NUTRIENT BALANCE IN WATER HARVESTING SOILS

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ABSTRACT: Dryland farming on Fuerteventura and Lanzarote (Canary Islands, Spain), which has an annual rainfall of less than 150 mm/year, has been based traditionally on water harvesting techniques (known locally as "gavias"). Periods of high productivity alternate with those of very low yield. The systems are sustainable in that they reduce erosive processes, contribute to soil and soil-water conservation and are largely responsible for maintaining the soil's farming potential. In this paper we present the chemical fertility status and nutrient balance of soils in five "gavia" systems. The results are compared with those obtained in adjacent soils where this water harvesting technique is not used. The main crops are wheat, barley, maize, lentils and chick-peas. Since neither organic nor inorganic fertilisers are used, nutrients are derived mainly from sediments carried by runoff water. Nutrients are lost mainly through crop harvesting and harvest residues. The soils where water harvesting is used have lower salt and sodium in the exchange complex, are higher in carbon, nitrogen, copper and zinc and have similar phosphorous and potassium content. It is concluded that the systems improve the soil's natural fertility and also that natural renovation of nutrients occurs thanks to the surface deposits of sediments, which mix with the arable layer. The system helps ensure adequate fertility levels, habitual in arid regions, thus allowing dryland farming to be carried out.

Key words: fertility, water harvesting, nutrient balance

INTRODUCTION

The lack of water in arid and semi-arid regions is considered the main factor limiting crop development. However, an equally -or even more- limiting factor, in the opinion of some authors, is soil nutrient deficiency (Klaij and Vachaud, 1992; Breman et al., 2001; Fox et al., 2005). Diminished nutrient content is considered to be among the chemical processes implicated in soil degradation (Syers, 1997). Continued removal by crops and the non-replacement of elements through organic matter or mineral fertilisers lead to a nutrient imbalance.

Sánchez et al. (1997) calculate that between 1960 and 1990 an average of 22 kg de N, 2.5 kg of P and 15 kg of K were lost per hectare/yr in cultivated land in 37 African countries. In East Africa, micronutrient loss in the arable layer of the soil has been even greater: 40 kg of N, 6.6 kg P and 33.2 kg of K per hectare/yr (Smailing et al. 1997). Mutert (1996) found negative nutrient balances in many crops in Asia. Similarly, other studies conducted in Asia, particularly China, have shown a negative balance for potassium (Sheldrick et al., 2002). These figures give an idea of the extent of the problem and of the progressive depletion of nutrient content in many farming soils worldwide. The problem is now considered one of the leading causes of crop failure and a serious handicap for food production.

Water harvesting (WH) systems are frequently used in arid regions to collect what little runoff water is available and allow at least some dryland farming (FAO, 1991,1994). Systems of this type play an important role in soil and soil-water conservation. Although much has been written on the systems' design and water collection and conservation methods (Reij et al., 1988; Tauer and Humborg, 1992; Ben-Asher and Berliner, 1994; Lovenstein, 1994), literature on the properties -particularly the fertility of the soils- is less common. Nabhan (1984), compares long-cultivated WH soils in the Sonora Desert with similar soils which were not cultivated and found no significant differences, leading to the conclusion that no nutrient reduction was caused by prolonged farming use. Sandor et al. (1986), in a semiarid region of New Mexico, with annual rainfall of 250-400 mm, found that WH soils had less carbon, nitrogen, assimilable phosphorous, total phosphorous and copper than nearby uncultivated soils in which WH was not used. Different results were obtained in Eritrea by Tesfai (2001), who noted that plots receiving runoff had higher content of these elements than soils not receiving runoff. He associated the positive balance seen in the WH soils with contributions from sediments, as had already been noted by Neiemeijer (1998), in the Teras of Sudan.

In the eastern Canary Islands of Lanzarote and Fuerteventura, both of which are extremely arid, a traditional water harvesting system known as "gavias" has allowed cereals and legumes to be grown for decades without chemical or organic fertilisers.

In the present work we present the results of the chemical characterisation of the arable layer of soils in five gavias, together with those from adjacent natural soils not affected by runoff and sediments contributed by a series of floodings. We also evaluate the balance for three micronutrients (N, P, K) in the cultivated soils, which will help us assess the sustainability of the system in terms of soil nutrients (Tesfai, 2001).

MATERIALS AND METHODS

Study area and system description

Lanzarote y Fuerteventura, the location of the systems studied, are the easternmost islands of the Canarian archipelago. Lying between parallels 29º 14’ 21” and 28º 02’ 16” north latitude, they are a mere 115km from the west coast of Africa. The islands are of volcanic origin and have an arid and homogenous climate. Most of the territory receives an average of less than 150 mm rainfall per year and in no parts does the level exceed 300 mm. The rainfall is seasonal, from November to March, with high inter-annual variability. Though the rain tends not to be heavy, in most years maximum values above 10 mm h^{-1} are recorded, which Díaz (2004), notes as the intensity threshold as of which the gavias receive water on both islands. The high amount of sunshine and high temperatures, combined with the strong or moderate winds, make for a very high evaporation rate (in the region of 2000 mm yr^{-1} in an evapometric tank).

The *“gavia”* system can be included in the type of WH known as macrocatchment (Tauer and Humborg, 1992; Lovenstein, 1994), since the catchment area corresponds to variable-sized basins, often with different soil types and different hydrological properties and in all cases outside -and quite far from- the storage zone. The catchment surface - cultivated plot size ratio varies from 8:1 to 50:1. Runoff, which usually flows along a drainage network, is diverted and channelled into the interior of the flat homogenous plots which are of different sizes and surrounded with earthen walls, also of different heights. The water is retained and stored in the soil profile.

The water catchment area, situated on hills with variable slopes, corresponds to hydrographic basis formed by materials and soils of low farming potential. The low infiltration velocity, the formation of sealing crusts and the presence of lime crust, combined with the scattered brush vegetation, all contribute to run-off generation and the intake of water by the gavias, even at rainfall intensities not usually considered as being erosive. The drainage network is dry year-round, except immediately after rainfall.

The cultivated plots are located in flat or unsteep parts, usually in foothills, and are oriented perpendicular to the catchment area. They usually lie alongside or near to small waterways. Where necessary, stones were removed from the land and this was levelled to ensure homogenous flooding. Plot sized varied greatly, from 600-10,000 m^2. The soils most commonly used in the system are Torrifluvents, Paleargids, Calciargids, Natrargids, Haplocalcids and Petrocalcid (Soil Survey Staff, 1999).

Laboratory experiments

In order to compare the fertility of the gavia soils with that of the adjacent natural soils, 16 samples -eight from the soils cultivated using the gavia system, eight in the natural soils- were taken at random from the arable layer (top 25 cm) in each of the five selected zones. For each sample the following were calculated: pH and electrical conductivity in saturated extract, exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), carbonates, organic matter, total nitrogen, assimilable phosphorous and micronutrients (Fe, Mn, Cu, Zn, B).

A Principle Components Analysis was carried out to study the sample ordination and distribution with respect to the variables, using the CANOCO Programme, version 4 (ter Braak and Smilauer, 1998).

The treatment response depended on the study site and hence it was not possible to apply a global statistical model for all five systems. Instead, statistical analysis was carried out for each separately, and the values of the different variables for the gavia and natural soils were compared. For variables fitting a normal distribution (Kolmogorov-Smirnov test), a T test for independent samples was used. For variables not presenting a normal distribution, the Mann-Whitney non-parametric U-test was used (Zar, 1984). In both cases, SPSS for Windows, version 10.0.6 (SPSS Inc., 1999) was used. Differences were considered statistically significant at $p < 0.05$.

Sediment samples were taken in all five gavias after they were filled with water. For this purpose the gavia soils were covered, prior to periods of rainfall, with permeable cloth meshes to allow water through, but not the sediments. The sediment samples were tested for the same parameters as the soils.

Finally, the nutrient balance was estimated. Like other authors, Janssen et al. (1990), consider that crop growth in many non-fertilised soils is constrained by the low content of one or several of the micronutrients N, P and K, even when relatively large amounts of secondary nutrients and trace elements are present. For this reason we concentrated on these three elements in our balance estimation.

RESULTS AND DISCUSSION

Figure 1 shows the sample ordination for the parameters analysed. The gavia soils are indicated by circles and the adjacent natural soils by triangles. The percentage of variance, explained with two components, is 91.9 %, a rather high figure indicating that the conclusions derived from the 2-dimensional figure are representative of the true sample ordination.

The gavia soils form a clearly-defined group, notwithstanding any differences that might be due to geographical or edaphic dissimilarities. Conversely, the soils outside the gavias are extremely heterogeneous. The marked homogeneity of the gavia soils is likely due to the transportation or material, either colloidal or in solution, from the entire catchment basin.

The gradient for electrical conductivity, exchangeable sodium and boron increases towards the samples from the non-gavia soils, indicating the effect of salt leaching caused by flooding of the cultivated plots. Conversely, magnesium, exchangeable calcium, zinc and copper content are higher in the gavia soils, as are the pH values.

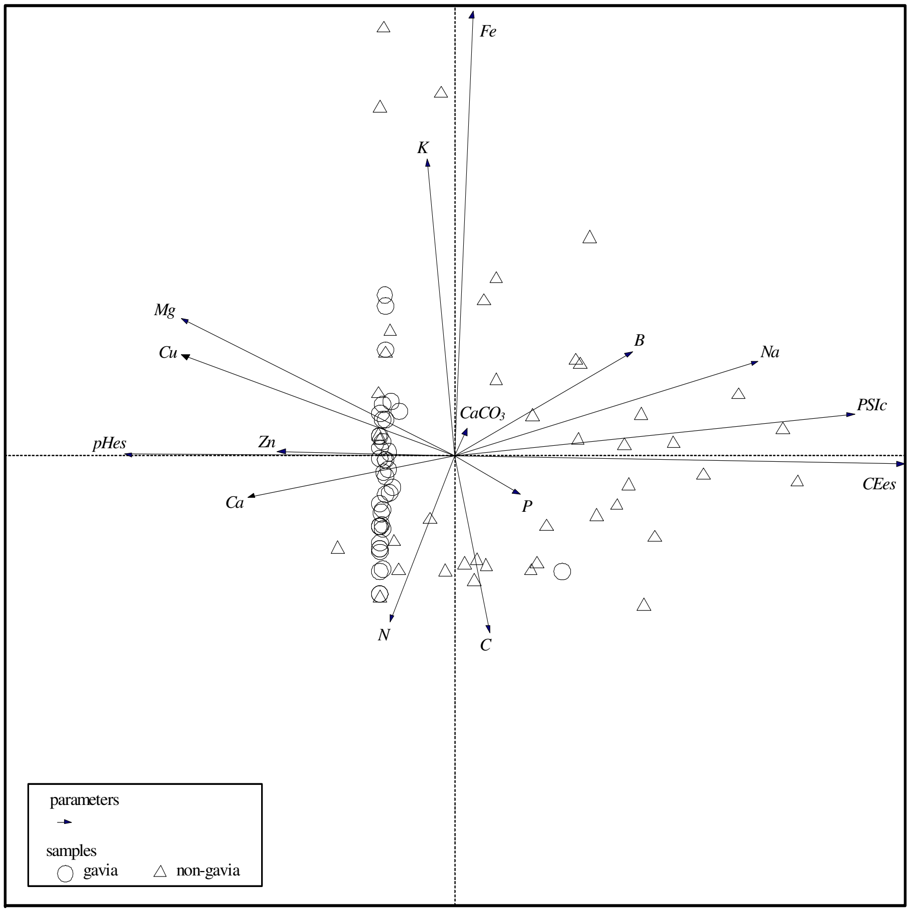

Figure 1. Soil sample ordination using PCA
Value of axis I and II, 0.857 and 0.062 respectively

We then analysed separately the results obtained for three micronutrients (N, P, K):

Total nitrogen.- Total nitrogen levels were always slightly higher in the gavia soils, although in most cases the differences were not statistically significant (figure 2). In both the gavias and the natural soils, the levels were found to be low, under 0.1% (Metson, 1961), although these figures are quite normal for an extremely arid territory with sparse vegetation and very low biomass production. The results obtained for organic carbon were similar.

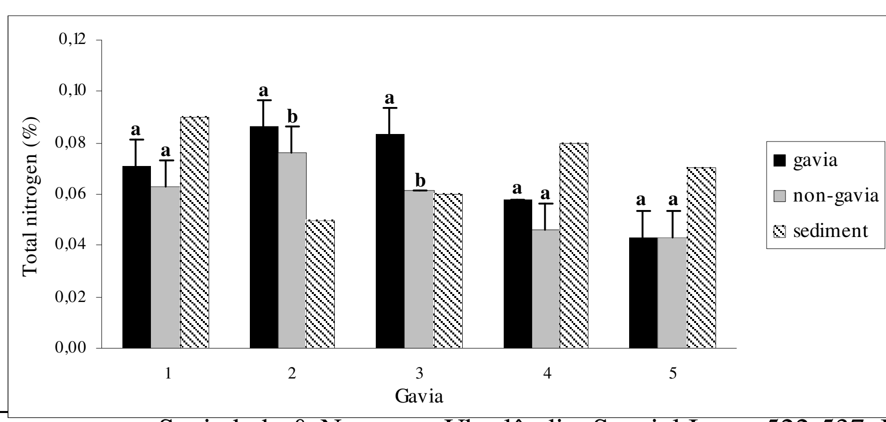

Figure 2. Total nitrogen content
Two different letters above columns indicate significant differences ($p < 0.05$). Error bars represent the standard deviation.

The slightly higher nitrogen content seen in the gavia soils may be due to the presence of plant residues and organic remains from livestock, deposited by the runoff from the catchment area. In most of the gavias, the nitrogen levels in the sediments (figure 2) were higher than in the soils. The values translate to deposits of between 80 and 164 kg of nitrogen, per hectare and per cm of deposited sediment. These quantities enable slightly higher levels of nitrogen to be maintained within the system, despite the uptake from the crops. The limited crop residue remaining on the ground –most is used as livestock feed- and the larger amount of weeds growing in the gavias after rainfall may also be contributing factors.

These findings match those of Halldorf (1994), Niemeijer (1998) and Tesfai (2001), who studied similar systems in other parts of the world, although the differences they noted were greater that those we obtained in our study, due largely to the fact that their sediments were also richer in nitrogen. The findings are at odds, however, with Sandor et al. (1986), who found lower nitrogen content in soils affected by runoff, although this is probably because the soils studied had been abandoned and had not been operational for decades.

Olsen phosphorous.- Although average phosphorous content was slightly higher in the gavia soils than in the natural ones (13.3 compared to 11.9 mg kg^{-1}), there was no common pattern: in some cases the content was higher in the gavias; in others the reverse was true, and in others still levels were the same (Figure 3).

Using as a reference the Olsen phosphorous levels established by Landon (1991) for crops with a low phosphorous requirement, such as maize or cereals, -the crops most commonly grown in the studied systems- gavias 1, 2 and 4 had adequate levels (> 8 ppm), while the levels in 3 and 5 were low (< 8 ppm). Thus, no conclusions can be drawn, except that phosphorous content was between normal and low in most cases, apart from one soil - gavia 2- where levels were higher. Sediment analysis shows the influence of the sediments in the case of this gavia: whereas the sediments deposited in the other gavias had Olsen phosphorous levels of 10 to14 mg kg^{-1}, those in gavia 2 contained 38 mg kg^{-1}.

Niemeijer (1998) and Tesfai (2001), both found higher phosphorous concentrations inside WH systems than outside (3.3 and 1.6 times higher, respectively), while Sandor et al. (1986) found between 15 and 18 % less.

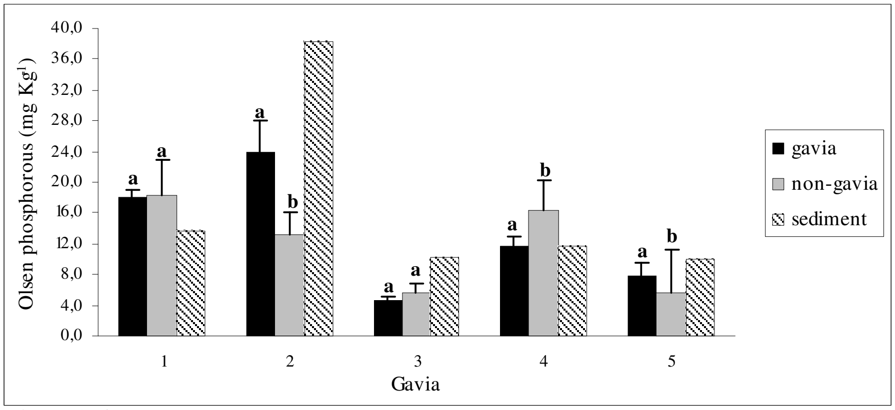

Figure 3. Olsen phosphorous content
Two different letters above columns indicate significant differences ($p < 0.05$). Error bars represent the standard deviation.

Potassium.-Potassium content was, on average, slightly lower in the five gavia soils than in the adjacent ones (2.8 compared to 3.1 $cmol_c\ kg^{-1}$). As with the phosphorous, no common pattern was evident (figure 4). Taking into account MAFF limits (1967), the levels can be considered high both inside and outside the system, since they exceeded 0.6 $cmol_c\ kg^{-1}$. Average content in sediments was the same as in the gavia soils (2.8 $cmol_c\ kg^{-1}$).

From the above data we can conclude that the gavia soils are rich in potassium and deficiencies are therefore unlikely to occur.

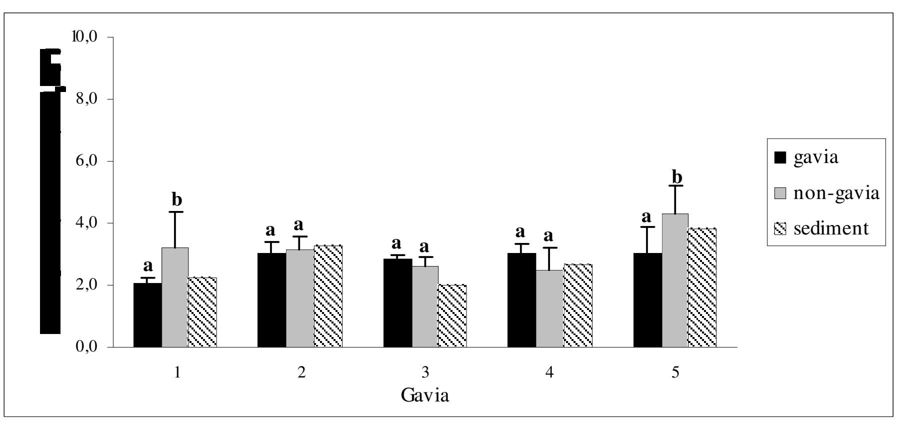

Figure 4. Exchangeable potassium content
Two different letters above columns indicate significant differences ($p < 0.05$). Error bars represent the standard deviation.

Nutrient balance

The nutrient balance is defined as the difference between the amount of nutrients deposited in the soil and the amount extracted or removed from the arable layer (Tesfai, 2001). A positive balance indicates accumulation of nutrients, whereas a negative balance reflects progressive nutrient loss. Reuler and Prins (1993) note that sustainable development requires the nutrient balance to be close to neutral..

Nutrient input can be from various sources, among them organic or inorganic fertilisers, dustfall, biological nitrogen fixation or from sediments transported in runoff water. Nutrient loss can be due to uptake by crops or crop residues, leaching, loss in gaseous form or erosion (van der Pol, 1992; Smaling et al., 1997).

In the case of the gavias, no organic or inorganic fertilisers are used, while the crop residues are used as livestock feed. Hence the sediments transported by runoff waters are the main source of nutrients, followed probably by dustfall. Biological nitrogen fixation might occur during the years in which legumes are grown but as this is not common and is difficult to quantify it was decided not to include the source in the balance.

Removal of nutrients from the system is mainly due to crop (or crop residue) uptake. Losses through leaching of the root zone are considered to be negligible and will not be taken into account therefore (Tesfai, 2001). Losses in gaseous form account for an estimated 25% of total nitrogen (van der Pool, 1992). Regarding loss through erosion, Torres (1995), states that erosion does not occur in maintained gavias and hence these processes are also omitted from the balance.

The nutrient balance for each of the elements is thus calculated as follows:

$$\text{Nutrient balance (kg ha}^{-1}\text{ yr}^{-1}\text{)} = (S+D) - (C+R+V)$$

where S represents nutrients deposited by the sediments, D the input from dustfall, C and R the uptake by the crops and crop residues respectively and V the loss in gaseous form (volatilization).

INPUT

* From sediments

Table 1 gives, for the sediment samples in each of the five gavias studied, the bulk density (ρ) and average thickness of the layer during the year 2000, as well also total N, P and K content.

Sediment	**ρ g cm^{-3}**	**Thickness mm**	**Total analysis (g kg^{-1})**		
			N	**P**	**K**
1	1.9	3	0.90	1.32	14.11
2	1.7	4	0.50	1.19	16.93
3	1.8	6	0.60	1.19	18.26
4	1.6	4	0.80	0.79	21.91
5	1.6	4	0.70	0.44	21.33

Table 1. Sediment Analysis

Nutrient deposition by sediments is usually expressed in kg ha^{-1} yr^{-1} and is calculated as follows:

$$\text{Deposit (kg ha}^{-1}\text{ yr}^{-1}) = (\rho * NC * T) * 0.01$$

where ρ is the bulk density of the deposited sediments in kg m^{-3}, NC the nutrient content in mg kg^{-1}, T is the thickness of the sediment layer expressed in m yr^{-1} and 0.01 is the conversion factor for hectares. Table 2 gives the results for the three elements.

Sediment	**N**	**P**	**K**
	kg ha^{-1} yr^{-1}		
1	51.3	75.2	804.3
2	34.0	80.8	1151.4
3	64.8	128.3	1972.1
4	51.2	50.7	1402.4
5	44.8	28.2	1365.2

Table 2. Sediment deposits of N, P and K

* From dustfall

Nutrient deposits from dustfall were calculated using the equation developed by Stoorvogel and Smaling (1990).

$$\text{Total N deposit} = 0.14 * (\text{Precipitation})^{1/2}$$

$$P_2O_5 \text{ deposit} = 0.053 * (\text{Precipitation})^{1/2}$$

$$K_2O \text{ deposit} = 0.11 * (\text{Precipitation})^{1/2}$$

Bearing in mind that average precipitation is 130 mm yr^{-1}, the deposits are thus 1.60 kg of N, 0.27 kg of P and 1.04 kg of K per hectare per year.

UPTAKE AND LOSS

* By crops

The main crops cultivated in the gavias are wheat, barley, maize, lentils and chickpeas. As stated above, due to the difficulty in calculating the biological nitrogen fixation, legumes are omitted from the balance. Of the remaining crops, wheat is probably the most important and was therefore chosen as the basis for the nutrient balance.

Components	**N**	**P_2O_5**	**K_2O**
	Kg of nutrient per ton of grain production		
Grain	20	10	5
Stems and leaves hojas	8	3	15
TOTAL	28	13	20

Table 3. Nutrient uptake by wheat crop

Table 3 gives the average nutrient uptake by wheat, expressed in kg of nutrients per ton of grain production, in accordance with Domínguez Vivancos (1997).

According to data from the Ministry of Agriculture, Fisheries and Food (1988), average wheat yield in gavias is between 700-1200 kg ha^{-1}. Taking a maximum crop of 1200 kg ha^{-1}, the annual nutrient uptake would be as follows (Table 4):

Components	**N**	**P**	**K**
	Kg ha^{-1} yr^{-1}		
Grain	24.0	5.3	5.0
Stems and leaves hojas	9.6	1.6	14.9
TOTAL	33.6	6.9	19.9

Table 4. Nutrient uptake in a wheat crop of 1200 kg ha^{-1}

* Gaseous loss

According to van der Pool (1992) and Niemeijer (1998), gaseous N loss accounts for an estimated 25% of total nitrogen. Nitrogen lost through denitrification or volatilisation for each of the sediments would therefore be as follows (Table 5).

Sediment	**N (kg ha^{-1} yr^{-1})**
1	13.2
2	8.9
3	16.6
4	13.2
5	11.6

Table 5. Gaseous nitrogen loss

Taking into account all the above nutrient gains and losses, the balance for the year is as follows (Table 6):

Gavia	Input (kg ha^{-1} yr^{-1})			Uptake and Loss (kg ha^{-1} yr^{-1})			**Balance (kg ha^{-1} yr^{-1})**		
	N	P	K	N	P	K	**N**	**P**	**K**
1	52.9	75.5	805.3	46.8	6.9	19.9	**+6.1**	**+68.7**	**+785.4**
2	35.6	81,1	1152,4	42.5	6.9	19.9	**-6.9**	**+74.2**	**+1132.5**
3	66.4	128.6	1973.1	50.2	6.9	19.9	**+16.2**	**+121.7**	**+1953.2**
4	52.8	51.0	1403.4	46.8	6.9	19.9	**+6.0**	**+44.1**	**+1383.5**
5	46.4	28,4	1366.2	45.2	6.9	19.9	**+1.2**	**+21.6**	**+1346.3**

Table 6. Nutrient balance

The nutrient balance is positive for each gavia and for all three micronutrients, with the exception of the nitrogen balance in gavia 2, which is negative. This suggests that, overall, there is no progressive depletion of nutrients, since crop uptake is compensated for by deposits carried by the sediments.

In gavia 2, the system presenting a negative nitrogen balance, the soil nitrogen content is gradually falling and additional amounts must therefore be provided to compensate for the losses. The other nitrogen balances are positive, albeit close to neutral. Hence, during years in which the sediment layer is thinner the balance will probably become negative. Legumes are therefore important because of their capacity to produce biological nitrogen fixation, thus compensating for the depletion occurring during these years.

CONCLUSIONS

Sediments deposited by runoff water in the gavia system contain sufficient nutrients to prevent a progressive reduction of the nutrient content to below natural levels. This circumstance, in tandem with the fact that the gavias have been cultivated for years without any inorganic or organic fertilisers, leads us to believe that these soils maintain a nutrient balance, unlike other tropical farming systems (Stoorvogel and Smaling, 1990; van der Pol, 1992).

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Although soil nutrient balance is often used to assess the sustainability of a productive system (Tesfai, 2001), it is important to remember that the balance merely indicates tendencies regarding the impoverishment or enrichment of certain elements, which do not in themselves indicate whether the nutrients available for plants are adequate. Hence, such results need to be considered in conjunction with soil nutrient levels (Syers et al., 2002).

From the comparative analysis of the gavia soils and the uncultivated adjacent soils, it may be concluded that the former are more fertile, particularly because they are less affected by salinity and sodicity, which are two crucial factors. In terms of other parameters, although in some cases no statistically significant differences were observed, there was a clear tendency for levels of carbon, nitrogen and certain micronutrients (Cu and Zn) to be higher in the gavia soils. This indicates that in these soils, which have been cultivated for decades, certain elements are replaced naturally, a process rendered possible by the nutrient deposits of the sediments transported in the runoff. The deposits enable fertility levels to remain reasonably high, a similar situation to that described by Tesfai (2001) for the Sheeb area of Eritrea. Nonetheless, bearing in mind the most frequently-used references, levels of organic matter, nitrogen, iron and phosphorous are insufficient for crop requirements and an additional input of these elements might be necessary.

Although the results of the nutrient balance match the tendencies observed, considerable caution must be exercised when interpreting the findings not only because of the number of assumptions made but also for two further reasons. Firstly, the regression analyses often used -for example, to calculate dustfall contamination- are designed for continental scale models and, secondly, deposited nutrients are in some cases not immediately available to plants as they are in solid form (Tesfai, 2001).

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