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Spatial variability of soil pH and phosphorus in relation to soil run-off following slash-and-burn land clearing in Sumatra, Indonesia

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Abstract

Slash-and-burn land clearing on sloping land may lead to increased soil run-off following disappearance of the protective vegetative cover. In turn, soil run-off and redeposition affects soil fertility and spatial patterns of fertility parameters in a field. This study seeks to clarify the role of spatial patterns of post-burn dead biomass (necromass) in soil run-off and redeposition and their combined effect on spatial patterns in soil pH and resin-extractable P. The study is carried out on a post-productive rubber (*Hevea brasiliensis*) agroforest in Sumatra, Indonesia. Soils are classified as Dystric Fluvisols. After slash-and-burn of vegetation, the field was planted with rubber seedlings and rice (*Oryza sativa*). For comparison the adjacent rubber agroforest site was sampled. Soil run-off is expressed here as the quantity of downward moving soil that passed the specific location of a flow trap. Existing physical soil run-off barriers and crop performance were scored. Despite serious soil run-off from the steeper upper slopes little soil was actually lost because of the slope form of the field, presence of natural soil run-off barriers, and the planted crop. Spatial variability of soil pH decreased at the expense of small-scale, within-strata, variability mainly because of the patchy distribution of soil run-off barriers. Soil run-off, aggravated by slash-and-burn, did not result in development of a clear soil fertility gradient down slope. In areas of high soil run-off potential, clear burns should be avoided because soil run-off barriers like remnants of slash-and-burn and surface litter maintain the soil and its fertility.

Keywords: Soil run-off; Slash-and-burn; Spatial variability; Soil pH; Resin-extractable P; Small-scale agriculture; Rubber plantation; Indonesia

1. Introduction

Slash-and-burn is a commonly used land clearing method at Sumatra, Indonesia (Van Noordwijk et al., 1998a). Slashing of secondary forest and post-productive agroforests or plantations, is followed by a primary broadcast burn. The remaining fuel is piled and set on fire a second time (secondary pile-burn). In farmers' perception this practice has clear benefits: it consumes slashed vegetation, increases field accessibility, provides a fertilizing layer of ash, improves soil structure and reduces weed tree competition as well as occurrence of pests and diseases (Ketterings et al., 1999). In contrast, fire

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is often responsible for large nutrient losses due to particulate movement off the field and volatilization during the fire (Juo and Mann, 1996; Kleinman et al., 1996). Also, nutrients may be lost by soil run-off, which is the process of downward moving of soil caused by water flow and gravity forces. Soil run-off is enhanced by disappearance of vegetative cover and surface litter following the burn (Alegre and Cassel, 1996; Young, 1997). Surface litter is an important soil run-off controller (Lal, 1990; DeBano et al., 1998; Kiepe and Rao, 1994; Young, 1997). It protects soil from the soil run-off initiating splash-effect (inter-rill run-off), caused by the impact of rain (Lal, 1990).

Soil run-off and sedimentation processes at field and landscape scale can cause a net soil loss and can also affect spatial variability of soil fertility within a field or landscape (Van Noordwijk et al., 1998b). Soil run-off is most severe on sloping lands and occurs mainly in the first year after burning, particularly if slash-and-burn is followed by high-intensity rainfall (DeBano et al., 1998). Therefore, slash-and-burn may thus increase spatial variability of soil fertility. It was shown that slash-and-burn increased spatial dependence of soil fertility indicators but decreased their ranges of influence (Ketterings and Bigham, 2000). This increase results from the patchy character of the burn. Effects of soil run-off and sedimentation may occur superimposed on ash patterns.

Studies on effects of soil run-off, following slash-and-burn, on spatial patterns of soil properties are limited. Information on these effects can support decision making at the soil tillage and crop management level. Known spatial variability within a farmer's field may be an advantage as a risk reducer (Brouwer et al., 1993). If, for example, slash-and-burn results in a clear soil fertility gradient, the farmer may adjust its crop choice, or alter fertilizer input strategy. Also, a study on the effects of slash-and-burn on sloping land may highlight the risk of severe and irreversible environmental degradation.

This study focuses on soil run-off patterns following slash-and-burn on a sloping field. Soil run-off is expressed here as the quantity of soil that moved downwards, passing, and being caught at, the specific location of an flow trap. The objective is to quantify the effect of spatial patterns of post-burn necromass on soil run-off and the effect of soil run-off following slash-and-burn on spatial patterns of soil pH ($CaCl_2$) and resin-extractable P. Field studies were conducted in Jambi province, Sumatra, where slash-and-burn of post-productive agroforests or secondary forests is often practiced on sloping hillsides.

2. Materials and methods

2.1. Study site

The study was conducted in the piedmont (foothill) zone of Rantau Pandan (101°50′–101°56′E and 1°36′–1°41′S) in Jambi province, Sumatra. This location was selected by the International Center for Research in Agroforestry Southeast Asia (ICRAF-SEA) as representative of the Piedmont Ecological Zone in the Buffer Zone of Kerinci Seblat National Park. The wet west monsoon affects the entire region between November and March. Mean annual rainfall, averaged over the last 10 years, is 2982 mm (Rachman et al., 1997).

A 1 ha convex–concave sloping field with slopes varying from 0 to 69% and having a high potential soil run-off risk was selected for this study. The first field, here called the SB-field, is a post-productive rubber agroforest, slashed-and-burned by the farmer in July 1998 to renew the plantation with rubber trees. The slash-burn resulted in a spatial pattern of felled trees, dead wood and branches, as well as unburned necromass and charcoal. Most of the trees had been felled with the crown falling downhill. One year old rubber trees were planted all over the field at a density of 350–400 trees/ha. In 61% of the field, rice was planted between the young rubber, at a density of 7–8 plant pockets/m^2, whereas 39% contained young (<1 year) rubber plants and necromass. As a comparison, a 0.7 ha neighboring field covered with a mixture of forest and plantation tree species (F-field) was studied. This is an abandoned mixed rubber agroforest, approximately 20 years of age, and is dominated by *Mimosa* spp. *Melastoma affine*, *Chromolaena odorata*, *Hevea brasiliensis* and *Cinnamomum burmanii*. Prior to slash-and-burn, the SB-field had the same vegetative composition as the F-field. Both fields are bordered by a small river on the lower side and secondary to primary forest on the upper side of the hill. Slopes in this valley have Oxic, Typic and Lithic Dystropept (or a fine-grained mosaic of them) soils, while valley-bottom soils are classified as Typic Tropofluvents (Rachman et al., 1997). Soil organic carbon in the two study fields in the upper 5 cm was 25.9 g kg^{-1} (SB-field, after the burns) and 32.8 g kg^{-1} (F-field). Field measurements were done between the beginning of October 1998 (90 days after the burn and 75 days after planting of the first rice) and the end of January 1999 (200 days after the burn). Rainfall during the soil run-off measurement period ranged from 0 to almost 90 mm per day. Cumulative rainfall over this period was 391 mm.

2.2. Stratification and mapping

For mapping purposes, the two fields were divided into a grid with each cell of the grid being 100 m^2. The SB-field was divided by 121 grid nodes into 100 cells, the F-field by 88 grid nodes into 70 cells. Both fields were divided into three strata: low (SB_L and F_L) and medium (SB_M and F_M), each containing three rows of cells, and high (SB_H and F_H), containing four rows of cells. The L strata covers the first 30 m, M strata the second 30 m and H strata the part from 60 to 100 m. At the grid nodes of the SB-field altitude was measured relative to a fixed zero-point at the river (Fig. 1). Both fields have a convex–concave slope becoming steeper with increasing elevation (mean slopes are equal to: 16.5% for SB_L, 35.3 for SB_M and 67.0% for SB_H, and 11.2% for F_L, 53.2 for F_M and 68.6% for F_H, respectively).

2.3. Soil run-off measurements

Soil run-off was measured with flow traps made of PVC pipes with a depth of 30 cm and a diameter of 11.4 cm, corresponding to a catchment area of 102 cm^2. Pipes were inserted into the soil with the upper part aligned as accurately as possible with the soil surface (Fig. 2). Traps were regularly checked and re-aligned with the soil surface after each rain shower by pressing them deeper into the soil whenever necessary. Each pipe contained a sac of cheesecloth to catch soil run-off (particles >2 μm) and drain rainwater. The SB-field contained six transects, laid out in a fan shape, with flow traps at 15 locations in a zigzag pattern along each transect. The F-field contained three transects, each with 10 flow traps at 10 equidistant locations (10 m) along the slope. In the *x*-direction, traps were installed closer to each other at higher positions, following slope form (Fig. 3). The number of traps was lower in the F-field, because previous soil run-off measurements in this field indicated less

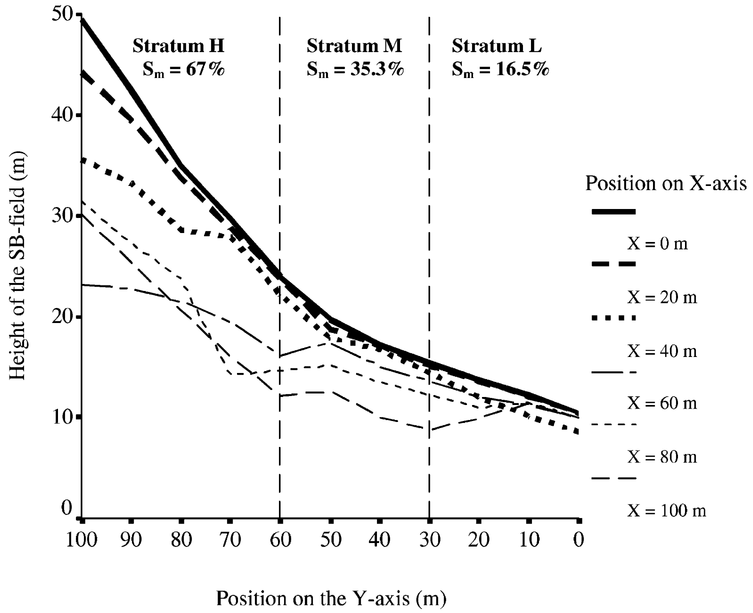

Fig. 1. Side views of the SB-field showing the form of the slope at six positions along the *x*-axis between $x = 0$ and 100 m.

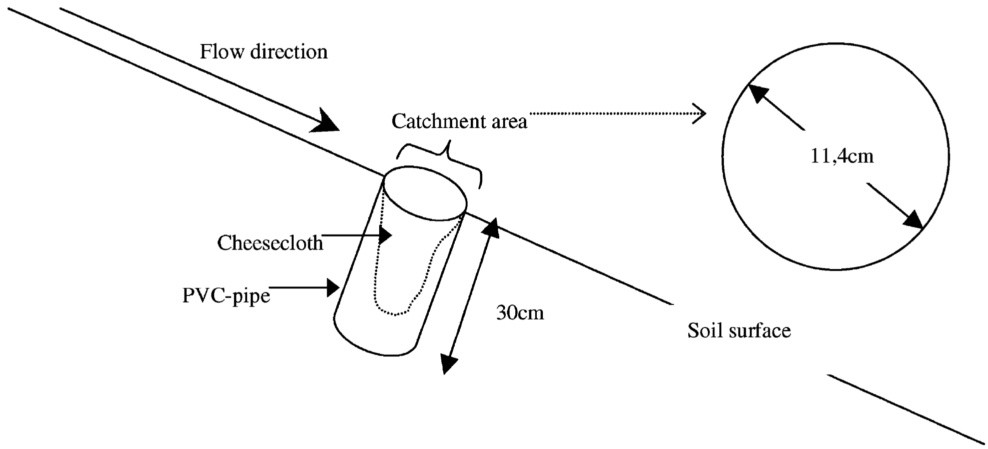

Fig. 2. Schematic presentation of a flow trap measuring soil run-off, its catchment area and its position in the ground.

soil run-off (38 kg ha^{-1}) as compared to the SB-field (3560 kg ha^{-1}).

Each flow trap received scores for four roughness indicators: (a) vegetative cover (*V*); (b) dead wood (*W*); (c) surface litter (*L*); (d) depressions (*D*) located in the up-slope direction from the trap. Variables *V*, *W* and *L* were scored at two positions: between 0 and 1 m from a trap, yielding V_1, W_1 and L_1 and between 1 and 10 m from a trap, yielding V_{10}, W_{10} and L_{10}. Depressions, e.g. presence or absence of local spots with higher sedimentation potential, were scored between 0 and 10 m up-slope from each trap (D_{10}). Possible scores were 1 (absence of roughness elements), 0.5 (intermediate presence of roughness elements) and 0 (abundant presence of roughness elements). Scoring was done by one person to maintain consistency. In addition, slope percentage was measured at three locations up-slope from each trap: within the 1 m area (0–1 m) and twice within the 10 m where run-off was to be expected (at 2.5 and 7.5 m).

Trapped run-off soil was collected and dried after 24 rain events, including four major events exceeding 40 mm. Run-off soil in the SB-field was collected three times because it was severe and flow traps had a limited capacity. Collected run-off soil passed through a 1 mm sieve to separate coarse litter from soil and weighed for each trap individually. For chemical analyses, 12 composites of run-off soil from the SB-field and two from the F-field were made based on position of the flow trap on the slope.

2.4. Soil sampling scheme

The SB-field soil under rice was sampled to clarify slash-and-burn, soil run-off, soil fertility and crop production relationships. Rice was planted between young rubber trees, in 61 out of 100 cells: 19 in SB_L, 24 in SB_M and 18 in SB_H. Within 23 of those plots, selected at random, 55 soil sampling locations were positioned. The number of sampling locations per cell (4, 2 or 1) was also chosen at random. In the F-field 48 cells were sampled, 16 per stratum equally divided over two rows of cells (eight cells per row). Four cells were sampled in each row: one at four locations, one at two locations and two cells at one location. Such a scheme ensures that the field is equally covered with observations and that soil samples are clustered to obtain a reliable variogram estimator for small distances. Soil was sampled twice: at t_1 between 8 and 11 October 1998 (100 days after burn, 85 days after first rice planting date) and at t_2 between 26 and 27 November 1998 (150 days after burn, 135 days after first rice planting date), next to the first position. This allowed us to compare changes in soil fertility in time within each field. Samples were obtained from the upper 5 cm of soil without removing any present surface ash.

2.5. Soil chemical analyses

Soil from soil sampling and soil run-off measurements was passed through a 1 mm sieve and air-dried

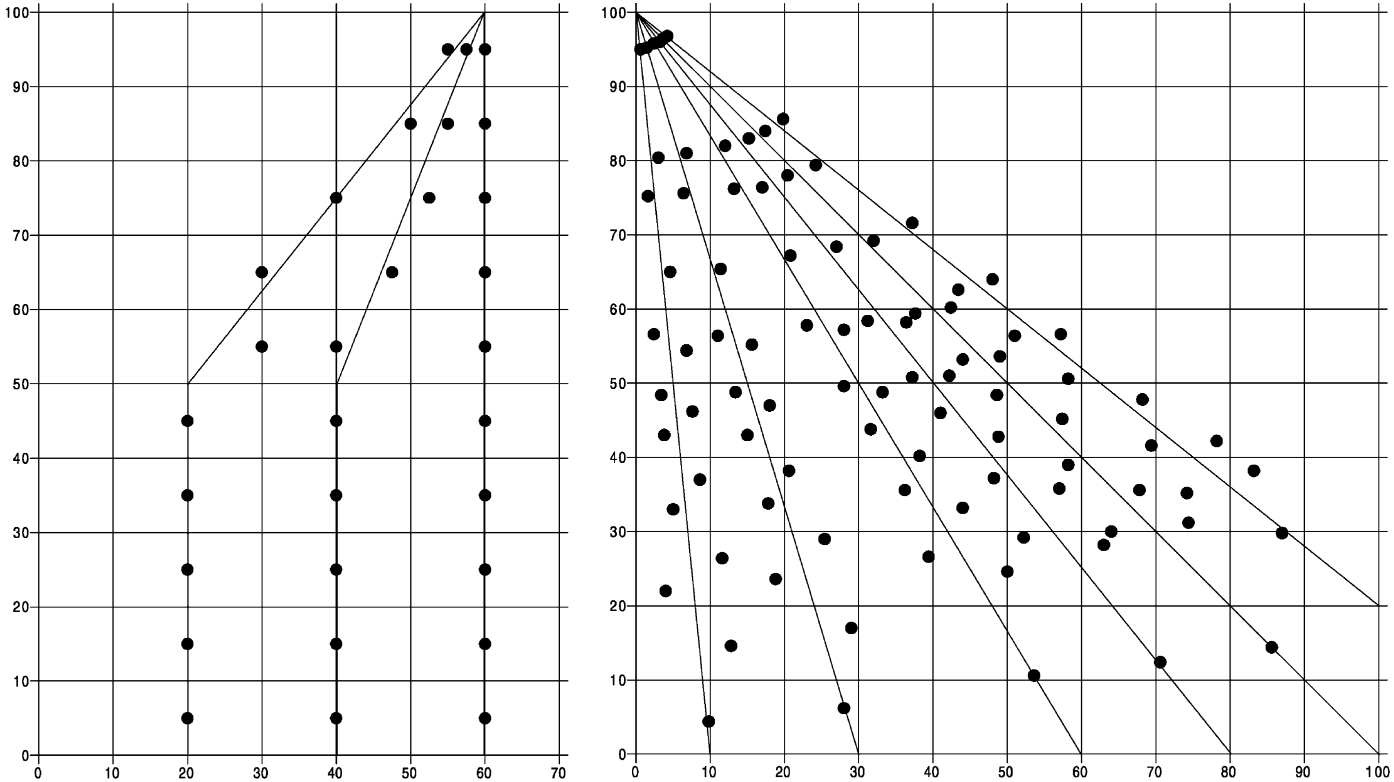

Fig. 3. Trap-scheme for soil run-off measurements in the F-field (left) and the SB-field (right).

before chemical analyses. Samples were analyzed for pH ($CaCl_2$), resin-extractable P (soil samples) denoted by P_{resin}, and for Bray-1 extractable P (run-off soil), denoted by P_{Bray}. Soil pH was determined in a suspension of 20 g air-dried soil in five times its volume of 0.01 M $CaCl_2$ after shaking with a mechanical shaker for 5 min. For P_{resin}, resin strips of 1 cm^2 were shaken with 4 g soil in distilled water with a mechanical shaker for 17 h. P was extracted from the strips in a 50 ml 0.5 M HCl solution that was shaken for 30 min. Colorimetric estimates of P were determined using the Murphy–Riley solution (containing boric acid). Extractable P of soil from run-off measurements was determined following the Bray-1 method (Bray and Kurtz, 1945).

2.6. Crop performance

Rice was planted in the first month after the burn at four different times between 15 July and 16 August 1998. For scoring of rice crop performance, the area planted with rice in the SB-field was divided into units of 1 m^2. Each unit received two scores, ranging from 1 to 5, for crop density and stand. The density-score was based on number of plants per square meter. The stand-score was based on height, a visual assessment of health and presence of ears at that particular growth stage. Good crop performance corresponds to a high score. The final score of each rice unit, ranging from 2 to 10, equals the sum of the two scores. To compare rice at different planting times, visual crop scoring was done at similar growth stages. Consequently, the second scoring was done one month after the first scoring. To reduce the number of units to score the cropped area was divided into three 20–30 m wide strips. One person did all the scoring. Destructive crop sampling of above ground biomass of rice was done 113 days after planting. Dry weight data (kg ha^{-1}) of none crop samples (three crop units with a score of 4 (2 + 2), three with score 6 (3 + 3) and three with score 10 (5 + 5)), were used to calibrate crop performance.

2.7. Statistics and geostatistics

A stepwise multiple linear regression analysis was carried out, with logarithm of soil run-off dry weight data (g per trap) as the response variable and surface roughness scores and slope percentage of the field as explanatory variables to assess local effects of surface roughness and slope upstream of a flow trap. A second linear regression analysis was done taking the logarithm soil run-off dry weight data (g per trap) as dependent variable and rice crop dry weight (CDW) production (t ha^{-1}) as an explanatory variable.

Geostatistical analyses in this study involved three steps. For each variable y in the two fields a geostatistical analysis was done by estimating the variogram $\gamma(h) = (1/2)E(y(x) - y(x+h))^2$, where x is the sampling location, h the distance to another sampling location and the expectation is taken over the whole field. It included calculation of empirical variogram values and determination of the best fitting model $\hat{\gamma}(h) = c_0 + c_1 f(b)$ as judged by the mean squared error, where $f(b)$ is any permissible variogram function, c_0 the nugget variance, c_1 the sill value and b the range (Chilès and Delfiner, 1999). Variograms were used in geostatistical interpolation (kriging), followed by display of predicted values as a map. Throughout the study we assume isotropy of the variability structure.

The number of samples was too small to assess variability of each stratum in each field separately. As an alternative, a so-called within-strata variogram was made, using only pairs of points within the same stratum (Voltz and Webster, 1990). Such variograms are defined as $\gamma_S(h) = (1/2)E(y(x) - y(x + h))^2$, where expectation is taken within-strata. It includes determination of the best fitting model $\hat{\gamma}_S(h) = c_{0,S} + c_{1,S} f(b_S)$ with stratum specific nugget values ($c_{0,S}$), sill values ($c_{1,S}$) and ranges (b_S). To reveal existence of differences in spatial variability within- and between-strata, ratios r were calculated

$$r = \frac{c_0/c_1}{c_{0,S}/c_{1,S}} \quad (1)$$

If $r < 1$, i.e. $c_0/c_1 < c_{0,S}/c_{1,S}$, and hence the nugget/sill ratio for the whole field is smaller than the nugget/sill ratio within-strata, the spatially structured part of the within-strata variation is smaller than that of the whole field. Taking the nugget/sill ratio as a measure for the spatially structured part of spatial variation, we noticed that the r ratio serves to compare within-strata spatially structured variability with the spatially structured variability in the field as a whole.

Soil run-off processes are dynamic and are likely to redistribute soil fertility parameters. As a consequence, an increase in whole field spatial variability of soil fertility in time was expected in the SB-field compared to the F-field caused by an increase in between-strata variability. For that reason, ratios (r) of t_1 to t_2 were compared. A decrease in r over time would imply an increase in the contribution of between-strata variability to whole field variability, thus confirming the correctness of this assumption. Other direct comparison in this study is replaced by a more qualitative approach.

3. Results and discussion

3.1. Soil run-off and surface roughness

Table 1 shows mean weights of trapped soil run-off (g per trap) and mean pH ($CaCl_2$) and P_{Bray} values, as affected by position on the slope. A weighted mean is included, being the average amount of soil run-off, calculated over all traps. Soil run-off in the SB-field peaks in the middle part of the slope. The soil run-off map of the SB-field superimposed on the elevation map, resulting from kriging of these data, illustrates this pattern (Fig. 4). Soil run-off was 17.4 times more severe at the SB-field than at the F-field. However, severity of soil run-off quickly ceased at the bottom causing little to no soil loss from this field.

Soil run-off peaks occur in the middle part of the slope of the SB-field, where transport capacity of run-off water is likely to be at its maximum. In lower parts of the slope, decreasing slope percentage caused a decrease in transport capacity and hence sedimentation. This supports the theory of Horton (1945) of undisturbed overland flow. Peaks of soil run-off in the upper parts of the F-field may be explained by the presence of fallow spots. Soil run-off on convex parts of the slope in the SB-field was aggravated most likely as a result of removal of the protective vegetative cover. Redistribution of soil without soil loss from the field can be ascribed to the concave–convex slope type and the presence of soil run-off barriers.

To relate soil run-off with remnants from burning, we developed a regression model, after first log-transforming the soil run-off (SRO) data to meet the assumption of normal distribution:

$$\log(\mathrm{SRO}_{\mathrm{SB}}) = 1.141 + 0.884L_1 + 0.517W_{10} + 0.434V_{10} \quad (2)$$

$$\log(\mathrm{SRO}_{\mathrm{F}}) = 1.393 + 1.916L_1 - 0.843D_{10} \quad (3)$$

Both equations were highly significant ($P < 0.05$) with R^2 values equal to 0.362 for Eq. (2) and 0.606 for Eq. (3). Surface litter (L_1) was most important for controlling soil run-off, thus confirming conclusions of Kiepe and Rao (1994) and Young (1997). In the SB-field, with low L_1-values because of the burn, soil run-off was severe. In the F-field where surface litter is abundant and soil run-off almost absent, however, surface litter had a higher coefficient (Eq. (3)). Vegetation was significant in the SB-field with low V_{10} values, showing its retarding effect on flow velocity as well as maintaining the soil because of root presence

Table 1
Mean weights of trapped soil run-off (g per trap), soil pH and P_{Bray} for the two fields at several positions along the slope[a]

Position on the slope	SB-field[b]			F-field[c]		
	Weight (g per trap)	pH	P_{Bray} (mg kg^{-1})	Weight (g per trap)	pH	P_{Bray} (mg kg^{-1})
Bottom	67	5.18	21.7			
Low	233	5.14	16.2	10	4.78	15.0
Middle (L)	569	4.59	11.9			
Middle (H)	652	4.35	8.54			
High	351	4.39	15.1	30	3.91	11.5
Top	118	4.50	10.8			
Weighted mean	362	4.69	14.0	21	4.35	13.2

[a] Presented values of pH and P_{Bray} of the SB-field are means of two individual values.
[b] Low: soil run-off from traps 1 and 2 of transects 1–6; middle (L): soil run-off from traps 3–5 from transects 1–6; middle (H): soil run-off from traps 6–8 from transects 1–6; high: soil run-off from traps 9–11; top: soil run-off from traps 12–15 of transects 1–6.
[c] Low: soil run-off of the lower 15 traps (traps 1–5) of transects 1–3; high: soil run-off of the upper 15 traps (traps 6–10) of transects 1–3.

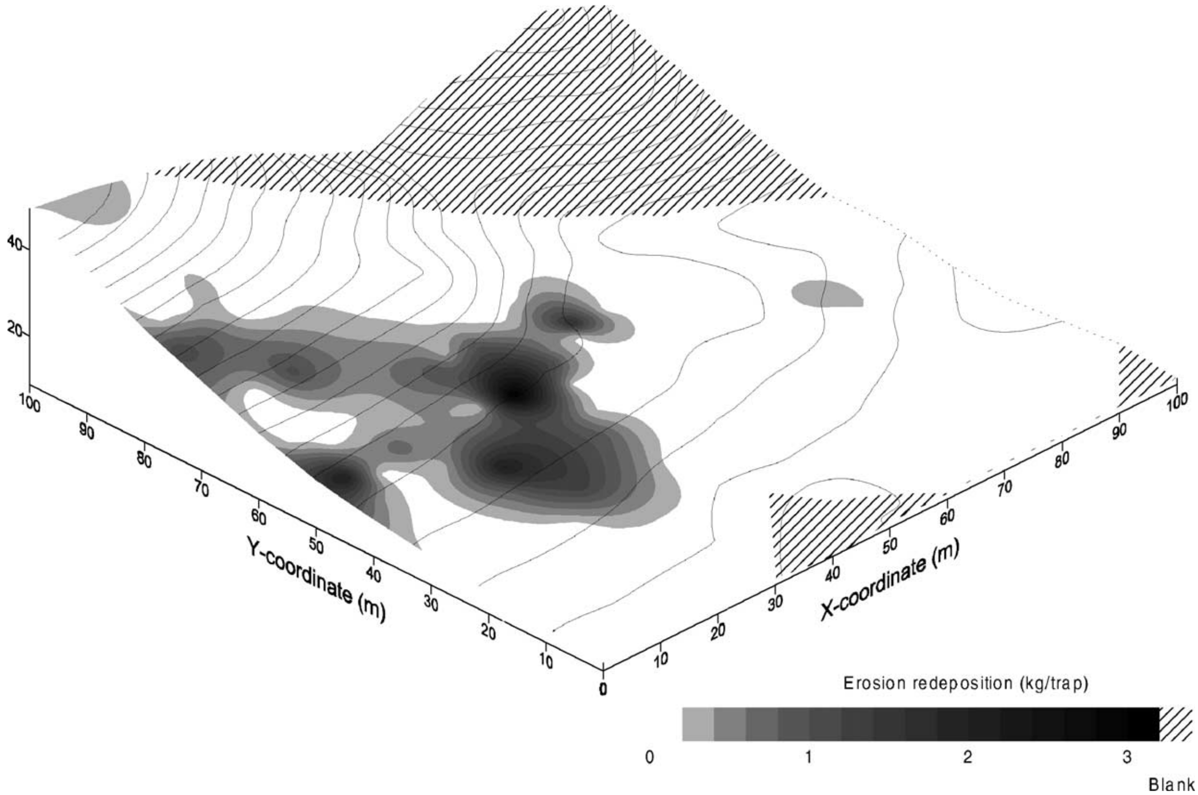

Fig. 4. Map showing soil run-off (kg per trap) as superimposed on elevation for the SB-field.

(Young, 1997). In the SB-field, dead wood (W_{10}) was a significant run-off controller, confirming earlier assumptions that sedimentation occurs where dead wood forms a barrier to soil run-off. Finally, depressions (D_{10}) also reduced soil run-off in the F-field. Our results support an earlier hypothesis by Van Noordwijk et al. (1998b) that deposition of run-off soil occurs in places with high infiltration capacity or high roughness. Sedimentation locations can therefore not be predicted by the theory of Horton (1945) only.

A linear regression relating CDW production to soil run-off (SRO_{SB}):

$$\log(SRO_{SB}) = 2.843 - 0.418\,CDW \quad (4)$$

with $P = 0.001$ and $R^2 = 0.33$, showed that large CDW production reduces soil run-off, although it explains only a minor part of the total variation. This either confirms the protective function of the crop or implies crop performance to be better on less erosive parts. Crop performance was noticeably better on lower parts of the slope where active soil run-off turns into sedimentation, raising soil fertility.

3.2. Soil run-off and soil fertility

Table 2 shows descriptive statistics of soil pH ($CaCl_2$) and extractable P_{resin} of the upper 5 cm of both study fields at t_1 and t_2. In both fields soil pH was extremely low, with means of 3.71 (t_1) and 4.05 (t_2) in the SB-field and 3.26 (t_1) and 3.39 (t_2) in the F-field. In addition, pH was very variable in the SB-field, ranging from 3.32 to 6.95 (at t_2). Mean P_{resin} in the SB-field was significantly higher than in the F-field at both t_1 and t_2 with a large range, indicating high variation. Mean soil pH and P_{resin} increased significantly with time ($P < 0.05$, using independent sample t-test) in both fields. Run-off soil pH in the SB-field was significantly higher ($P < 0.05$) than pH

Table 2
Descriptive statistics of soil pH ($CaCl_2$) and P_{resin}, at t_1 and t_2 and results of independent sample t-test for differences between the two fields (SB and F)

Time	Field	N	Mean	Minimum	Maximum	S.D.	t	d.f.	P
pH									
t_1	SB	55	3.71	3.18	6.13	0.57			
	F	48	3.26	2.97	3.75	0.15	5.3	101	0.000
t_2	SB	55	4.05	3.32	6.95	0.57			
	F	48	3.39	3.02	3.70	0.15	7.70	101	0.000
P_{resin}									
t_1	SB	55	2.36	0.27	19.49	2.87			
	F	48	1.12	0.54	2.98	0.47	2.97	101	0.004
t_2	SB	55	5.21	1.31	17.35	3.5			
	F	48	2.71	1.10	5.65	1.03	4.71	100	0.000

of the upper 5 cm of the soil: 4.69 vs. 3.71 (at t_1) and 4.05 (at t_2). For the F-field the difference was 4.35 vs. 3.26 (at t_1) and 3.39 (at t_2), but soil run-off data of this field consisted of only two values. For P such a direct comparison was not possible because different extraction methods were used (P_{resin} vs. P_{Bray}).

Run-off soil pH at lower parts (overall mean: 4.97) of the SB-field was significantly higher ($P < 0.05$) than pH at higher parts (overall mean: 4.30). Such a gradient was also present for P, but not significant ($P = 0.081$). The average amount of P_{Bray} collected in 40 days of soil run-off measurements was 5.08 mg per trap in the SB-field as compared to 0.28 mg per trap in the F-field.

A map of soil run-off (Fig. 5) shows a peak at y-coordinate 50 in the SB-field. Maps of soil pH (Fig. 6) and extractable P (P_{resin}) (Fig. 7) showed peaks for both pH and P_{resin} between y-coordinates 60 and 70 and x-coordinates 30 and 40 in the SB-field. In the F-field a peak in P_{resin} occurs around y-coordinate 60 and x-coordinate 10, coinciding with a small peak in soil run-off. In the top of the F-field the small soil run-off peak coincided with very low P_{resin} values. Low soil run-off at the bottom of the field coincided with higher P_{resin} values. Peaks in soil pH occurred in the middle part of the F-field where soil run-off is low.

In this study, redistribution of soil occurred over small distances. Soil run-off affects distribution of soil fertility in the field, since it is severe and run-off soil exhibits a relatively high chemical fertility. As sedimentation occurred on lower parts of the slope these parts were expected to be more fertile. This hypothesis was not fully supported by soil fertility maps. Distribution of soil fertility as a consequence of soil run-off and sedimentation after slash-and-burn depends upon type, number and pattern of obstacles down slope. Locally high soil fertility at the top of the SB-field was probably caused by nutrient-rich ash patterns that are protected (field observations) against the severe soil run-off that occurred elsewhere in this part of the field. High soil run-off in these parts possibly also coincided with high local sedimentation where soil run-off barriers occur. This amplifies small-scale spatial variability in soil fertility. Soil run-off after slash-and-burn affects spatial variability of soil fertility with outcomes that are hard to predict. As soil run-off in the abandoned agroforest site was low it is not likely to affect soil fertility. Variation in pH and extractable P, in this field, may be explained by variation in quantity and quality of surface litter and vegetation, soil moisture, and microclimatic conditions. Mean P_{resin} values were low in both fields but still within the expected range for fields in this region (Rachman et al., 1997).

3.3. *Spatial variability of soil fertility*

Results of the variogram analyses are presented in Table 3. Nugget effect of soil pH at t_1 contributed 50% of the total variance for both fields. Main difference in spatial variability in pH between both fields at t_1 was the range. In the SB-field, the range extended to 25.2 m (the effective range being 43.6 m), whereas in

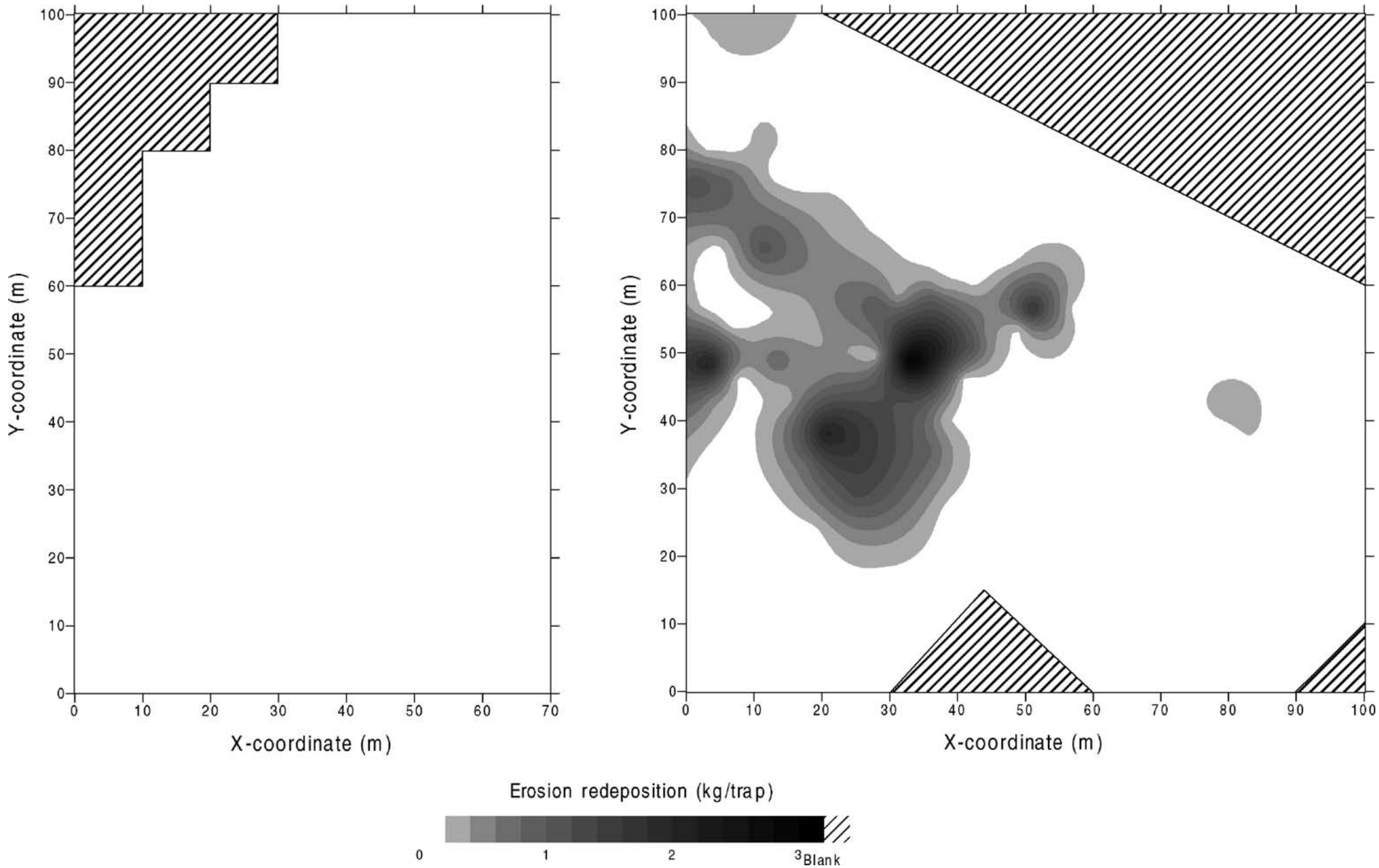

Fig. 5. Soil run-off (kg per trap) at the SB-field (left) and the F-field (right).

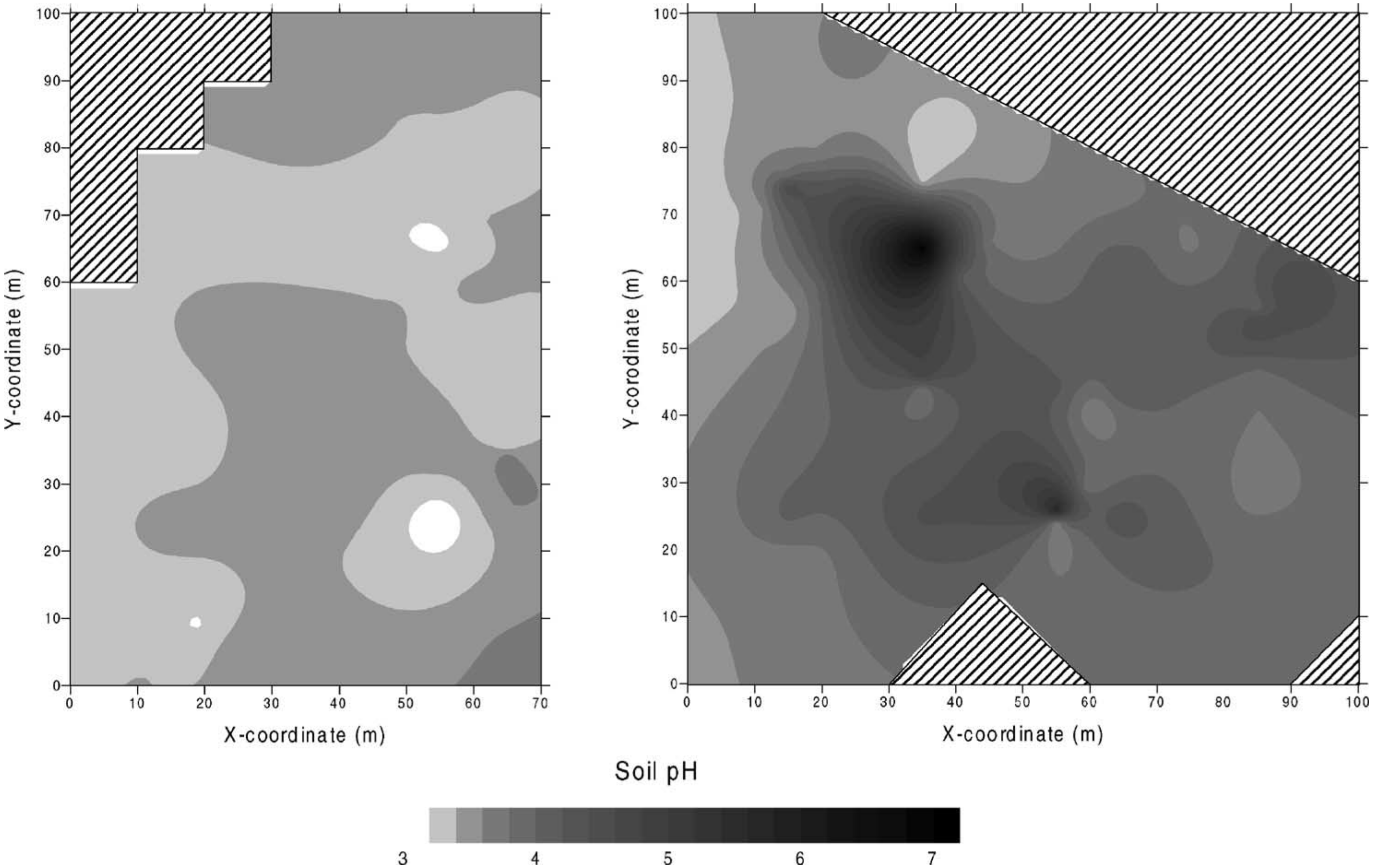

Fig. 6. Soil pH ($CaCl_2$) in the SB-field (left) and the F-field (right) at t_2.

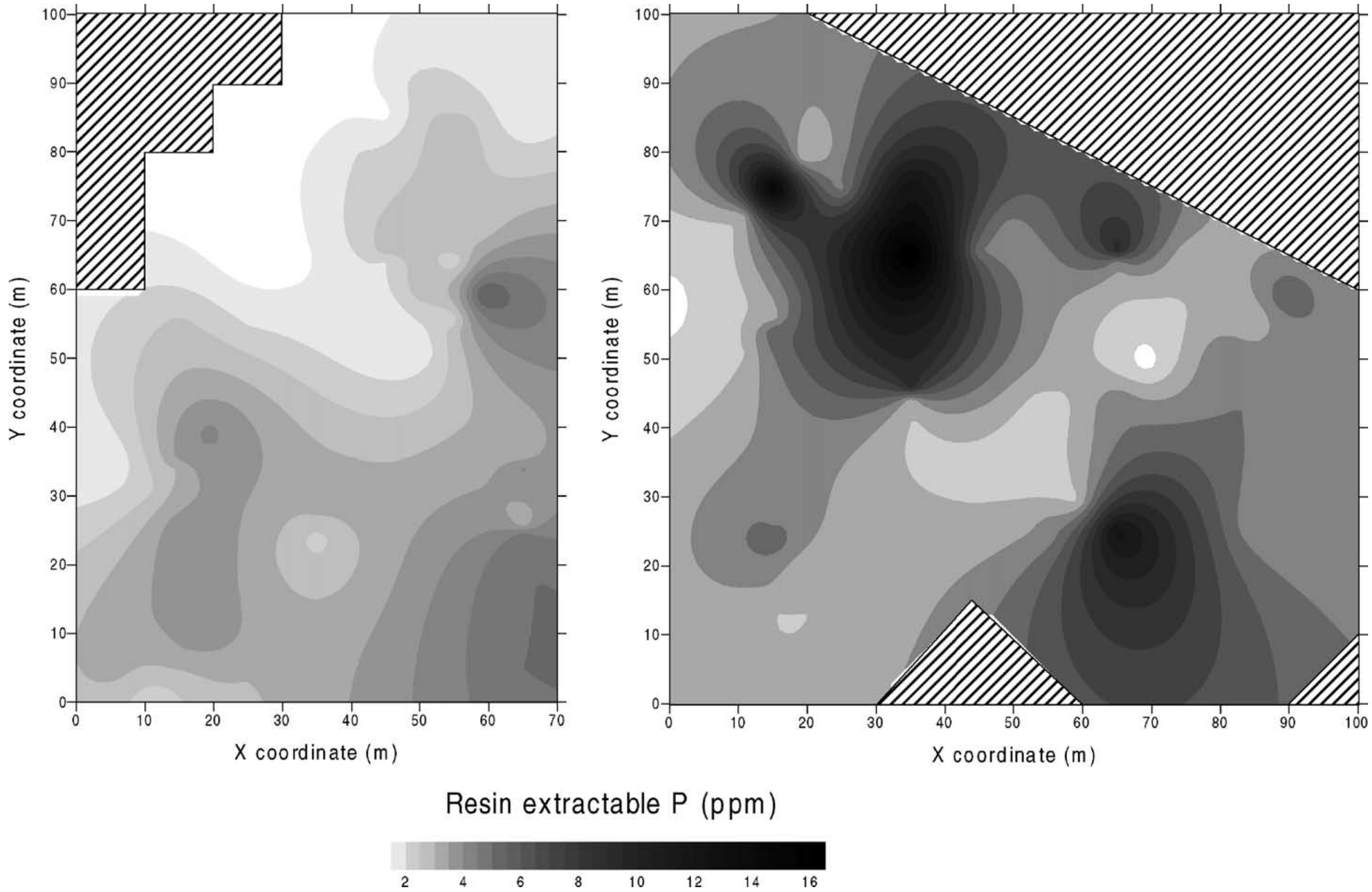

Fig. 7. Resin-extractable P in the SB-field (left) and the F-field (right) at t_2.

Table 3
Variograms of soil pH ($CaCl_2$) and P_{resin} at t_1 and t_2 in the two fields (SB and F)

Time	Field	Nugget	Sill	Range (m)	Nugget/ sill ratio	Model
pH						
t_1	SB	0.243	0.463	25.2[a]	0.525	Gaussian
	F	0.008	0.016	9.52	0.518	Spherical
t_2	SB	0.188	0.362	5.86	0.520	Spherical
	F	0.016	0.022	12.6	0.714	Spherical
P_{resin}						
t_1	SB	8.22	8.22	–	1.000	Nugget
	F	0.046	0.179	8.38	0.256	Spherical
t_2	SB	1.3	12.1	7.54	0.107	Spherical
	F	0.435	–	–	–	Linear

[a] For the Gaussian model the effective range is equal to 43.6 m.

the F-field it was limited to 9.5 m. Spatially dependent variation of pH decreased between t_1 and t_2 in the F-field but remained the same for the SB-field, where only the range decreased to 5.86 m. In the SB-field, P_{resin} was spatially independent at t_1, whereas it was spatially dependent in the F-field, although the range of spatial dependence was small (8.38 m). At t_2, P_{resin} was spatially dependent in the SB-field but with a small range (7.54 m). Its spatial dependence in the F-field was best described by a linear model and consequently lacks a nugget sill ratio.

Table 4 compares within-strata spatial variability with unstratified (whole field) spatial variability in the two fields by means of the r ratio. Both within-strata spatial variability and unstratified spatial variability of pH in the SB-field decreased between t_1 and t_2. This was also observed for the range of spatial dependence (89% decrease for unstratified and 88% for within-strata range of variability). The ratio between the two remained the same. Magnitude of spatial variability of P_{resin} changed between t_1 and t_2 from a pure nugget effect to a spherical model with a high r ratio indicating dominance of within-strata variability over between-strata variability, but with a small range (7.54 m). In the stratified vs. unstratified geostatistical analysis, variability of pH in the F-field at t_1 and t_2, both within-strata and unstratified, was not spatially dependent. Variability of P_{resin} in the F-field at t_1, was spatially dependent both within-strata and unstratified. The observed spatial dependence had a small range (8.38 m; Table 3).

Table 4
Ratio (r) of the nugget to sill ratios for pH and P_{resin} of the whole field to within-strata at t_1 and t_2 for the two fields (SB and F)

Time	Field	r
pH		
t_1	SB	1.13
	F	0.73
t_2	SB	1.20
	F	0.97
P_{resin}		
t_1	SB	[a]
	F	1.04
t_2	SB	2.04
	F	[b]

[a] Variograms are pure nugget effects.
[b] Variograms are linear models.

A comparison between P_{resin} in the SB-field and in F-field was not possible as the nugget sill ratios of SB-field in t_1 and F-field in t_2 could not be determined as a consequence of the linearity of the models. Between the SB-field and the F-field as well as between t_1 and t_2 a complete comparison of spatial variability was only possible for soil pH.

For pH in the SB-field, magnitude of spatial variability after slash-and-burn remained the same but the range decreased in time (Table 3). At the F-field, spatial variability as expressed by both nugget and sill increased and also the range increased from 9.52 to 12.6 m, hence with 32.4%. Only the SB-field revealed a spatial variability in soil pH. From the analyses on stratified vs. unstratified variability, and its change over time, it appears that only in the F-field between-strata variability dominated soil pH. In the SB-field, between-strata variability did not dominate nor increase in time, for both pH and P. Within-strata variability therefore, was the most important source of spatial variability in the SB-field (Table 4). Based on these outcomes we disprove the assumption that after slash-and-burn spatial variability in soil pH would shift to being more pronounced between-strata variability.

4. Conclusions

Soil run-off causes a redistribution of soil within a sloping slash-and-burn field. However, little to no soil was lost from the field due to its particular convex–concave shape and presence of soil run-off barriers like surface litter, dead wood and vegetation. This particular slope shape causes highest soil run-off in the middle part of the slope and a subsequent slowing down of soil run-off in the lower part. With high crop performance, rice can serve as a soil run-off reduction factor and as such may reduce this side effect of slash-and-burn.

Soil run-off and sedimentation processes influence the distribution of soil fertility in the field as P movement in the SB-field was 18.4 times higher than in the F-field. This explains changes in soil pH over time. Soil run-off aggravated by slash-and-burn did not, as assumed, increase the overall field spatial variability of soil pH. Instead, spatial variability in soil pH on the scale of study decreased at the expense of small-scale, within-strata, variability.

In areas of high soil run-off potential, intensive clear burns should be avoided because presence of remnants of slash-and-burn and surface litter help maintain the soil and its fertility. Soil run-off after slash-and-burn did not result in an expected development of a clear gradient in soil fertility down slope. Adaptation of specific crops or input management strategies to the field after slash-and-burn should, therefore, be more targeted to the arisen patchy distribution of soil fertility.

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