to play a secondary role in controlling runoff, although it is still an important variable, as shown by higher runoff rates measured at the beginning of the fallow period when plant cover was very low.

Evapotranspiration is the main output of water from the agroecosystem. Although the comparative importance of the different kinds of evaporation (transpiration, evaporation of the foliage-intercepted water,

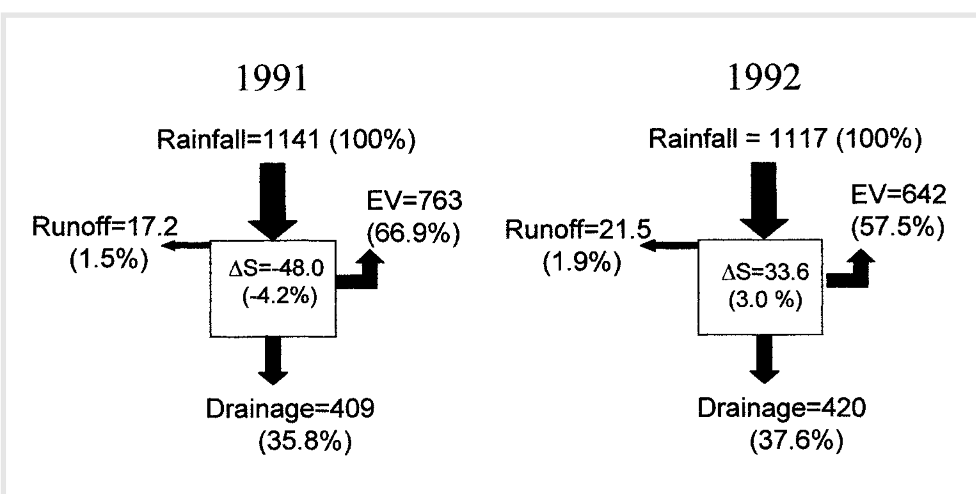


FIGURE 7 Annual water balance for the cultivated plots in 1991 and 1992 (values in mm).

and direct evaporation from the soil) was not directly evaluated, the results suggest that direct soil evaporation is the most important. This high rate of evaporation can be linked to the sandy soil texture as well as the dark color of the soil. Moreover, despite the low mean air temperature, soil temperature at the surface and in the first few centimeters is high for several hours each day, favoring direct evaporation.

Considering that plant cover is lower on the cultivated plots than in the fallow areas during most of the year and that plant cover reduces direct evaporation from the soil, it may be assumed that agricultural use will lead to an increase of evaporation to the detriment of drainage. As a consequence, water availability in the lowlands and regional hydrology will be altered.

The figures for soil loss and runoff obtained in this study are of the same order of magnitude or inferior to those reported for other ecosystems and agroecosystems in the Venezuelan Andes. However, all these studies have been carried out under wet conditions where the soil organic matter content is high. Under drier conditions, such as those prevalent in many interandean valleys, the soils have less organic matter and consequently greater erodibility and lower infiltration capacity. Thus, the conservation of soil organic matter, using organic manure or long fallow periods, may be one of the keys to sustainable Andean agriculture.

In conclusion, the long fallow agriculture practiced in the Venezuelan *páramos* does not increase the rates of soil loss and can be considered a sustainable practice on a local scale. An evaluation of the regional hydrological effects requires further research. However, our results suggest that agriculture favors evaporation and could cause a decrease in drainage, the consequences of which must be evaluated in order to assess the regional sustainability of this high mountain agricultural system.

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