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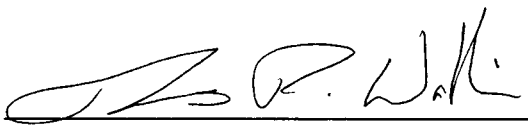
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QUANTIFYING TRAIL-RELATED SOIL EROSION AT TWO SITES IN THE HUMID TROPICS: JATUN SACHA, ECUADOR, AND LA SELVA, COSTA RICA

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Thomas Ryan Wallin

May 1995

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To my parents,

who have always had the courage

to let me choose my own path.

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ABSTRACT

The relationship between trails and soil erosion in temperate areas has received considerable study. In tropical areas, however, no comprehensive research has been done on the subject of trail-related soil erosion. This study is the first to quantify the effect of trails on runoff generation and sediment mobilization in the humid tropics.

Field research was conducted at two ecotourism sites in the humid tropics: Jatun Sacha Biological Station, Ecuador, and La Selva Biological Station, Costa Rica. To gauge the difference in runoff and sediment production between adjacent on and off-trail sites, portable rainfall simulators were used. Forty-one rainfall simulation tests were conducted on trails and 44 tests were conducted in the adjacent, undisturbed forest. Total runoff volume was measured and samples were taken of both entrained sediment and rainsplash. To quantify trail soil compaction, soil bulk density and soil penetration resistance were measured.

The results show that both runoff generation and sediment mobilization were significantly higher on trails than in off-trail areas. These results are similar to those of past studies undertaken with the same equipment in East Tennessee. Compared to the Tennessee trail sites, trails in this study produced a comparable, but slightly higher coefficient of runoff and an average of 66 to 84% less detached sediment.

Bulk density measurement showed striking differences between trail and adjacent off-trail sites -- trail bulk density was higher due to the loss of organic material and compaction due to trampling.

The static cone penetrometer was found to be useful for measuring relative differences in soil compaction. Highly localized differences in soil characteristics made the penetrometer unusable as a predictive measure for bulk density. Neither bulk density nor soil penetration resistance was found to provide a good analogue for infiltration rate.

Using trail length and sediment mobilization data, I determined an erosional potential for trails in the two reserves. At Jatun Sacha, the 1.9 km of trails on alluvial soils mobilize an average of 22 kg of sediment per millimeter of rain and the 12.7 km of trails on residual soils mobilize 212.4 kg. Thus, in a 15 mm precipitation event, 3,186 kg of sediment would be mobilized for possible transport on the trails of Jatun Sacha. At La Selva, a 15 mm rain event would mobilize 3163.5 kg of sediment on alluvial soils and 1552.5 kg on residual soils.

Overall, this study shows that compacted trails in humid tropical environments act as partial area runoff and sediment sources, as in temperate environments. While their exact effects may differ somewhat (i.e., greater coefficient of runoff and less sediment detachment in tropics), they follow the same broad pattern of increased sediment and runoff production on trails.

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CHAPTER 1

INTRODUCTION

Ecotourism -- nature-oriented travel -- is a development scheme that has rapidly gained acceptance as public interest in the preservation of natural areas has increased. It represents a new and growing market in the travel industry and promises employment and income generation in rural areas (Boo, 1990; Norris, 1992). Additionally, ecotourism can provide an economic incentive for the conservation of natural areas that might not otherwise receive protection (Boo, 1990). Thus, traditionally, ecotourism has been viewed as a development scheme that provides both economic gain and habitat protection with only minimal environmental impacts. For this reason, it has been endorsed and advertised by participating countries as an environmentally friendly avenue for sustainable development.

However, some negative effects of ecotourism have become apparent, including tourist overcrowding, litter, water pollution, and soil erosion. As tourist numbers have grown, park managers and researchers have become increasingly concerned about the effects of trail and road related soil erosion in the neotropics (Boo, 1990; Rovinski, 1991). Despite anecdotal evidence of degradation and the fact that roads and trails are documented as major sources of sediment in temperate areas, in ecotourism areas (Boo, 1990), and in the humid tropics in general (Dunne and Dietrich, 1982), comprehensive scientific studies of the erosional impacts of trails are lacking.

The long history of study of the erosional importance of roads and trails in temperate areas (Trimble and Sartz, 1957; Megahan, 1977; Weaver and Dale, 1978; Kay, 1981; Dunne and Dietrich, 1982; Wilson and Seney, 1994) has shown that trails in temperate environments act as

partial-area runoff sources, contributing far more runoff and detached sediment per unit area than other drainage basin surfaces. This erosional importance out of proportion to their area is partially the result of the soil compaction that occurs even with light trail use (Weaver and Dale, 1978). Compaction decreases pore space within the soil, which can result in decreased infiltration capacity and a resultant increase in surface runoff and soil erosion (Hammitt and Cole, 1987; Harden, 1992).

In contrast to the situation in temperate environments, basic questions remain about the erosional influence of trails in tropical environments. Do trails in the humid tropics produce erosional effects similar to those of trails in previously studied temperate regions, or are differences in runoff generation and sediment detachment between on- and off-trail sites in humid tropical environments less pronounced? Are differences between tropical and temperate soils, flora, fauna, and precipitation sufficient to change the expected relationships between trails, rainfall runoff, and soil erosion? In this study, I obtained rainfall and trail extent data, conducted simulated rainfall experiments, and measured bulk density and soil penetration resistance in two ecotourism areas in a first attempt to characterize and estimate the magnitude of the erosional effects of trails in the humid tropics.

To be suitable for the study of the erosional impact of trails in humid tropical areas within the context of ecotourism, study sites need to meet certain criteria. First, each must have an extensive network of trails that supports regular foot traffic. Second, each site must be known to tour companies both in-country and abroad. And third, visitation by ecotourists, whether nationals or foreigners, must be a fairly regular event. The two sites selected for study -- Jatun Sacha Biological Station, Ecuador, and La Selva Biological Station, Costa Rica -- meet these criteria. Both are known to tour companies outside their respective countries and are frequented by ecotourists (Laarman, 1987; Healy, 1988; Rovinski, 1991). Each station has an extensive network of trails that receive enough foot traffic to make it an excellent choice for the study of ecotourist-aided trail soil erosion.

The following are the specific questions that have guided my research:

Problem

-- How do trails in the humid tropics affect soil compaction and erosion?

Questions

-- How do runoff generation and sediment mobilization differ between on-trail and off-trail sites at Jatun Sacha and La Selva? What do these differences mean in terms of trail degradation and net sediment movement?

--Do soil bulk density values differ between on-trail and off-trail sites within the same immediate area? Do Jatun Sacha and La Selva bulk density values differ in general?

-- Are the differences in measures of infiltration -- time to runoff and coefficient of runoff (runoff divided by total rainfall) -- between rainfall simulator sites attributable to differences in bulk density or soil penetration resistance?

-- How accurately do static cone penetrometer measurements predict soil bulk density values? Is use of the penetrometer a viable alternative to bulk density measurement?

CHAPTER 2

TRAILS AND SOIL EROSION

In this chapter, I first present information concerning various factors and relationships that influence trail-related soil erosion: the relationship between trampling and soil compaction, the relationship between soil compaction and increased runoff and erosion, and general points drawn from the literature on the basic relationships between trails and soil erosion. Second, I review the current state of trail erosion research in the humid tropics.

Trampling and Soil Compaction

Bulk density, the ratio of the mass of a unit of soil to its volume, is a measure of general soil characteristics and also a convenient indicator of soil compaction. Bulk density values reflect the volume of pore space and the average density of individual soil particles within a given volume of soil (Hillel, 1971). Bulk density can be affected by a number of different factors -- soil compaction, texture, structure, and organic matter content. Undisturbed soils that are high in clay content tend to have lower bulk densities than soils that are rich in larger particles such as sand. Clay particles, because of their smaller size, allow a greater percentage of soil volume to be accounted for by soil pores. Thus, the mass of a given volume of clay-rich soil will be less, yielding a lower bulk density (Uehara and Gillman, 1981; Brady, 1984). Compaction related to trampling acts to increase bulk density by decreasing the space occupied by macropores (pores > 0.06 mm) and micropores (< 0.06 mm) (Brady, 1984).

Studies have reported that both compaction and reduction in macroporosity of soil occur even at low trail use levels (Cole and Fitchler, 1983; Marion and Merriam, 1985). The implication of these changes is that all but the most infrequently used trails should show some

signs of soil compaction soon after they are constructed. Weaver and Dale (1978), in a study of trampling effects in meadows and forests, found that soil compaction continued to increase with an increasing number of passes over a trail section; so, despite the fact that compaction begins early in the life of a trail, it is exacerbated with repeated use. Also, they found that compaction was greatest on slopes due to the greater vertical force components involved in propelling a hiker upward or braking a hiker's descent. On trails in general, Weaver and Dale (1978) and Harden (1992) found that bulk densities usually exceeded those of untrampled areas nearby, sometimes by a factor of 1.5 or more. Bulk density appears to be a contributing, but not a primary factor in determining the amount of runoff produced by a site (Harden, 1992).

Besides bulk density measurement, another method of determining the degree to which a soil is compacted is to use a standard cone penetrometer. Penetrometer values are much simpler to obtain in the field and many more replicate readings can be taken than is the case with bulk density samples, but there is a major drawback to the use of the penetrometer. The ease with which the cone can penetrate the soil is not solely determined by soil density, but can be greatly influenced by equipment factors, such as the size and shape of the probe and soil-metal friction, and by site specific factors, such as soil particle size distribution, water content, shear strength, clay mineralogy, organic matter content, and stone content (Campbell and O'Sullivan, 1991; Runion et al., 1993). Therefore, penetrometer values determined for one site may not readily compare to those determined for another. This variability also exists over time, as soil strength can change even without the occurrence of changes in water content and bulk density (Campbell and O'Sullivan, 1991).

Soil Compaction and Erosion

Arguably the most important environmental consequence of soil compaction is a reduction of infiltration rates. This reduction is related largely to the decrease in macroporosity of soils that undergo trampling (Glinski and Lipiec, 1990). Compaction is especially pronounced in

fine-textured soils because they generally start out with a greater percentage of pore space (40 to 60%) than sandy soils (35 to 50%). Assuming that undisturbed finer soils start out with a larger percentage of pore space, they can undergo a greater *reduction* in pore space than coarse-grained soils, and hence undergo greater increases in bulk density with trampling (Uehara and Gillman, 1981; Brady, 1984). A decrease in porosity in general, however, does not affect infiltration capacities in fine-grained soils nearly to the extent that a decrease in macroporosity does. Herein lies a key difference, with respect to infiltration capacity, between coarse and fine-grained soils. Even when a sandy soil is considerably compacted, a large portion of its total pore space will still be made up of macropores due to large individual particle size, irregular shapes, and inefficient packing. Conversely, in a fine-grained soil, when compaction occurs, macroporosity decreases greatly, while microporosity (which is a far less important determinant of infiltration capacity) decreases only slightly (Glinski and Lipiec, 1990). Thus, if a sandy soil and a fine-grained soil were compacted to the same total porosity, infiltration capacity would be much higher in the sandy soil due to the greater proportion of macropores (Brady, 1984).

Hammitt and Cole (1987) noted that, in a number of studies, a twentyfold difference was found between infiltration rates for compacted soils and those for undisturbed soils. At these greatly diminished infiltration rates, it becomes much more likely that a trampled site will undergo Hortonian overland flow (flow due to the fact that rainfall intensity outstrips the infiltration capacity of the soil). Morgan (1986) asserted that vegetation is an important variable in determining whether a site produces runoff by Hortonian overland flow or by saturation overland flow (in which the soil is simply waterlogged, not related to infiltration capacity). He argued that the removal of vegetation can increase the frequency of Hortonian overland flow. This is likely true, as the presence of growing vegetation would tend to work the soil, increase macroporosity (Glinski and Lipiec, 1990), and reduce the impact energy of raindrops through interception, thereby reducing the likelihood of formation of a surface seal.

At the same time, Wilson and Seney (1994) noted that the decrease in porosity associated with compaction can exacerbate vegetation losses along trails by reducing both aeration and the rate at which water can move through the soil. Whether vegetation is lost prior to, or as a result of, soil compaction, however, there is agreement that increased soil erosion due to Hortonian overland flow is more likely in the aftermath of vegetation removal (Morgan, 1986; Wilson and Seney, 1994). The resulting Hortonian overland flow during a rainstorm provides both a transport mechanism (a sheet of flowing water) and detachment mechanisms (falling raindrops and shear stress), which result in a much more efficient downslope transport of sediment than would likely be possible otherwise.

General Relationships between Trails and Soil Erosion

Hiking trails in the U. S. have frequent erosional problems. Manning (1979) listed a number of symptoms that a typical trail exhibits in the progression to eventual increased soil erosion:

1 - removal of leaf litter and humus
2 - reduction in organic matter incorporated into the soil
3 - compaction and reduction of soil macroporosity
4 - reduction of air and water permeability
5 - reduction in water infiltration rate
6 - increase in water runoff
7 - increase in soil erosion

With the rapid decomposition of organic material in humid tropical environments, it could be argued that the first two steps are of less importance in the tropics. Regardless of the presence or absence of the first two steps, it appears that soil compaction plays the dominant determining role in this scenario. There is, however, another mechanism besides compaction that can be responsible for drastically reducing infiltration rates -- the formation of a surface seal by raindrop impact.

Soil particles often clump into aggregates, some of which are exposed at the surface. During a rainstorm, if hit by a raindrop, an aggregate will disintegrate into smaller particles, which are then carried into soil pores by rainwater, and end up blocking the pores and increasing runoff (Brady, 1984; Morgan, 1986; Hallsworth, 1987; Bradford and Huang, 1992). Blockages can occur in as little as five minutes with high-intensity rainfall, and can clog macropores up to five mm in diameter (Ela et al., 1992). Very large decreases in infiltration rate are regularly observed with soil sealing and also with the crusts that are formed when these seals dry. The vulnerability of a soil to sealing decreases with increasing fractions of clay and organic material, since these provide greater strength to the soil aggregates. Thus, because of their lack of cohesiveness, loams and sandy loams are the soil textural classes most vulnerable to surface seal formation (Morgan, 1986; Roth, 1992). Soils such as Oxisols, that are not normally prone to this phenomenon, can exhibit surface sealing due to the high rainfall amounts and intensities frequently found in the tropics (Roth, 1992).

Whatever the means of initiation, once erosion begins on a trail, it usually continues whether trail use continues or not. As such, trail use should be thought of as a causative factor, but not an actual agent of erosion (Hammitt and Cole, 1987). Other general trends noted include the observations that erosion tends to widen and deepen trails (Weaver and Dale, 1978; Hammitt and Cole, 1987), and that slope gradients are positively correlated with sediment loss, trail widening, and trail deepening (Weaver and Dale, 1978; Wilson and Seney, 1994).

As for sediment detachment, Wilson and Seney (1994) found that horse's hooves and hiker's boots made more sediment available for transport than did motorcycles or off-road bicycles on trails in Montana. This effect was accentuated on prewetted trails, where the greatest sediment yields found in their tests were generated, due to the fact that the increase in soil moisture reduces the ability of the trail to bear a moving load. In the same vein, Weaver and Dale (1978) found that hiker damage on slopes (where forces are highest) increased as

slope increased, and was greater going downhill due to the greater amount of energy imparted by braking. Thus, they recommend that trail slopes steeper than 15° should not be permitted in natural areas and that hikers should, if possible, ascend steeper slopes and descend shallower ones to minimize their erosional effects.

Current State of Trail Research in the Humid Tropics

In contrast to the long history of study (Trimble and Sartz, 1957; Weaver and Dale, 1978; Kay, 1981; Dunne and Dietrich, 1982; Megahan, 1977; Wilson and Seney, 1994) that trail erosion has received in temperate areas, I was able to locate no other studies undertaken in tropical wet forest environments that focused specifically on erosion caused by trails. This apparent lack of research on trail-related soil erosion comes despite the fact that mean annual rainfall, a potential sediment transport mechanism, is generally greater in humid tropical areas than in temperate areas, many times by a factor of three or more. Additionally, trail degradation and trail-related soil erosion have been observed by park managers at many locations in the tropics frequented by tourists; for example, La Selva Biological Station, Costa Rica (David Clark, personal communication, June 1993); Monteverde National Park, Costa Rica (Boo, 1990; Rovinski, 1991); Manuel Antonio National Park, Costa Rica (Rovinski, 1991); Jatun Sacha Biological Station, Ecuador (Neill, personal communication, June 1993); and Galapagos Islands National Park, Ecuador (Boo, 1990). This widespread incidence of soil erosion on trails, coupled with weather, soils, fauna, and vegetation much different than in well-studied temperate areas, underscores the need for scientific studies such as this one to assess the potential long-term impacts of trail use in ecotourism areas of the humid tropics.

CHAPTER 3

SITE DESCRIPTIONS

The following are descriptions of the two research stations where our group -- Dr. Carol Harden, UTK graduate student Chris Buhi, and I -- conducted field work. We were in the field at Jatun Sacha from June 8 to June 14, and at La Selva from June 22 to June 27, 1993. I returned to La Selva from February 19 to 23, 1994 to repeat collection of a portion of our data that was affected by equipment malfunction.

Jatun Sacha Biological Station

Location

Jatun Sacha Biological Station (1° 4' S, 77° 36' W) is located approximately 150 km southeast of Quito in the Napo Province of the Oriente of Ecuador (Figure 3.1). The reserve is situated on the south side of the Río Napo about 6 km southeast of the town of Puerto Misahuallí. The station covers a discontinuous area of about 750 hectares, encompassing both floodplain and alluvial terraces of the Río Napo in the north and steeply rolling low hills in the south.

History

Jatun Sacha was founded in 1986 by a group of private Ecuadorian and international conservationists. It was originally a 200 hectare reserve made up of land owned by the founders. Donations from various sources have allowed the expansion of the reserve by over 500 hectares to its present size (Jatun Sacha Foundation, 1992). This does not, however, mean that

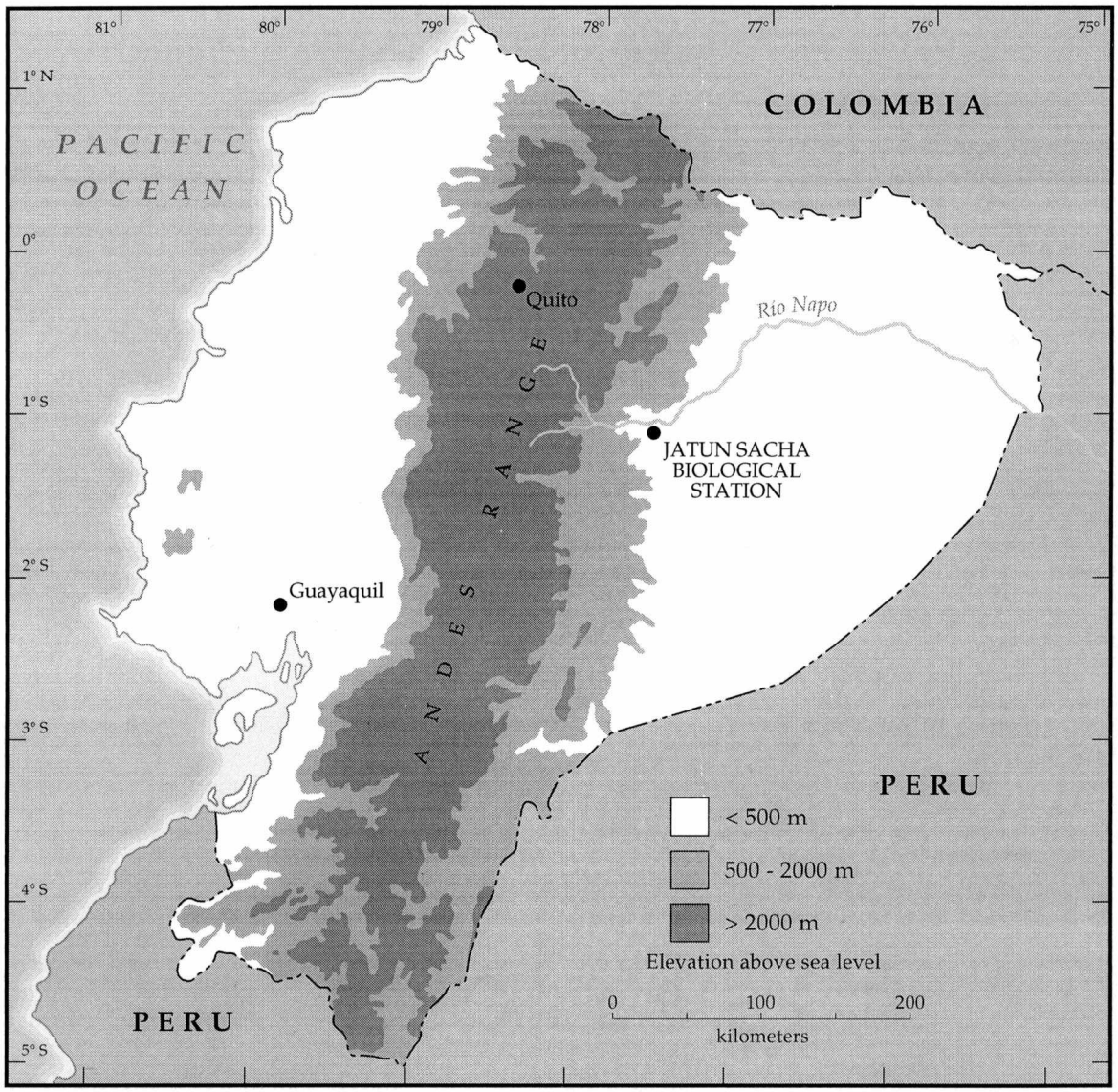


Figure 3.1 Map of Ecuador. Adapted from Bartholomew, 1980.

the reserve is composed of 750 hectares of virgin rainforest. While the literature for Jatun Sacha states that 70% of the reserve is in primary forest and 30% is in secondary growth (Jatun Sacha Foundation, 1992), the exact definition of these terms is not clear, as much of the area of the reserve was in agriculture until 1976, including areas classed as primary forest. Also, there is evidence of prehistoric disturbance -- pot sherds (of unknown age) are numerous and fairly easy to find in the hilly portion of the reserve in the vicinity of the main station.

The majority of trails at Jatun Sacha are bare earth, while a small percentage have raised boardwalks. David Neill, one of the founders of Jatun Sacha, estimated that Jatun Sacha receives about 500 person days of visitor use each year (Neill, personal communication, April 1995).

Climate

Over the seven-year period of measurement (April 1986 - March 1993), annual rainfall averaged 3678 mm, falling relatively evenly throughout the year, but with a moderately dry period from December to February and a moderately wet period from April to June. Jatun Sacha is classed as a Tropical Wet Forest life zone in the Holdridge climatic classification system (Jatun Sacha Foundation, 1992).

Topography, Geomorphology, and Soils

Jatun Sacha can be divided into two distinctly different areas based both on topography and geomorphology. The first is an area of low hills and the second encompasses the floodplain and terrace areas of the Río Napo.

The hilly section of the reserve averages about 420 m in elevation and includes most of the reserve southeast of the Tena/Ahuano road (Figure 3.2). In this area, local relief is between 10 and 30 m and slopes range between 12 and 70%. The hills are formed of alternating layers of clay and sand that were deposited during the middle Tertiary, when the region was covered by a retreating epicontinental sea (Mejía, 1992). Changes in the geologic and paleontological character of the sediments occurred as the seas continued to shrink. Finally, during the upper Miocene, biological sediments were being produced that were characteristic of either lacustrine or estuarine environments, which suggests that the portion of the sea that was covering the area was, by then, dominated by fresh water, with only occasional incursions of salt water. Together, these deposits form the Curaray Formation, which is composed mainly of

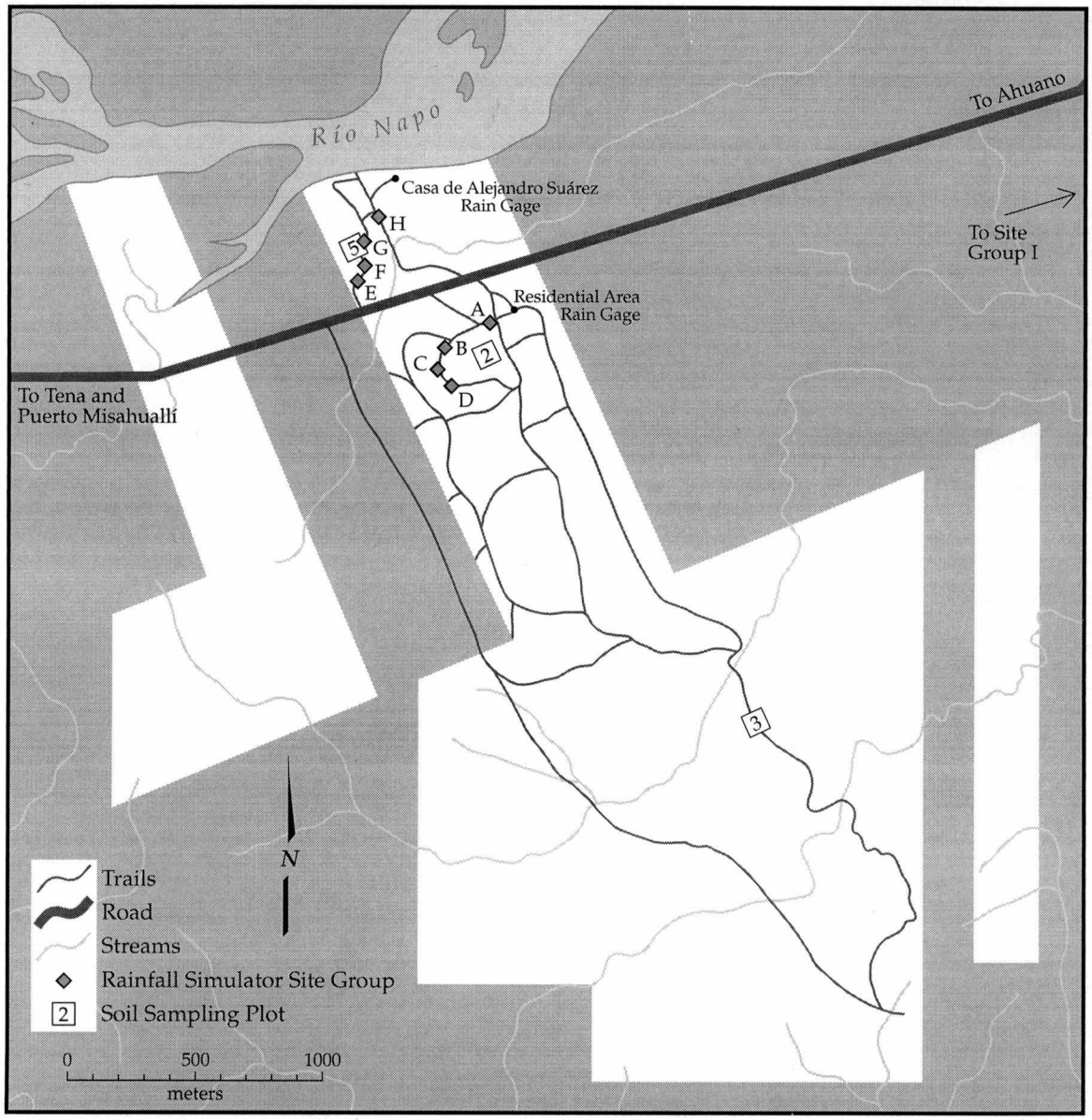


Figure 3.2 Jatun Sacha Biological Station, Ecuador. Adapted from Instituto Geográfico Militar, 1988 and Jatun Sacha Foundation, n.d.

layered clays and fine to medium grained sands. Gypsum is found in some areas, and, in the upper part of the formation, ash, lignite, and carbon-rich clays are present (Mejía, 1992).

The floodplain and terrace areas of the Río Napo lie mainly on the northwest side of the Tena/Ahuano road that divides the reserve. This section of the reserve lies at an average elevation of about 380 m. Local relief is slight. Mejía (1992) described the area as flat to

undulating with slopes of less than 5%. The floodplain area is composed of both alluvial and alluvial/colluvial material -- mainly gravel, sand, and silt. In addition to the present floodplain, there are alluvial terraces created by downcutting of the Napo River, possibly due to a change in flow regime and/or regional tectonic uplift. In his geomorphic survey of the reserve, Mejía (1992) noted that the older terraces correspond to Pleistocene time while the younger ones are of Holocene origin.

There is no extensive soil survey at Jatun Sacha. In fact, the only detailed classification of soil types comes from samples taken by Mejía (1992) on just three plots (these plots are 3 of 5 permanent research plots designated at Jatun Sacha) -- one in the mid to lower alluvial terrace area, one near the station center, and one in the southern portion of the reserve. Two of these plots, however, are located in close proximity to the two clusters of rainfall simulator sites, and can thus serve to approximate soil type for each set of simulator sites.

The alluvial terrace soil sampling site, plot 5, corresponds to rainfall simulator site groups E (sites 11-12), F (13-14), G (15-16), and H (17-18) (Figure 3.2). The soil of plot 5 is classified as a Typic Tropofluvent that, in the 8 cm O0 horizon, has 44% sand, 40% silt, and 16% clay (Mejía, 1992). The only significant difference with depth is that the silt percentage increases while the sand percentage decreases (from 44% sand and 40% silt in the O0 layer to 26% sand and 55% silt in the C3 horizon, which was sampled to a depth of 100 cm). Throughout the length of the 100 cm profile, however, the clay percentage remains virtually unchanged (16% in O0 to 19% in C3). The soil texture is classified as a loam in the O0 horizon and a silty loam in all other levels sampled.

The plot 2 soil survey area is located just south of the central area of the station and is representative of rainfall simulator site groups A (sites 1-3), B (4-6), C (7-8), D (9-10), and I (19-20 -- these sites were actually located on forested lands adjacent to the upland area of Jatun Sacha). The soils in this hilly area are classified as Typic Distropepts. In the A/B horizon (5-20 cm) these soils are classified as silty loams, with 20% sand, 55% silt, and 17% clay. In the

B1 horizon, the percentage of sand decreases to 15% while the clay percentage increases to 30%, producing a silty clay loam. In the B and C horizons, the percentage of silt decreases while the clay fraction continues to increase, producing a silty clay from 40 to 100 cm. In the lowest layer sampled (60-100 cm), sand accounts for 13%, silt 45%, and clay 42% (Mejía, 1992).

La Selva Biological Station

Location

La Selva Biological Station (10° 26' N, 83° 59' W) is located approximately 60 km north-northeast of San José near the town of Puerto Viejo in the Atlantic drainage of Costa Rica (Figure 3.3). It is a lowland rainforest reserve of 1536 hectares situated at the confluence of the Sarapiquí and Puerto Viejo Rivers. The main area of the reserve is bounded on the north by these rivers and on the south by an extension of Braulio Carillo National Park (McDade, 1994).

History

Despite the existence of large tracts of seemingly undisturbed rainforest at La Selva, the area has a long history of human disturbance, though not as recent as that of Jatun Sacha. Various evidence, including the discovery of pot sherds and worked stone (McDade, 1994), and the widespread existence of soil charcoal (Horn and Sanford, 1992), has led to the determination of a date of 3000 years BP for the first human habitation of the river terraces in the area.

In 1953, Dr. Leslie Holdridge acquired a large tract of land on which to start an experimental farm -- Finca La Selva -- for testing methods of sustainable forest agriculture. The Organization for Tropical Studies (OTS) purchased La Selva from Dr. Holdridge in 1968. At the time of purchase, about 95% of the 587 hectare tract was in "primary" forest, while the remainder was occupied by agricultural or developed areas (McDade, 1994). From 1970 to the

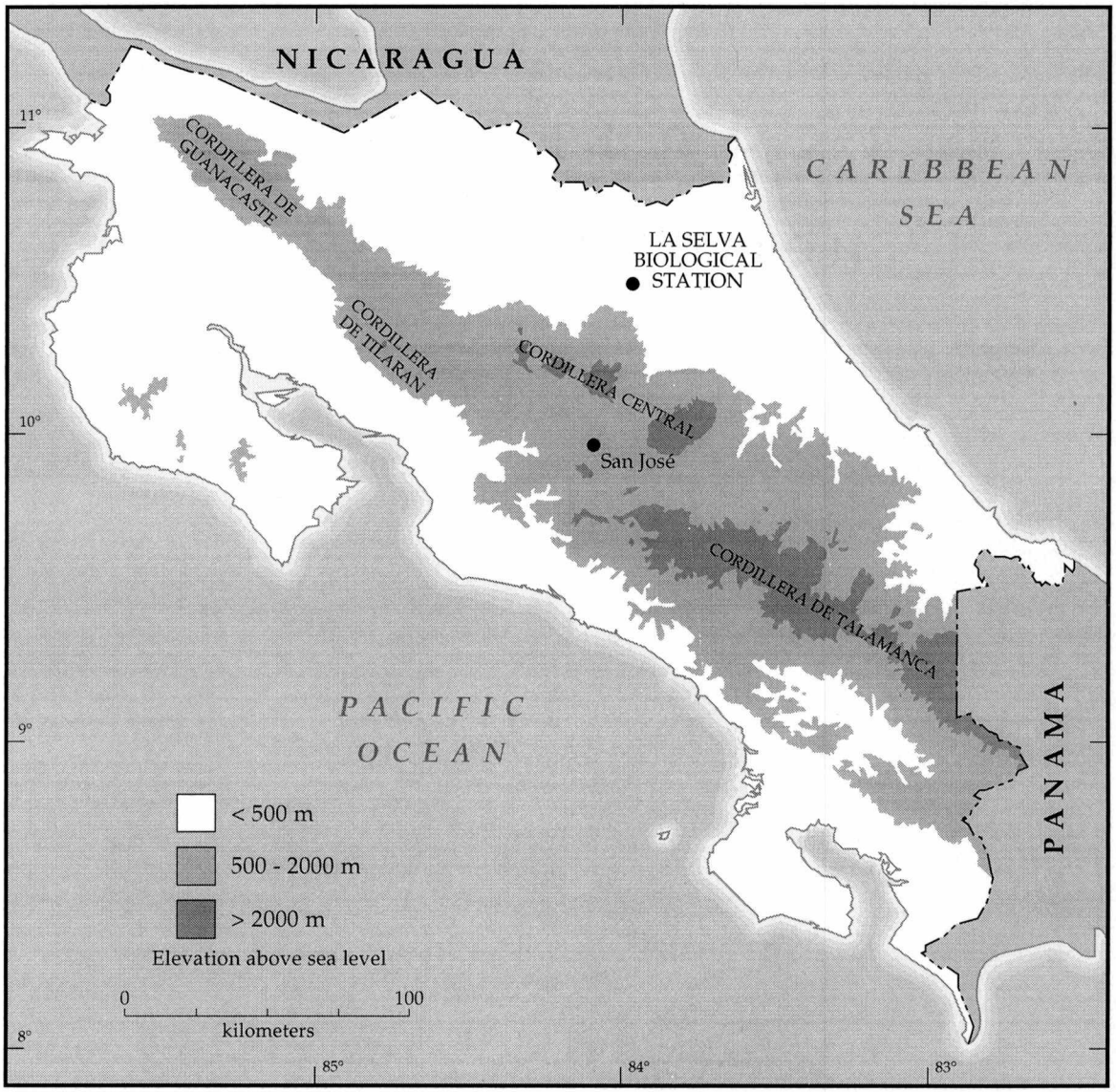


Figure 3.3 Map of Costa Rica. Adapted from Instituto Geográfico Nacional, 1983.

present, the reserve was gradually expanded through land purchases and donations to its current size of 1536 hectares.

Trails at La Selva are predominately bare earth, but there are significant lengths of boardwalk and cement trails as well. Deborah Clark (co-director of La Selva at the time of our 1993 visit) estimated that the station receives about 10,000 visitors annually. The majority of

these visitors, however, never leave the concrete trails near the central area of the station (Deborah Clark, personal communication, June 1993).

Climate

The average annual precipitation at the Rafael's Point measurement station (Figure 3.4) at La Selva is 3962 mm over the period of record from 1963-1991. The lowest annual total during this period was 2605 mm in 1983 while the highest was 5659 mm in 1970 (Sanford et al., 1994). During this 28-year period, March was the driest month, with an average of 152 mm of rainfall, while July was the wettest, with an average of 481 mm of rainfall (Sanford et al., 1994).

Sanford et al. (1994) presented a record of monthly averages of air temperatures recorded at the La Selva Bridge Station (Figure 3.4) from 1984 to 1991. The average temperature through the year is 25.8°C. The average temperature of the coolest month, January (24.7°C) is only 2.4°C lower than the average for the warmest month, August (27.1°C). This annual range (2.4°C) of average monthly temperatures is far less than the daily range of 6 - 12°C. The rainfall and temperature characteristics of La Selva place it in the Tropical Wet Forest life zone (cool, dry transition) of the Holdridge climatic classification system (Holdridge et al., 1971).

Topography, Geomorphology, and Soils

La Selva ranges in elevation from about 35 m along the Río Puerto Viejo to 137 m at the southwest corner of the station (McDade, 1994). According to a preliminary geomorphic study by Alvarado (1985), the terrain at La Selva is formed primarily by three ancient, chemically distinct lava flows, areas of Holocene swamp alluvium, and a number of Holocene and late Pleistocene alluvial terraces.

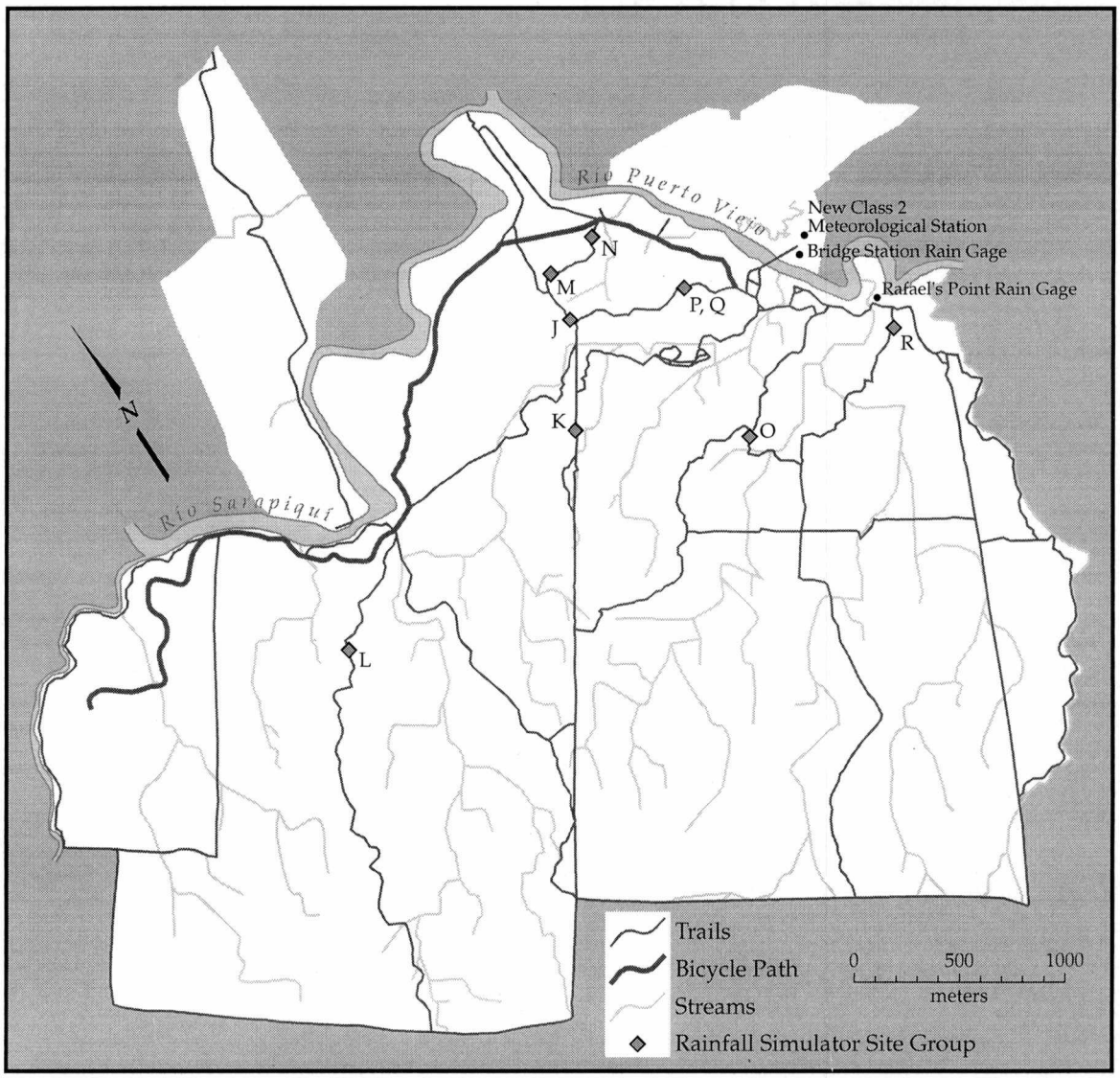


Figure 3.4 La Selva Biological Station, Costa Rica. Adapted from Organization for Tropical Studies, 1993.

The three lower Pleistocene (Sanford et al., 1994) lava flows that cover a significant portion of the reserve are the Esquina Andesites, the El Salto Basalt-Andesites, and the Taconazo Basalt-Andesites. The Esquina and El Salto flows both have widespread surface exposure while the Taconazo is only found in a few very small areas. These lava flows have slowly weathered to form the "residual" soils found at La Selva (Sollins et al., 1994). The two main soil units derived from lava flows -- and the only residual soils on which tests were

performed -- are the Matabuey and Jaguar consociations (a consociation was defined by Sollins et al. (1994) as "a mapping unit in which a single soil type occupies at least 75% of the area; similar but different soil types comprise the remaining area"). The Matabuey soils are derived from both the El Salto and Taconazo lavas while the Jaguar consociation is derived from the Esquina flow. Despite some differences in color, the Matabuey and Jaguar soils are, both chemically and physically, quite similar. Both are strongly acidic, rich in organic matter, and highly leached, and were classified by Sancho and Mata (1987) as Typic Tropohumults (Table 3.1). In fact, the main reason that the two units are separated at all is so that each can correspond with a particular lava flow (Sollins et al., 1994). Rainfall simulator site group K (sites 105-110) was located in the Jaguar unit, while group L (111-114) was located in the Matabuey consociation (Figure 3.4).

The remainder of the rainfall simulator sites at La Selva were on soils derived from alluvial material. All of these soils are on either the middle or upper terrace levels, as defined by Sollins et al. (1994), and all are classified as Inceptisols. In addition to soil physical characteristics, the alluvial consociations are divided based on whether they were formed by the action of the Río Puerto Viejo or the Río Sarapiquí.

According to Sollins et al. (1994), the Río Puerto Viejo has at least four major alluvial terrace levels. The Arboleda consociation, a Typic Humitropept, is located on the uppermost terrace and was the location of rainfall simulator site group O (sites 121-124). This consociation was originally mislabeled as residual in origin due to the fact that it is located just downslope from the Jaguar unit and that the uppermost, ancient terrace that it occupies is highly dissected and was not recognized until recently (Sollins et al., 1994). The Experimental consociation also occupies an upper terrace level of the Puerto Viejo. The land surface in this area is undulating and moderately dissected and lies at elevations between about 40 and 50 m. The dominant soil type is Andic Humitropept, while there are inclusions of Andic Dystropept. Rainfall simulator site groups M (115-117), P (125-127), and Q (128-132) were located in the Experimental

Table 3.1. Classification and general characteristics of La Selva Biological Station soils. Adapted from Sollins et al. (1994).

Mapping unit	Soil Type	Horizon and Depth (cm)	Clay %	Bulk Density g/cc	Organic Matter %
Jaguar	Typic Tropohumult	A 0-19 cm	40	.69	6.75
Matabuey	Typic Tropohumult	A 0-18 cm	41	.80	7.13
Arboleda	Typic Humitropept	A 0-14 cm	6	.55	4.03
Experimental	Andic Humitropept	A11 0-15 cm	35	.76	13.20
Holdridge	Andic Humitropept	A 0-22 cm	28	.68	8.91
Sainal	N/A	N/A	N/A	N/A	N/A
Chanchera	Andic Dystropept	A 0-9 cm	22	.82	7.71

consociation. The Holdridge consociation was the location of rainfall simulator site group R (133-135). This consociation occupies a middle terrace level and ranges in elevation from about 36 to 38 m. The terrain is flat to gently undulating and the dominant soil type is Andic Humitropept. Rainfall simulator site group N (118-120) was located within the Sainal consociation, which occupies a terrace that is at an elevation of about 36 m and is prone to occasional flooding (Sollins et al., 1994). There seems to be some general confusion about this latter grouping. Sancho and Mata (1987) originally named these soils the La Selva consociation and classified them as Andic Humitropepts. The name was later changed to Sainal to avoid confusion due to overuse of the term La Selva. Adding more confusion, the soil pit that was used in the 1987 soil survey to determine the characteristics of the La Selva consociation was actually located nearby in what is now recognized as the Pejiballe consociation. Thus, there are no soil chemical or physical data available for the Sainal consociation (Sollins et al., 1994).

The terraces of the Río Sarapiquí served as the location for only one group of rainfall simulator sites, group J (101-104). These sites were located on a middle terrace level and are within the Chanchera consociation. This consociation covers gently undulating land and the soils are classified as Andic Dystropepts.

CHAPTER 4

METHODS

Rainfall Simulation

To gauge the difference in infiltration and sediment detachment between trails and adjacent, relatively undisturbed forest, Dr. Harden and I (with assistance from Juan José Espinoza, Glenn Hyman, Gustavo Quiros Aguilar, and Nathalie Beaulieu) conducted paired tests using two McQueen portable rainfall simulator/infiltrometers (McQueen, 1963) (Figure 4.1). These devices have 91 orifices that produce raindrops with a kinetic energy typical of drops in an average I_{30} = 25mm hr^{-1} rainstorm. The drops then fall into a base ring 15.2 cm in diameter. The methodology used for these tests is described below, and is that of Harden (1991, 1992). It involves minor modifications of the method described in the original McQueen (1963) article.

All individual rainfall simulation test sites were paired with nearby sites to form site groups (one or more trail sites and one or more off-trail sites) to make comparison between trail and off-trail sites possible. Site groups are denoted by letters while individual test sites are denoted by numbers.

The first criterion for placement of site groups was soil type -- we conducted rainfall simulation experiments in two different soil types at Jatun Sacha and seven different types at La Selva. Once the general area for a site group was determined from a soil map, the main criteria in selecting an on-trail test site was whether it was fairly "representative" of the character of the trail it was located on. In addition, sites had to be level or gently sloping and could not have macropores or large roots visible at the surface. Once an on-trail site was chosen,

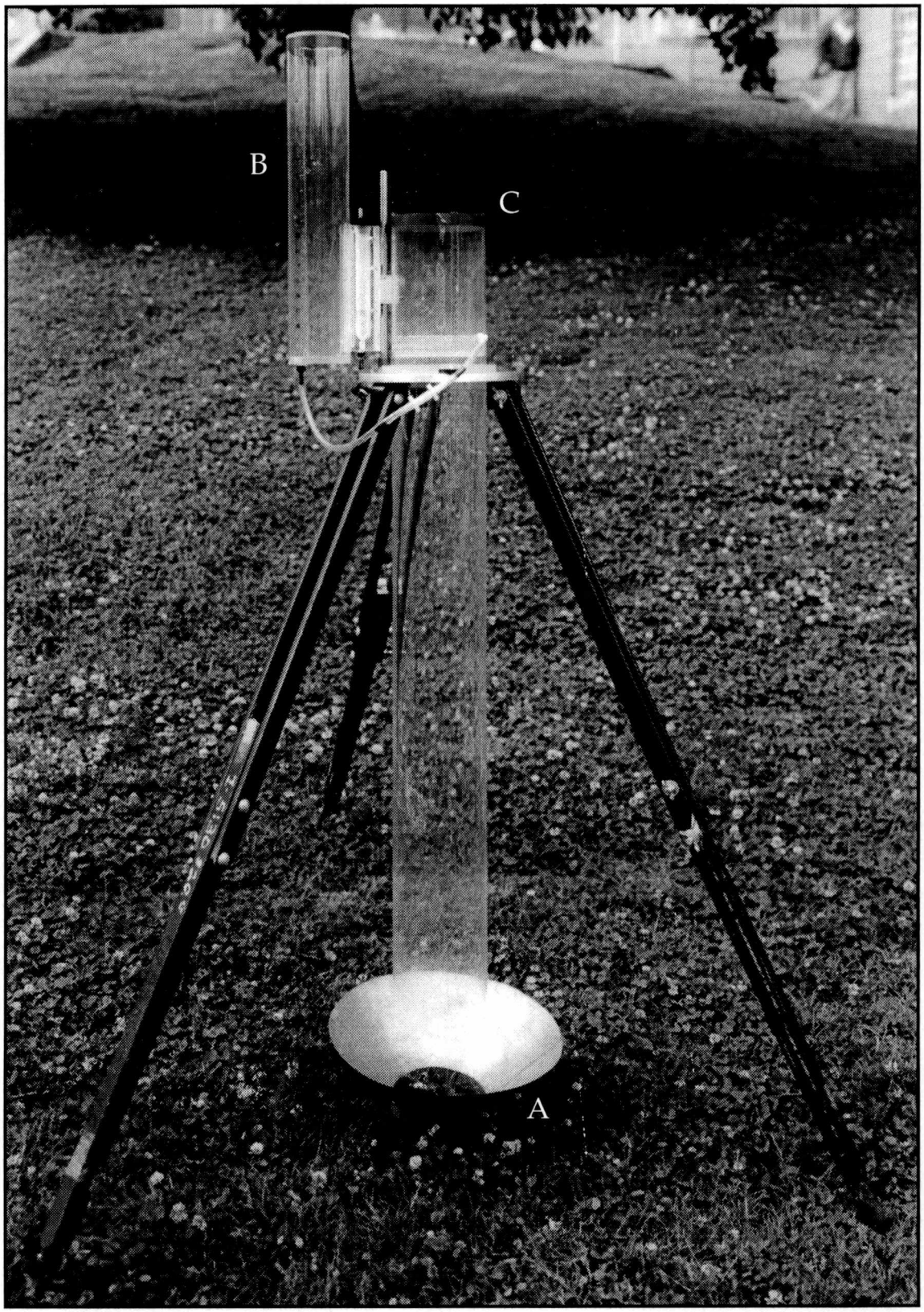


Figure 4.1 McQueen rainfall simulator/infiltrometer. A - basepiece. B - reservoir. C - rainulator head.

the paired off-trail site was positioned a few m away in the adjoining forest. Criteria for the selection of an off-trail site were much the same as those for an on-trail site with the main difference being that off-trail sites were required to have very little or no visible human disturbance.

The intent in performing paired on and off-trail rainfall simulation tests was to measure the response of two sites (considered to be identical except for the presence or absence of trails) to identical rainfall conditions. In the field, however, this goal of identical rain amounts on the paired sites was functionally unattainable for a variety of reasons. First, we were using two rainfall simulators -- generally one would be used for a number of on-trail tests at varying intensities while the other would be used for a number of off-trail tests, also at varying intensities. Each simulator was hand-made and thus has a particular flow rate (rainfall intensity) for a particular head of water above the drop-producing orifices. Thus, the only way to exactly match rainfall intensities between the two simulators involves trial and error and experience. Adding to this difficulty, the clearances in the drop-producing orifices are so small that even very small amounts of dust or sediment in the water used in the simulators can make a vast difference in the rainfall intensity that will be produced by a given head of water. Thus, over the course of a day of tests as dirt collected in the orifices, we had to rely on experience to arrive at a desired flow rate.

Despite these difficulties, however, we were able to approximately match rainfall amounts for the majority of on and off-trail sites. For t-tests and regressions of the characteristics of off-trail versus on-trail sites, I created two different databases: one unpaired (all events except for three extremely high intensity off-trail tests) and the other with on and off-trail paired sites only. The databases were assembled and all statistics were calculated in Microsoft Excel 4.0 for Macintosh.

In the procedure outlined by McQueen (1963), prewetting of the test site is required to bring the soil to field capacity. During field work at Jatun Sacha and La Selva, rain fell nearly

every day. Thus, for our purposes, we considered the soils to be at or near field capacity and omitted this step.

Both on and off-trail sites were cleared of most of their undecayed surface organic material. We removed this material because while one leaf shielding the soil beneath it would not appreciably affect the infiltration rate of a large area of forest floor, it could have a very large effect on the infiltration rate of the 182 cm^2 test area. As a result, we removed all leaves that were undecayed enough to be lifted away whole or in large sections. We also removed all sticks and twigs that could interfere with the placing of the simulator basepiece (described below).

After removing the leaves and woody material from the surface, we pressed a metal basepiece (A, Figure 4.1) a few cm into the soil to prevent lateral surface flow of water out of the test area. Once the basepiece was placed in the ground, the rainfall simulator assembly was placed directly overhead and leveled. Next, we placed plastic sheeting over the basepiece and filled the reservoir (B, Figure 4.1) with water. We then opened the valve regulating flow into the rainulator head (C, Figure 4.1) and allowed the water level in the rainulator to rise to the point where it reached a fairly constant head (i.e., constant rainfall intensity). When the water flowing into the rainulator head reached the desired level, we removed the plastic sheeting from the basepiece, started a stopwatch, and began the test.

Immediately after the stopwatch was started, we checked and recorded the water level in both the reservoir and the rainulator head. These levels were then rechecked and recorded every five minutes for the duration of the thirty-minute test to determine the total volume of water that had fallen on the test site. Also, water ponded at the surface of the test site (hereafter referred to as "runoff") was suctioned off with either a turkey baster or an eye dropper at each five-minute interval. We transferred all runoff water collected during each sampling period to a graduated cylinder for measurement and temporary storage. The final runoff collection -- after completion of the 30-minute test -- was slightly different than the

others. Instead of removing the runoff while water continued to drip from the rainulator head as the test continued, we physically moved the simulator so that any water that fell after completion of the test did not fall on the test site. We recorded cumulative runoff volume at each five-minute interval during the thirty-minute test.

Following completion of each test, we poured the runoff water stored in the graduated cylinder through a cotton filter bag (Hubco sand sample bags) to entrap sediments entrained in runoff water by raindrop impact. Similarly, following each test, we collected in a separate filter bag all material splashed onto the basepiece by raindrop impact (hereafter referred to as "rainsplash"). To accomplish this, we removed the basepiece from the ground, thoroughly cleaned the edge that had been in contact with the ground, rinsed the rainsplash material into a clean bowl using a wash bottle, and then rinsed the contents of the bowl into a clean filter bag. I had numbered and weighed (to within 0.001 g) all filter bags prior to the beginning of field work. This allowed us to oven-dry the filter bags and then re-weigh them to determine a dry weight of sediment entrained in runoff or material deposited as rainsplash.

Our procedure called for the bags to be dried at 105°C for 12 to 24 hours. We dried all sample bags at La Selva and attempted to follow this procedure, but as a result of a malfunctioning oven thermostat, some bags were scorched. This scorching resulted in a reduction of the weight of affected bags, and thus made a simple determination of the dry weight of rainsplash or runoff material impossible. To account for this change in weight, I performed a test in which I oven-dried five empty, pre-weighed bags for 8 to 12 hours at incrementally increasing temperatures. After each oven-drying session, the bags were weighed and the color, extent, and location of scorching on each bag was compared to that of the bags scorched at La Selva. By this means, I calculated an approximate change in weight for each affected sample bag depending on its visible degree of scorching. This change in weight was then added to the oven-dried bag weight, and thus I was able to determine a corrected dry weight for materials in scorched bags. All weights for runoff sediments and rainsplash materials given in the text are

either unaffected by scorching or are corrected for scorching. A more thorough description of the test procedure is located in Appendix A and a listing of all sample bags is included in the complete database in Appendix B.

Bulk Density

Chris Buhi, Glenn Hyman, and I took bulk density samples using a standard hammer auger sampling device. The sampling head is made up of a 8.5 cm long, thick-walled steel tube with an inner (sampling) diameter of 4.85 cm. The tube is threaded at the top and the bottom is tapered and sharpened. The aluminum sampling sleeves that fit inside the cutting head are 5 cm long and are the same inner diameter as the cutting edge. These sleeves allow for the easy removal and storage of bulk density samples in the field. The only departure from standard sampling practice was the substitution of a T-shaped twist auger handle for the sliding hammer due to field equipment weight limitations. I am confident, however, that our sampling method prevented this substitution from affecting our results. When sampling in the field, we inserted the sampling head to a depth that would fill most of the sampling sleeve with soil, but still left a small amount of space below the top wall of the sampling head (we later measured the depth of the empty space to determine an accurate sample volume before drying). We thus avoided the possible soil compaction that would have resulted from forcing an already full sampling head further into the soil.

We took bulk density samples at sites that seemed to best represent both the spots chosen for rainfall simulation and the surrounding forest floor or trail areas. Where possible, we took samples directly on rainfall simulator sites following tests. When samples were taken adjacent to rainfall simulator sites, all relatively undecayed plant material was removed so that the surface organic layer would be comparable to that of a rainfall simulator test site.

Samples collected at Jatun Sacha were stored in plastic bags and brought to La Selva due to the lack of an on-site laboratory oven and balance at Jatun Sacha. Following collection of

samples at La Selva, both batches were oven-dried and weighed on a digital balance in the La Selva laboratory. We collected a total of 22 samples (representing 16 site groups -- multiple samples from the same site group were averaged together) from on-trail sites and 25 (also representing 16 site groups) from off-trail sites. These samples provide approximate soil bulk density values for all but two of the rainfall simulator site groups (group H at Jatun Sacha, and group R at La Selva -- Figure 3.2, Figure 3.4, or Appendix B).

I compared bulk density values between Jatun Sacha and La Selva and between on and off-trail sites by generating box plots using the bulk density values that represent all rainfall simulator sites. Each bulk density value represents either a single sample or an average if multiple samples were taken in close proximity to an on or off-trail rainfall simulator site. I generated all plots in Deltagraph Pro version 3.5 for Macintosh.

Penetrometer Measurements

I measured soil penetrability while in the field using a static cone penetrometer. The penetrometer consists of a T-grip handle attached to a pressure gauge and housing assembly, a 0.75 m extension rod, and a sliding cone with a diameter of 1.5 cm^2 (Brainard-Kilman, n.d.). My sampling procedure was as follows: first, I checked to see if the maximum indicating pointer on the pressure gauge was resting at zero; second, I slowly and steadily inserted the penetrometer into the ground to a depth of 30 cm; third, I read and recorded the position of the maximum indicating pointer; and fourth, I removed the penetrometer and reset the pointer to zero. The only departure from standard procedure was that if, while inserting the instrument into the ground, I hit large roots or gravel, I immediately removed the penetrometer, reset it to zero, and repeated the measurement close by. At each site, both on and off-trail, I made penetrometer measurements at a number of points near the rainfall simulator site and bulk density sampling site. On-trail, I established transects of the trail at each site, with measurements taken at regular intervals (10 cm at La Selva and 50 cm at Jatun Sacha) across the trail and a short

distance into the surrounding forest on either side. Off-trail, I took a number of measurements (between 5 and 11) in close proximity to rainfall simulator test sites, but here, no transects were established, as the data were intended to be averaged.

Field use of the penetrometer at Jatun Sacha was trouble-free. However, the failure of a spring in the pressure gauge rendered it useless for a large part of our work at La Selva. As a result, on a return trip to La Selva in February 1994, I brought a repaired penetrometer and revisited all nine rainfall simulator site groups.

Rainfall Data Collection

At Jatun Sacha, rainfall data are collected in two places: Casa de Alejandro Suárez, which is in the floodplain and river terrace section of the reserve near the Río Napo, and at a site near the staff living quarters near the main station area. The type of collector used at both collection sites is a simple rain gage, and rainfall has been checked and recorded daily since 1986.

Daily rainfall data have been collected at La Selva for over 30 years (Sanford et al., 1994). Records of daily precipitation from the Rafael's Point measurement station run from 1963 to 1991. Daily records for the Bridge Station span from 1982 to 1991. In 1992, a class 2 meteorological station was installed adjacent to the workshop/generator building near the main entrance. In addition to daily precipitation data, the new station also automatically records hourly measurements. The hourly record used in this thesis covers the period from October 1992 to February 1994, the date of my second visit to La Selva.

Trail Extent Estimation

To calculate possible impacts from trail use, knowledge of the extent and character of the trail system at each reserve is absolutely essential. I determined the length of trails on different soil types in each reserve using a number of different maps and reference materials

(Instituto Geográfico Militar, 1988; Jatun Sacha Foundation, n. d.; Mejía, 1992; Organization for Tropical Studies, 1987; Sancho and Mata, 1987; and Sollins et al., 1994) and a Dietzgen map wheel. First, I measured trail lengths in each reserve and recorded the length of trails traversing each soil type. For La Selva, I then grouped all of the specific soil types into the two broad headings of residual and alluvial/valley-bottom soils to match the two Jatun Sacha soil types. Concrete trails were not included in this study primarily because the impermeable trail surface is not suited for the type of comparative on and off-trail rainfall simulation experiments that we conducted. At Jatun Sacha, deciding how much of the total trail length was made up of concrete trails was easy, as there were no concrete trails at all. At La Selva, however, this determination required a bit more leg work. On my return visit in February 1994, I walked all of the trails in the vicinity of the main station area, and was thus able to measure the length of all trail types -- cement, boardwalk, and bare earth -- for the majority of the reserve.

CHAPTER 5

RESULTS

Runoff Generation and Sediment Mobilization

Paired and Unpaired Databases

In total, there were 91 rain events to analyze (complete database is located in Appendix B). As a first step, I computed the mean and standard deviation of the volume of water applied at each test site. For all 91 sites, the mean was 354.9 ml (19.5 mm) with a standard deviation of 204.1 ml (11.2 mm). I decided to remove all outlier events that were located more than two standard deviations from the mean. When I applied this condition to the database, three rainfall events fit the criteria for removal. All were off-trail sites at La Selva, and in fact, all were located in the same site group -- J (Figure 3.4). These three sites represent tests for a runoff threshold on an off-trail area with extremely high infiltration rates. The first two tests of 49.2 and 50.1 mm in 30 minutes produced no runoff. The third test, at 93.1 mm of rain in 30 minutes, produced only 69 ml of runoff, which equates to 4.1% of total rainfall. With these outlier events removed, the descriptive statistics for the remaining sites changed substantially. The mean rainfall dropped to 327.1 ml (18.0 mm) and the standard deviation dropped to 120.7 ml (6.6 mm). The remaining 88 events became the "unpaired" database (Appendix B).

Using the unpaired database as a starting point, I constructed the "paired" database to minimize any field bias in the rainfall simulation data that would favor a rejection of the null hypothesis that there was no difference between on-trail and off-trail sites. To be included in the paired database, an on-trail site had to be matched with an off-trail site from the same site group that had received a comparable or greater amount of rain. To constitute a matched

pair, the rainfall at the off-trail site could in no case be more than 50 ml (2.7 mm) less than that at the on-trail site. There was no upper limit on the amount of off-trail rainfall if the off-trail site did not produce runoff (i.e., if an off-trail site did not produce any runoff at a given high intensity, it is reasonable to assume that it would not have produced any runoff at a lower intensity that matched that of the on-trail test). When an off-trail site with no runoff was paired with an on-trail site that had received less rainfall, the rainfall total of the off-trail site was reduced to match that of the on-trail site. In cases where an off-trail site did produce measurable runoff or splash material, it was only paired with the on-trail site if the rainfall off-trail was no more than 100 ml (5.5 mm) more than at the on-trail site. Seven off-trail sites and one on-trail site were paired with two or more sites within their site groups. The 45 matched pairs (Appendix B) that resulted represent all but one (group H) of the 18 site groups where rainfall simulation experiments were conducted and should thus be fairly representative of all the sites tested.

Runoff

Analysis of the paired and unpaired databases reveals that runoff production differs markedly between on and off-trail sites (Table 5.1). Despite the fact that simulated rainfall both on and off-trail (unpaired database) was higher at La Selva (17.7 mm versus 16.7 mm on-trail, and 21.3 mm versus 16.6 mm off-trail), Jatun Sacha sites had far higher on and off-trail runoff coefficients. At Jatun Sacha, off-trail sites averaged 12.7 ml of runoff while on-trail sites averaged 168.3 ml (4.8% versus 56.2% of rainfall). At La Selva, the trend was similar -- off-trail sites averaged 0.3 ml of runoff while on-trail sites averaged 87.1 ml (0.5% versus 33%). I performed four t-tests to determine whether the differences between on and off-trail sites in runoff volume and coefficient of runoff were significant at the .05 level. The t-tests were based on a null hypothesis of no difference between on and off-trail sites and an alternative

Table 5.1. Means and t-values for runoff volume and coefficient of runoff.

t-test	Paired Mean	Paired t-value	Unpaired Mean	Unpaired t-value
Jatun Sacha off vs on runoff volume	12.7 - off 168.3 - on	**-4.89**	18.2 - off 186.4 - on	**-5.02**
Jatun Sacha off vs on coefficient of runoff	3.9 - off 54.7 - on	**-6.21**	4.8 - off 56.2 - on	**-7.15**
La Selva off vs on runoff volume	0.3 - off 87.1 - on	**-5.01**	1.8 - off 114.2 - on	**-4.89**
La Selva off vs on coefficient of runoff	0.1 - off 29.8 - on	**-4.81**	0.5 - off 33.0 - on	**-5.28**

hypothesis that off-trail sites would produce significantly less runoff or have significantly lower runoff coefficients. As a result of my assumption of directionality in the results, all of the t-tests I performed were of the one-tailed variety. Results of the t-tests are listed in Table 5.1. The differences in runoff volume or coefficient of runoff between on and off-trail sites are significant in every case. In fact, the t-values for these tests were far below the critical t-value, which ranged from -1.70 to -1.74. For paired sites, average on-trail runoff was 13 times greater than off-trail runoff at Jatun Sacha and on-trail runoff was almost 300 times greater than off-trail runoff at La Selva.

Similarly, the unpaired database demonstrated significant differences in runoff response between on and off-trail surfaces (Table 5.1). The t-values were again quite low when compared with the critical value of t, which ranged from -1.69 to -1.72. Jatun Sacha unpaired on and off-trail sites showed a tenfold difference in runoff volume while unpaired La Selva on-trail sites had 63 times the runoff of off-trail sites.

To determine which variable had the greatest effect in producing the observed differences in rainfall response between on and off-trail sites, I computed regressions for both the paired and unpaired databases with runoff volume as a function of a number of different

variables (Table 5.2). First, I examined runoff as a function of rain intensity. Off-trail, there was absolutely no relationship between rain intensity and runoff, as would be expected due to the high percentage of sites that received large amounts of rainfall but produced no runoff. On-trail, however, the story was somewhat different -- the regression of runoff volume as a function of rainfall intensity produced an r-square of .14 in the paired database -- a weak relationship. However, the unpaired database, with the addition of eight on-trail rain events with greater than average intensity and runoff coefficient, gave an r-square value of .40 for the same regression. There was also a weak but highly significant negative relationship when runoff volume was regressed against time (in minutes) to runoff.

Regressions for on and off-trail coefficients of runoff against time to runoff yielded similarly significant results showing modest negative relationships.

Table 5.2 Regression results for runoff volume and coefficient of runoff as functions of rain intensity, time to runoff, and bulk density.

Regression	Paired r-square	p-value	Unpaired r-square	p-value
X = rain in mm Y = on-trail runoff volume	**.14**	**.0129**	**.40**	**.0000008**
X = rain in mm Y = off-trail runoff volume	.01	.4876	.02	.4611
X = time to runoff Y = on-trail runoff volume	**.26**	**.0004**	**.24**	**.0003**
X = time to runoff Y = off-trail runoff volume	**.34**	**.00005**	**.36**	**.00005**
X = bulk density Y = on-trail runoff volume	.06	.1228	.05	.1503
X = bulk density Y = off-trail runoff volume	.02	.4262	.002	.7680
X = rain in mm Y = on-trail coefficient of runoff	.007	.5804	.06	.0911
X = rain in mm Y = off-trail coefficient of runoff	.008	.5698	.008	.5837
X = time to runoff Y = on-trail coefficient of runoff	**.30**	**.0001**	**.32**	**.00002**
X = time to runoff Y = off-trail coefficient of runoff	**.34**	**.00002**	**.40**	**.00002**

Sediment Mobilization

My results show that far more sediment is mobilized by rainfall on trails than in off-trail areas. Sediment mobilization is expressed in three different ways in the data. The first is runoff weight, which is the dry weight of sediment entrained in water standing at the ground surface within the rainfall simulator basepiece during a test. Second is splash weight, which is the dry weight of material splashed by raindrop impact out of the test area and onto the large angled lip of the basepiece. The third component is total sediment weight, which is simply the sum of runoff weight and splash weight and represents the dry weight of all sediment collected during a single rainfall simulation test.

I performed six t-tests each for the paired and unpaired databases -- results of these tests are shown in Table 5.3. In these tests, I was looking for differences in the on and off-trail values for runoff weight, splash weight, and total sediment weight for both Jatun Sacha and La Selva. Like the tests of runoff volume in the previous paragraphs, all of these t-tests were one-tailed

Table 5.3. Means and t-values for runoff, splash, and total sediment weights.

t-test	Paired Mean	Paired t-value	Unpaired Mean	Unpaired t-value
Jatun Sacha off vs on runoff weight	0.07 - off 1.18 - on	**-5.53**	0.06 - off 1.16- on	**-6.26**
Jatun Sacha off vs on splash weight	0.06 - off 1.20 - on	**-3.46**	0.04 - off 1.09 - on	**-3.64**
Jatun Sacha off vs on total sediment weight	.12 - off 2.38 - on	**-5.79**	0.10 - off 2.24 - on	**-6.38**
La Selva off vs on runoff weight	0.02 - off 0.53 - on	**-3.43**	0.11 - off 0.62 - on	**-2.85**
La Selva off vs on splash weight	0.07 - off 0.77 - on	**-6.03**	0.26 - off 0.77 - on	**-2.68**
La Selva off vs on total sediment weight	0.09 - off 1.31 - on	**-5.41**	0.38 - off 1.39 - on	**-3.08**

because I performed them with the belief that off-trail sites would produce smaller amounts of sediment than on-trail sites. As in the t-tests for runoff generation, every test showed that there was a statistically significant difference in the amount of sediment produced by on and off-trail sites. Critical values of t at the .05 confidence level ranged from -1.75 to -1.68.

Regressions exploring relationships between the independent variables of rain intensity, runoff coefficient and bulk density, and the dependent variables of runoff weight, splash weight and total sediment weight for databases representing both Jatun Sacha and La Selva combined are shown in Table 5.4. The independent variable that best explains differences in sediment mobilization is the coefficient of runoff -- three regressions in the paired database and two in the unpaired database that included runoff coefficient were found to contain statistically significant relationships ($p < .05$). The strongest relationship was between on-trail runoff sediment weight and runoff coefficient. This moderate relationship lends weight to the conclusion that trail sites with greater runoff coefficients should also produce larger amounts of sediment entrained in ponded water at the surface by the energy of raindrop impact.

The second-strongest relationship was between on-trail total sediment weight and coefficient of runoff. This relationship owes virtually all of its strength to the portion of total sediment weight made up by runoff weight, as the regression for on-trail splash weight as a function of coefficient of runoff shows almost no relationship. Regression of off-trail runoff weight as a function of coefficient of runoff produces an r-square of .26 (paired, statistically significant) and .06 (unpaired, not significant). The only other regression that produced a statistically significant result was that of on-trail runoff sediment weight computed as a function of rain intensity. In the unpaired database, this regression produced a very weak relationship -- an r-square of .10 ($p=.0242$) while in the paired database, the same regression produced an r-square of .003 and was not statistically significant ($p=.0863$). Other regressions in Table 5.4 showed little or no relationship.

Table 5.4 Regression results for splash, runoff, and total sediment weights as functions of rain intensity, coefficient of runoff, and bulk density.

Regression	Paired r-square	p-value	Unpaired r-square	p-value
X = rain in mm Y = on-trail total sediment weight	.06	.1009	.04	.1427
X = rain in mm Y = off-trail total sediment weight	.01	.4491	.001	.8350
X = rain in mm Y = on-trail runoff sediment weight	.07	.0863	**.10**	**.0242**
X = rain in mm Y = off-trail runoff sediment weight	.03	.2865	.004	.7216
X = rain in mm Y = on-trail splash sediment weight	.02	.3723	.0004	.8963
X = rain in mm Y = off-trail splash sediment weight	.006	.6078	.0004	.9070
X = coefficient of runoff Y = on-trail total sediment weight	**.30**	**.0001**	**.28**	**.00006**
X = coefficient of runoff Y = off-trail total sediment weight	.08	.0564	.02	.3877
X = coefficient of runoff Y = on-trail runoff sediment weight	**.41**	**.000002**	**.43**	**.0000002**
X = coefficient of runoff Y = off-trail runoff sediment weight	**.26**	**.0004**	.06	.1289
X = coefficient of runoff Y = on-trail splash sediment weight	.06	.1158	.04	.1748
X = coefficient of runoff Y = off-trail splash sediment weight	.02	.3546	.01	.6390
X = bulk density Y = on-trail total sediment weight	.04	.1740	.04	.1986
X = bulk density Y = off-trail total sediment weight	.001	.8665	.07	.1188

Jatun Sacha on-trail sites averaged 1.16 g of runoff sediment while La Selva trail sites only averaged 0.62 g. A portion of this difference is likely to be a result of the difference in coefficient of runoff between the two reserves.

Bulk Density

Figure 5.1 shows the distribution of bulk density values for all off-trail sites versus all on-trail sites. The horizontal line through the center of the box represents the 50th percentile, the top of the box represents the 75th percentile, the bottom represents the 25th percentile, the

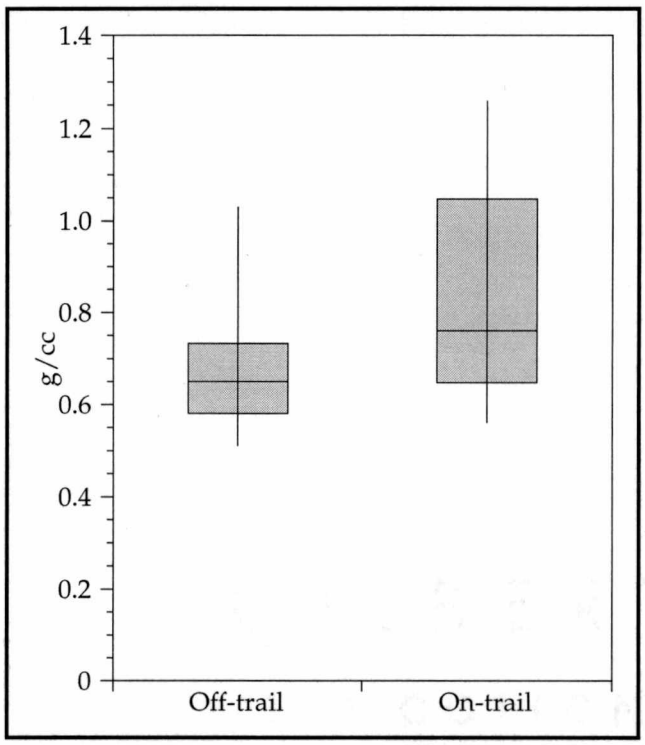


Figure 5.1 Off versus on-trail bulk density for all sites.

top whisker represents the maximum value, while the bottom whisker represents the minimum. The median of the off-trail values is 0.65 g/cc while the median of on-trail values, 0.76 g/cc, is greater than the 75th percentile off-trail value.

Differences become somewhat clearer when the data are split into separate categories for each station. From Figure 5.2, it becomes apparent that, for both off and on-trail values in Figure 5.1, the Jatun Sacha data basically made up the upper 50% of the box while the La Selva data comprised the lower 50%. Mean off-trail bulk density at Jatun Sacha is 31% greater than that at La Selva, while mean on-trail bulk density at Jatun Sacha is 41% greater than that at La Selva.

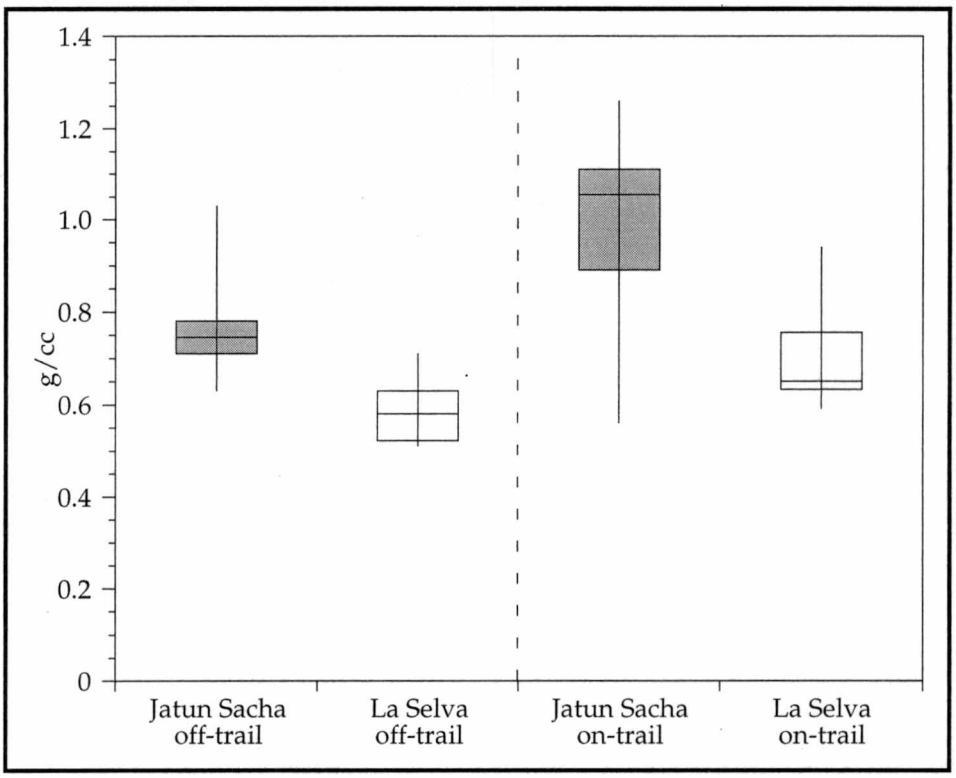


Figure 5.2 Off versus on-trail bulk density by reserve.

When soils are taken broadly to be residual or alluvial, some patterns in bulk density begin to emerge (Figure 5.3). For off-trail residual soil sites, the Jatun Sacha mean bulk density is 21% greater than the La Selva mean. Similarly, for off-trail alluvial sites, the Jatun Sacha mean is 25% greater than the mean for La Selva sites. On-trail, however, the gap between the means widens -- on residual soils, the Jatun Sacha mean is 36% higher than the La Selva mean; on alluvial soils, the mean for Jatun Sacha is 34% higher. Mean bulk density values for on and off-trail sites within the same broad soil type in the same reserve indicate further differences between the two stations. Jatun Sacha residual soils have an on-trail mean bulk density that is 27% higher than the off-trail mean, while Jatun Sacha alluvial soils have an on-trail mean 28% higher than off-trail. La Selva soils, however, do not show quite as much variation in means between on and off-trail sites. La Selva residual soils have an on-trail mean bulk density that is 14% higher than the off-trail mean. For alluvial soils at La Selva, the result is

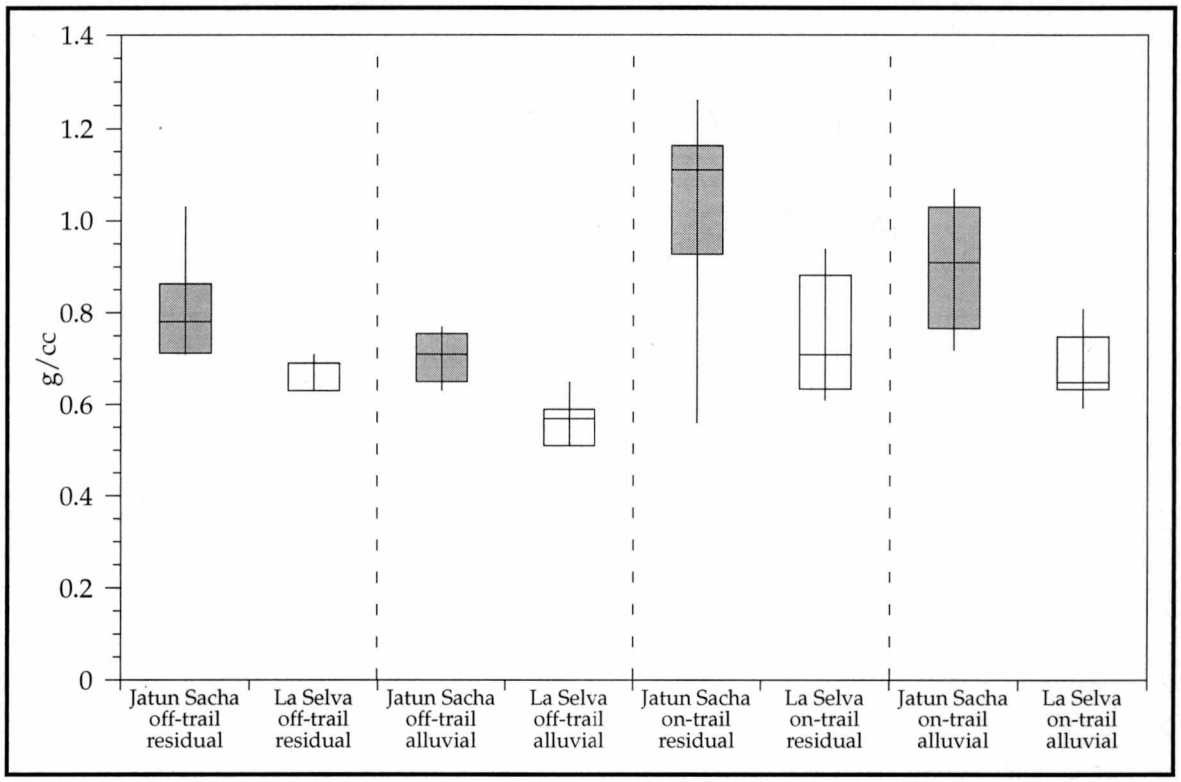


Figure 5.3 Off versus on-trail bulk density by reserve and broad soil type.

similar: on-trail sites have 19% higher mean values than off-trail sites.

Penetrometer Values

The penetrometer measurements tended to be highly variable over very short (20 cm) distances, and are thus hard to characterize in general terms. When one views the penetrometer results in graphic form, it appears that there is a weak trend toward higher values on than off trails. For La Selva, this perception is supported by the fact that the 1 m average on-trail penetrometer readings (the average of all penetrometer readings taken within 0.5 m of the center of the trail) are slightly higher than the average of off-trail readings. At Jatun Sacha, however, the reverse is true -- the off-trail readings are slightly higher than those on-trail. Graphic representations of on and off-trail penetrometer readings are shown in Figure 5.4 (Jatun Sacha) and Figure 5.5 (La Selva).

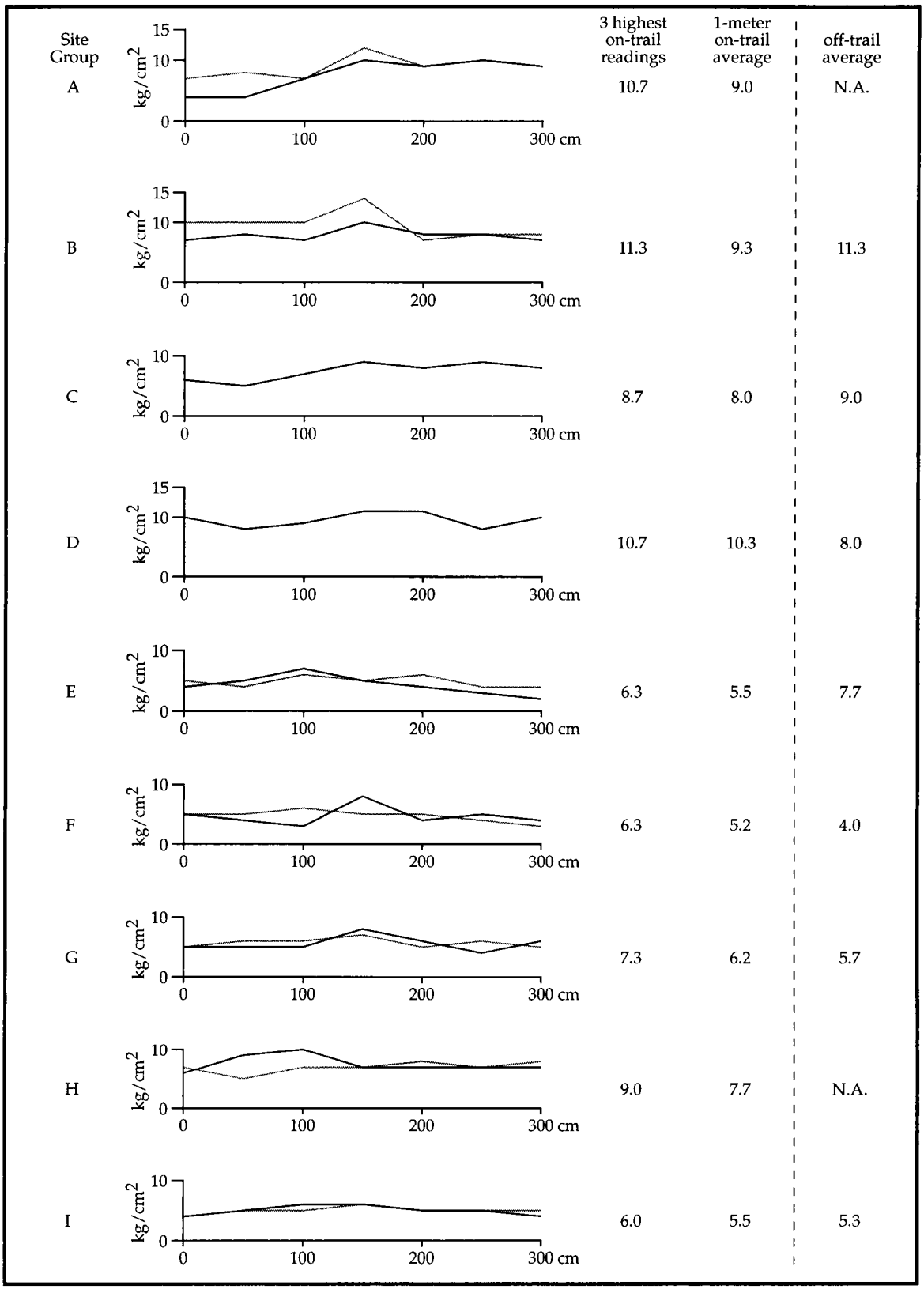


Figure 5.4 **Jatun Sacha penetrometer readings. Graphs with two lines represent site groups where I measured along two transects. Transects were centered on trail centers.**

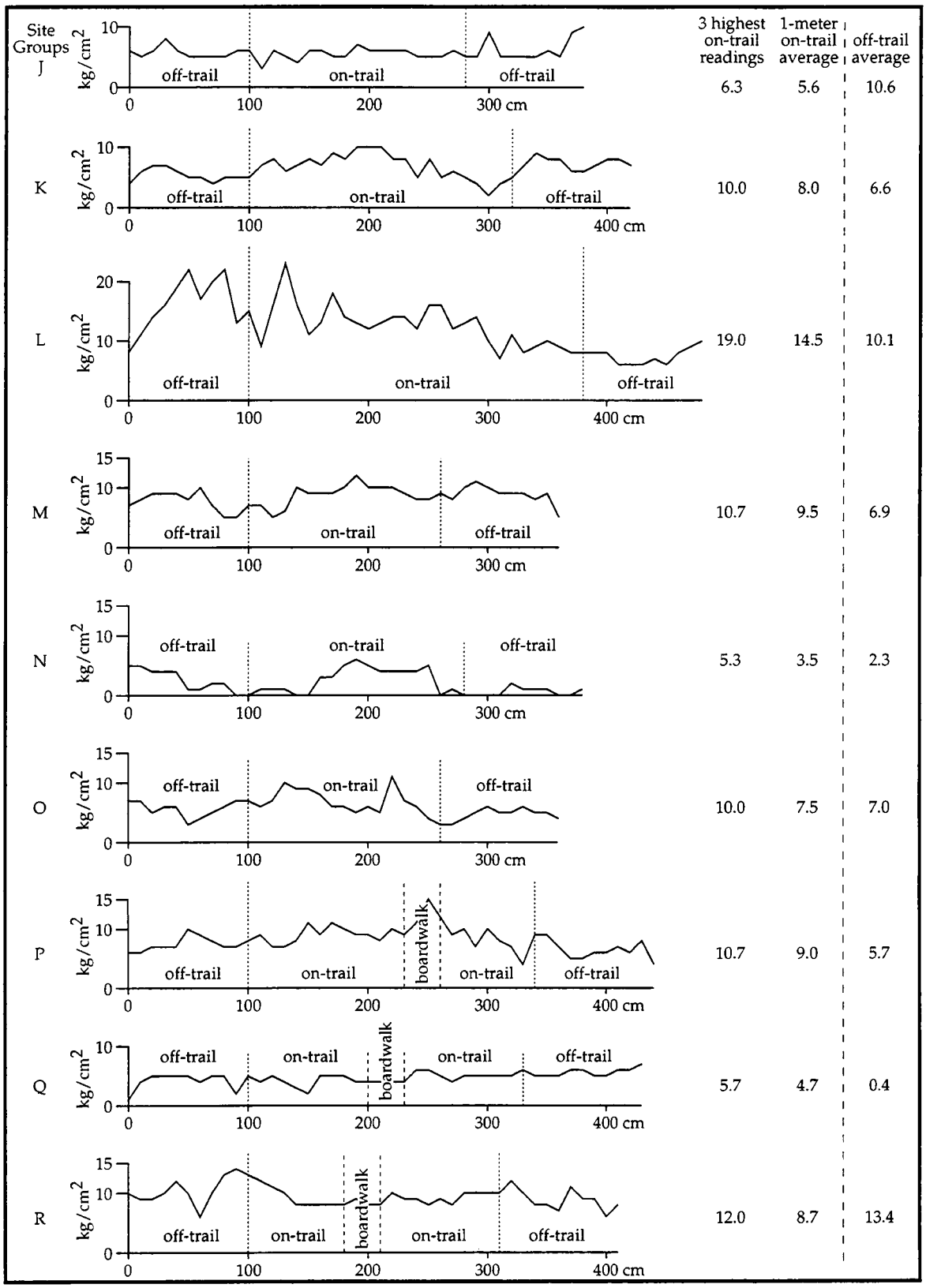


Figure 5.5 La Selva penetrometer readings. Dotted lines represent boundaries between off-trail, on-trail, and boardwalk areas.

The Relationship of Infiltration to Bulk Density Values and Penetrometer Readings

I calculated regressions to test for a relationship between bulk density and coefficient of runoff and time to runoff (surrogates for infiltration). In 12 regressions of the two infiltration measures as functions of on-trail, off-trail, Jatun Sacha, La Selva, and combined Jatun Sacha and La Selva data (Table 5.5), only one relationship even came close to being statistically significant. Coefficient of runoff calculated as a function of Jatun Sacha and La Selva on-trail bulk density values was just outside the .05 level of significance.

After the failure to find any statistically significant relationship between infiltration and bulk density, I tested for relationships between static cone penetration resistance and infiltration. I again calculated regressions, finding three statistically significant relationships and a fourth that was close enough to warrant attention (Table 5.6). All of the

Table 5.5 Time to runoff and coefficient of runoff as functions of bulk density.

Regression	r-square	p-value
X = Jatun Sacha on-trail bulk density Y = time to runoff	.000002	.9957
X = Jatun Sacha off-trail bulk density Y = time to runoff	.0004	.9304
X = Jatun Sacha on-trail bulk density Y = coefficient of runoff	.02	.5771
X = Jatun Sacha off-trail bulk density Y = coefficient of runoff	.02	.5875
X = La Selva on-trail bulk density Y = time to runoff	.008	.6484
X = La Selva off-trail bulk density Y = time to runoff	.008	.7277
X = La Selva on-trail bulk density Y = coefficient of runoff	.01	.5682
X = La Selva off-trail bulk density Y = coefficient of runoff	.04	.3989
X = JS+LS on-trail bulk density Y = time to runoff	.04	.2061
X = JS+LS off-trail bulk density Y = time to runoff	.01	.5921
X = JS+LS on-trail bulk density Y = coefficient of runoff	.08	.0621
X = JS+LS off-trail bulk density Y = coefficient of runoff	.004	.6908

Table 5.6 Measures of infiltration as functions of penetration resistance.

Regression	r-square	p-value
X = Jatun Sacha on-trail 3 highest readings Y = time to runoff	.19	.0777
X = Jatun Sacha on-trail 1-m average Y = time to runoff	**.25**	**.0407**
X = Jatun Sacha off-trail penetrometer average Y = time to runoff	.02	.5522
X = Jatun Sacha on-trail 3 highest readings Y = runoff coefficient	**.28**	**.0278**
X = Jatun Sacha on-trail 1-m average Y = runoff coefficient	**.35**	**.0112**
X = Jatun Sacha off-trail penetrometer average Y = runoff coefficient	.03	.4660
X = La Selva on-trail 3 highest readings Y = time to runoff	.003	.7611
X = La Selva on-trail 1-m average Y = time to runoff	.01	.7090
X = La Selva off-trail penetrometer average Y = time to runoff	.001	.9094
X = La Selva on-trail 3 highest readings Y = runoff coefficient	.01	.5436
X = La Selva on-trail 1-m average Y = runoff coefficient	.01	.6551
X = La Selva off-trail penetrometer average Y = runoff coefficient	.03	.5249
X = JS+LS on-trail 3 highest readings Y = time to runoff	.0002	.9097
X = JS+LS on-trail 1-m average Y = time to runoff	.004	.6909
X = JS+LS off-trail penetrometer average Y = time to runoff	.006	.6321
X = JS+LS on-trail 3 highest readings Y = runoff coefficient	.004	.6826
X = JS+LS on-trail 1-m average Y = runoff coefficient	.0004	.9012
X = JS+LS off-trail penetrometer average Y = runoff coefficient	.01	.4856

regressions with significant relationships were for Jatun Sacha on-trail sites. The two strongest relationships involved the runoff coefficient as a function of (1) the average of all readings taken in a 1-m section of the transect centered on the trail midline and (2) the average of the three highest on-trail penetrometer readings for each site. Time to runoff expressed as a function of the 1-m average was significant at .05, whereas the relationship between time to runoff and the average of the three highest on-trail readings was not. None of the other regressions calculated were close to statistical significance.

The Relationship of Penetrometer Readings to Bulk Density Values

To determine if penetrometer readings could be used as a surrogate for bulk density values, I examined three correlations. First, I computed the correlation coefficient of off-trail average penetrometer readings for each off-trail site at Jatun Sacha and La Selva with its recorded bulk density. This calculation produced an r-value of .52 and a p-value of .043 (Figure 5.6).

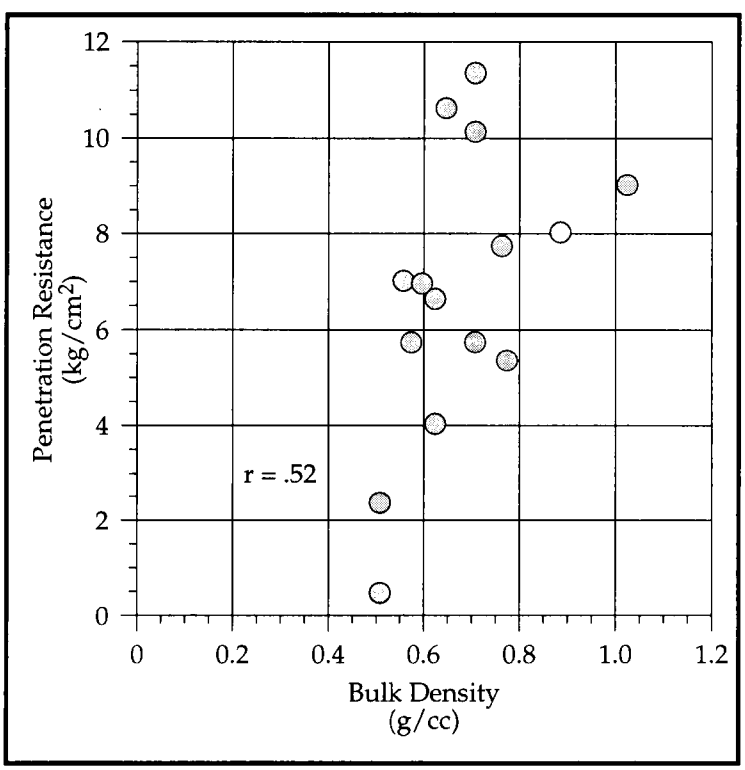


Figure 5.6 Off-trail average penetrometer reading as a function of bulk density.

Second, I looked for correlation between the average of the three highest penetrometer values for each on-trail site at both Jatun Sacha and La Selva and bulk density and found no relationship (r-value = .03, p = .912). In the third correlation, between the 1 m average penetrometer reading for each on-trail site at Jatun Sacha and La Selva and bulk density, I again found no relationship (r-value = .15, p = .529). Thus, while off-trail average penetrometer readings showed a significant relationship with bulk density, it appears that on-trail, there was little or no association between penetrometer values and bulk density values.

Trail Extent

Subtracting the cement trails from the La Selva total, I found that there are 19.2 km of trails on alluvial or valley bottom soils and 16.5 km of trails on residual soils. At Jatun Sacha, there are roughly 1.9 km of trails on alluvial soils and 9.6 km on residual soils.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

Discussion

How does runoff generation differ between on-trail and off-trail sites?

At both Jatun Sacha and La Selva, significantly more runoff was generated on trail sites than on sites in the surrounding undisturbed forest. At Jatun Sacha, unpaired trail sites had a coefficient of runoff that was, on average, twelve times greater than that for off-trail sites. At La Selva, there was a sixty six-fold difference in average coefficient of runoff between on and off-trail sites. These striking differences are consistent with the general pattern of increased runoff on trails observed in temperate regions (Megahan, 1977; Dunne and Dietrich, 1982; Wilson and Seney, 1994) and in the more temperate environments of Andean Ecuador (Harden, 1992). Harden (1992) found average coefficients of runoff for trails in two areas in Ecuador and one in Tennessee to be between .51 and .59 -- comparable to Jatun Sacha values, but nearly twice as high as those at La Selva. These values translated to differences in average coefficient of runoff between on and off-trail sites of between 3 and more than 100 times -- again, comparable to results found at Jatun Sacha and La Selva.

The rainfall simulator findings of far more runoff on-trail than off are supported by field observations made during natural rain events. The following excerpt is from Dr. Harden's field notes for June 10, 1993, a day when there was a steady, 4-hour rain event at Jatun Sacha which her forest floor rain gauges recorded (depending on their placement) at 25 to 34 mm:

> Runoff is definitely occurring on the trails -- it's not a subtle phenomenon -- it cascades down the surface and is quite turbid. Where there is little slope, water ponds on the trails. In contrast, we don't think we see surface

flow in the forest. The closest thing to forest runoff is clear drops of water moving downhill across un-decomposed leaves.

In addition to the great differences in runoff generation between on and off-trail sites in this study, trail sites at Jatun Sacha produced, on average, two to three times more runoff (depending on which database is used) than those at La Selva, and off-trail runoff was nearly four times greater at Jatun Sacha. These differences occur despite the fact that average simulated rainfall at La Selva was even slightly greater than at Jatun Sacha, both on and off-trail. The average simulated rainfall depth for paired sites at Jatun Sacha was 15.7 mm on-trail and 15.9 mm off-trail, while at La Selva on-trail sites averaged 16.3 mm and the mean for off-trail sites was 16.1 mm. In the unpaired database, Jatun Sacha had a mean on-trail rain of 16.6 mm and a mean off-trail rain of 16.7 mm, while La Selva sites averaged 17.7 mm on-trail and 21.3 mm off-trail. What factors other than rainfall amount could account for this difference in runoff generation? Compaction due to trail use appears to play a major role in increasing runoff from trail surfaces in both reserves. With a more recent history of major disturbance (forest clearing, farming, ranching), however, it is possible that all of the soils (on and off-trail) at Jatun Sacha are in a relatively more compacted state, and are thus less readily infiltrable than they might otherwise be, giving rise to greater runoff than at La Selva, where major disturbance occurred in the more distant past.

Differences in runoff and infiltration may also be due to differences in soil texture and clay mineralogy. Clay percentages of the upper layers of La Selva soils are much higher than those of Jatun Sacha. Normally, this would lead to the conclusion that La Selva soils would have lower infiltration capacities due to the greater percentage of smaller soil pores associated with clays. However, this is not the case -- La Selva infiltration capacities are considerably greater than those of Jatun Sacha. I propose two possible explanations for this fact. First, the parent materials from which the soils in the two reserves are derived are quite different. At La Selva, the soils, both alluvial and residual, are formed from volcanic materials of fairly recent origin (two million years B. P. or less) (Sollins et al., 1994); at Jatun Sacha, however, the

residual soils are formed from quite old (middle Tertiary to upper Miocene) layers of clay and sand deposited by a shallow epicontinental sea (Mejía, 1992). The different source materials and different lengths of exposure to weathering processes should have resulted in the presence of different types of clay minerals at the two sites. With different responses to water, it is possible that the characteristics of these different clay minerals might account for much of the difference in infiltration. In fact, Radulovich et al. (1992) noted that certain soils of La Selva are unusual in that they behave like sands with regard to infiltration and drainage, but like clays with regard to their water-holding capacity. This unusual property is due to the fact that these soils are highly microaggregated (which results in a greater proportion of macropore-like flow). On one La Selva soil, in fact, the initial infiltration rate has been measured as high as 1,587 mm h^{-1} (Radulovich and Sollins, 1985). Another explanation for the discrepancy is the possible formation of surface seals on Jatun Sacha soils. It is possible that the difference in the clay fraction (16.5% average at Jatun Sacha, and 33.2% average at La Selva (when Arboleda soils with only 6% clay percentage are not included in the average)) could be enough of a textural difference to cause a greater incidence of seal formation from aggregate destruction by raindrops on Jatun Sacha soils, which would lead to the observed increased runoff volumes (Brady, 1984; Morgan, 1986; Hallsworth, 1987; Bradford and Huang, 1992).

It appears that Jatun Sacha and La Selva soils follow a pattern of impact similar to the model presented by Manning (1979). For example, Radulovich and Sollins (1985) found that the extremely high initial infiltration rate of the soil in their study decreased by roughly one-third with very light foot traffic over bare ground. Thus, with only a few passes of foot-traffic, it is possible for Manning's progression to soil erosion to begin.

How does sediment mobilization differ between on-trail and off-trail sites?

Like the results for runoff generation, all tests done to determine whether there was a significant difference between sediment generation on and off-trail produced results that showed statistically significant differences. The moderate (r-square = .40) and highly significant relationship between on-trail entrained sediment weight and runoff coefficient suggests a possible model for increased soil erosion. First, infiltration rates decrease with compaction, resulting in an increase in the runoff coefficient. This provides a transport mechanism (runoff) for sediment, as water gradually collects at the surface. While this is occurring, sediment is continually mobilized by raindrop impact -- a prescription for increased soil erosion. This would help to explain the observed difference in average on-trail sediment production between Jatun Sacha (1.18 g, in the paired database) and La Selva (0.53 g). With the twofold difference in runoff generation between Jatun Sacha and La Selva, greater sediment mobilization should occur at Jatun Sacha as a result of the greater volume of runoff. Differences in sediment generation between on and off-trail sites in a real rainstorm would almost certainly be greater than those found in rainfall simulation tests, because in the tests, water was not allowed to flow over the test site. In a real rainstorm, the downslope movement of water on trails would act to keep soil particles entrained and would almost certainly result in additional particle detachment.

The lack of runoff on most off-trail surfaces leads to the conclusion that little sediment movement will occur in these areas due to the lack of a surface transport mechanism. Additionally, the organic material generally found off-trail, even on these tropical soils, acts to inhibit rainsplash and the formation of surface seals by intercepting incoming raindrops. It is likely that only in situations where there is little or no organic material and where infiltration rates are quite low would conditions be conducive to the movement of significant amounts of sediment in undisturbed forest areas in the humid tropics.

What do these differences between on and off-trail sites mean in terms of trail degradation and net sediment movement?

To gauge the potential erosional impact of trails at Jatun Sacha and La Selva, I expressed mean sediment detachment as a function of rainfall per unit area. To do this, I averaged the simulated rainfall depths and the total detached sediment weight of on and off-trail rainfall simulator tests in both the alluvial and residual soils of both reserves (Table 6.1). When this measure of sediment detachment is coupled with data on trail length and width, it is possible to estimate a total amount of sediment being mobilized for transport at different areas within the reserves. This is not an actual measure of soil erosion, but is more accurately described as an erosion potential. Erosion would only occur with the addition of moving water as a transport mechanism.

Originally, boardwalk trail sites were grouped separately from bare earth trail sites. Based on the results of penetrometer measurements (Figure 5.5) and rainfall simulations, however, the compaction and runoff generation characteristics of boardwalk trail sites seem more similar to those of bare earth trail sites than to undisturbed forest areas. I believe that it is reasonable to assume that the area to the side of boardwalks receives a good bit of foot traffic due to the occasional lack of stability of these structures, the occasional lack of balance of their users, or a combination of the two. Thus, I considered boardwalk trails to simply be bare earth trails that happen to receive only sporadic usage. Concrete trails were subtracted from the La Selva totals primarily because we could not perform rainfall simulator tests on them. Additionally, I believe that, compared to boardwalk trails, there would be less trampling (and thus, less additional compaction) to either side of concrete trails following construction due to the fact that they are much wider (60 cm and 2 m at La Selva) and, therefore, easier to stay on top of.

At Jatun Sacha, trail width averaged 2 meters. The 1.9 km of trails on alluvial soils mobilize an average of 22 kg of sediment per mm of rain and the 12.7 km of trails on residual

Table 6.1 Calculated sediment detachment per mm of rainfall per m^2.

	Jatun Sacha on-trail	Jatun Sacha off-trail	La Selva on-trail	La Selva off-trail
Residual soils	8.36 g/mm/m^2	0.05 g/mm/m^2	2.85 g/mm/m^2	0.00 g/mm/m^2
Alluvial soils	5.80 g/mm/m^2	0.76 g/mm/m^2	4.99 g/mm/m^2	0.71 g/mm/m^2

soils mobilize 212.4 kg. Thus, in a 15 mm precipitation event (slightly below the average for rainfall simulations), 3,186 kg of sediment would be mobilized for transport on the trails of Jatun Sacha. At La Selva, where trails average 2.2 meters in width, each mm of rain that falls mobilizes 210.9 kg of sediment on the 19.2 km of trails on alluvial soils and 103.5 kg of sediment on the 16.5 km of trails on residual soils. In a 15 mm rain event, this translates to a sediment mobilization total for all trails of 4,716 kg.

The amount of sediment moved into streams and rivers is likely to be a fairly small percentage of these weights, as both reserves have trail areas that are nearly flat (and thus have no transport mechanism) or that drain into closed depressions. This small percentage, though, still represents a considerable amount of sediment lost from trails that could be deposited into streams. Take, for example, a hypothetical Jatun Sacha residual soil trail segment of 100 m that is concave in shape (to act as an efficient channel) and is sloped toward a stream so that 100% of all runoff water is transported to the stream. In a 15 mm rain, 17.4 kg of sediment would be deposited directly into the stream -- a large amount of sediment for such a small (200 m^2) source area. The comparable sediment loading from a trail on alluvial soil at La Selva would be 19.1 kg. At La Selva, according to the Sancho and Mata (1987) map, trails cross streams 35 times, and thus the possible impact of trails on water quality and on sediment accumulation in stream beds merits further consideration.

Even where trails do not drain directly to streams, the movement of sediment can have definite negative impacts. Steep trails anywhere in a reserve are faced with the problems of trail deepening and erosion. These problems are exacerbated by heavy foot traffic, which

makes even more sediment available for movement through mechanical detachment. In flat areas, the problem is not soil loss, but either ponding due to extremely low infiltration rates, or sediment deposition from run-on water associated with adjacent sloped trail areas. Both of these situations will produce soft or muddy footing for trail users. As a result, the trail will gradually widen as users go around muddy spots and trample trail-edge vegetation and compact the soil.

Off-trail sediment detachment values in this study represent a higher than normal mobilization of sediment because the organic cover that normally protects the ground surface from a majority of raindrop impacts was removed to make sites more comparable to trail sites. Thus, sediment mobilization off-trail probably occurs normally at much lower rates than the ones indicated by rainfall simulator tests.

As of April 1995, the La Selva Advisory Board is considering a proposal to expand the trail network to improve access to the southern and southwestern portions of the interior of the reserve (Sally Horn, personal communication, April 1995). Under this proposal, new cross-trails would run NW-SE (horizontally across Figure 3.4) to connect the southern portions of existing NE-SW trails (vertical on Figure 3.4). With this plan, however, would come at least two major problems. First, the proposed trails would cut through some of the most rugged topography at La Selva. Second, stream drainage at La Selva is basically perpendicular to the proposed route, so a large number of stream crossings is almost certain.

The rugged topography and remoteness of this section of the reserve would leave trail planners with five seemingly competing goals -- to minimize soil erosion, minimize physical danger, minimize travel time, minimize travel exertion, and maximize access to research sites. Simple measures, such as placing trails along natural contours whenever possible, would greatly reduce the potential for soil erosion, as a trail on a shallow slope would act as a less efficient runoff channel. Contouring would also minimize danger and exertion, but would likely increase travel time. Conversely, blazing a straight trail would be most efficient for access and

travel time, but the steep slopes involved could be quite taxing and hazardous, especially when wet. Erosion from steep slopes would be a problem, but with appropriate control measures, it could be greatly diminished. Water could be shunted from the trail surface onto the adjacent, readily infiltrable forest floor using angled drains or logs set into the trail. Alternatively, the trail could be laid out so that long, steep sections are punctuated by short switchbacks that turn slightly back uphill, allowing water to flow over the trail edge and onto the surrounding forest floor. The most practical solution is probably a combination of the use of contouring where natural benches or ridgetops are found, and straight trail blazing when no other route is convenient.

Whether these trails are contoured or straight-blazed, the problem of stream crossings must be addressed. In no case should a trail angle sharply down toward a stream. In fact, even trails that parallel streams on a shallow angle should have a generous buffer zone of undisturbed forest to absorb runoff water and filter out sediment.

How do runoff generation and sediment mobilization fit into the context of natural rainfall at Jatun Sacha and La Selva?

To answer this question, I analyzed rainfall data collected at both stations and unpublished results of experiments run with runoff detectors and rain gauges at both stations by Dr. Harden.

At Jatun Sacha, daily rainfall records have been kept since March, 1986. From these daily readings, one can only infer maximum values for 30-minute natural rains to use for comparison to the 30-minute intensities of rainfall simulator tests. The only information that I have about the intensity of rain at Jatun Sacha is that thunderstorms tend to occur from September to October and that, according to one of the founders of the reserve, David Neill, the storms are short (roughly 15 minutes) but quite intense (Neill, personal communication, June 1993). Over the six-year period from 1987 to 1992, 38 daily rainfall totals in Septembers and Octobers have exceeded 25 mm, with the highest being 143 mm. If at least a few of these 38

rainfall amounts over 25 mm represent precipitation from a single, short duration, high intensity thunderstorm, then it would be reasonable to expect to see at least a few events per year that match the upper range of simulated rainfall intensities (the mean simulated rainfall at Jatun Sacha was 16.7 mm and the high was 34.4) and a large number that match the lower intensities.

Another piece of evidence that rainfall simulations at Jatun Sacha were conducted at reasonable intensities comes from a series of tests run by Dr. Harden which showed that runoff occurs naturally at very low rainfall intensities. In the tests, she used modified 35 mm film canisters as runoff detectors on trails and the forest floor. After each rain event, she examined each detector, noting presence or absence of runoff, entrained sediment, and organic material. She also set up a number of small rain gauges near the runoff detector sites to measure the amount of natural rain that had fallen since the last recording interval. She found that even a very low intensity (1-3 mm/hr) precipitation event had the ability to produce runoff in all of the detectors, both on and off-trail. She noted substantial differences in the character of the runoff on and off-trail -- on-trail runoff is much more likely to entrain sediment while off-trail runoff is very likely to be completely clear (Harden, 1995). We observed one possible mechanism that could explain this clear runoff -- large *Cecropia sp.* leaves on the forest floor prevented immediate infiltration. As drops coalesced and began to move downslope, a few would make it into the collectors (organic material was not cleared away from around the runoff detectors as it had been for the rainfall simulator experiments). Off-trail runoff was always found in very small quantities (only ≤ 1 ml), while on-trail runoff was a much more pronounced phenomenon. As a result of the existence of large single-day rain events and the presence of natural runoff at low rainfall intensities, I believe that the rainfall simulations were conducted at intensities that were within the range of normal for Jatun Sacha.

Dr. Harden also used runoff detectors at La Selva, and found that runoff occurs on trails even during light to moderate rainfall, as at Jatun Sacha. For example, during one measurement

period (June 24-25, 1993), rain events of 3.1 mm over four hours and 1.0 mm over 2 hours (as recorded by the automatic rain gauge) produced runoff and sediment in all detectors on-trail and produced clear runoff in two of three off-trail detectors.

At La Selva, daily (24 hour) rainfall records have been kept consistently since late 1962. The most useful data for this study, however, come from the class 2 meteorological station installed in early 1992 (Sanford et al., 1994). This automated station was used to compile a record of hourly rainfall for the entire year of 1993. From these hour-long events, I was able to more exactly determine what thirty minute intensities are "normal" at La Selva (at least for this one year of data). I divided natural rainfall events for 1993 into categories for comparison to simulated rainfall intensities: 5-10 mm, 10-15 mm, 15-20 mm, and >20 mm. I then used two methods to attempt to infer a thirty minute intensity from hourly records. The first method is from Bell (1969). It involves the use of a depth duration ratio developed empirically from data collected in different parts of the world (continental U.S., Alaska, Hawaii, Puerto Rico, South Africa, Australia, and the former U.S.S.R.). In all of these cases, the ratio of 30 minute rainfall totals to 1 hour totals is about 0.79. Thus, multiplying the hourly totals of the La Selva data by 0.79, I can arrive at a good approximation of the intensity of 30-minute events. The second method is simple as well. If all of the rain recorded in a one hour period fell within the first 30 minutes, then the recorded hourly rain figure would represent the 30 minute figure. Conversely, if the rain event was evenly spread over the hour measuring period, then the two 30 minute measuring periods would each contain exactly half of the recorded hour rainfall. This gives maximum total and minimum total rainfall intensities. I divided these two groups (maximum possible and minimum possible rainfall intensity event totals) into the categories described above (5-10 mm, etc.) and counted the number of events that fell within each category. I took the mean of the maximum intensity and minimum intensity counts to represent the probable number of events occurring in each category. A graphic comparison of all La Selva rainfall simulation events with the results of these two different methods of inferring 30

minute natural rainfall is shown in Figure 6.1. The calculated number of events for 1993 represented in this figure comes from rainfall data recorded in what was a slightly drier than average year, with 3736 mm of precipitation as opposed to the long-term average of 3962 mm.

The detailed information the 1993 hourly rainfall record provides shows that rainfall simulation experiments were conducted well within the normal range of rainfall at La Selva. Also, the occurrence of runoff and the mobilization of sediment on trails that occurred with low-intensity natural rains in the runoff detector experiments leads me to believe that the low-end cutoff point of 5 mm in Figure 6.1 is fairly conservative in terms of the erosional potential of low-intensity natural rain events.

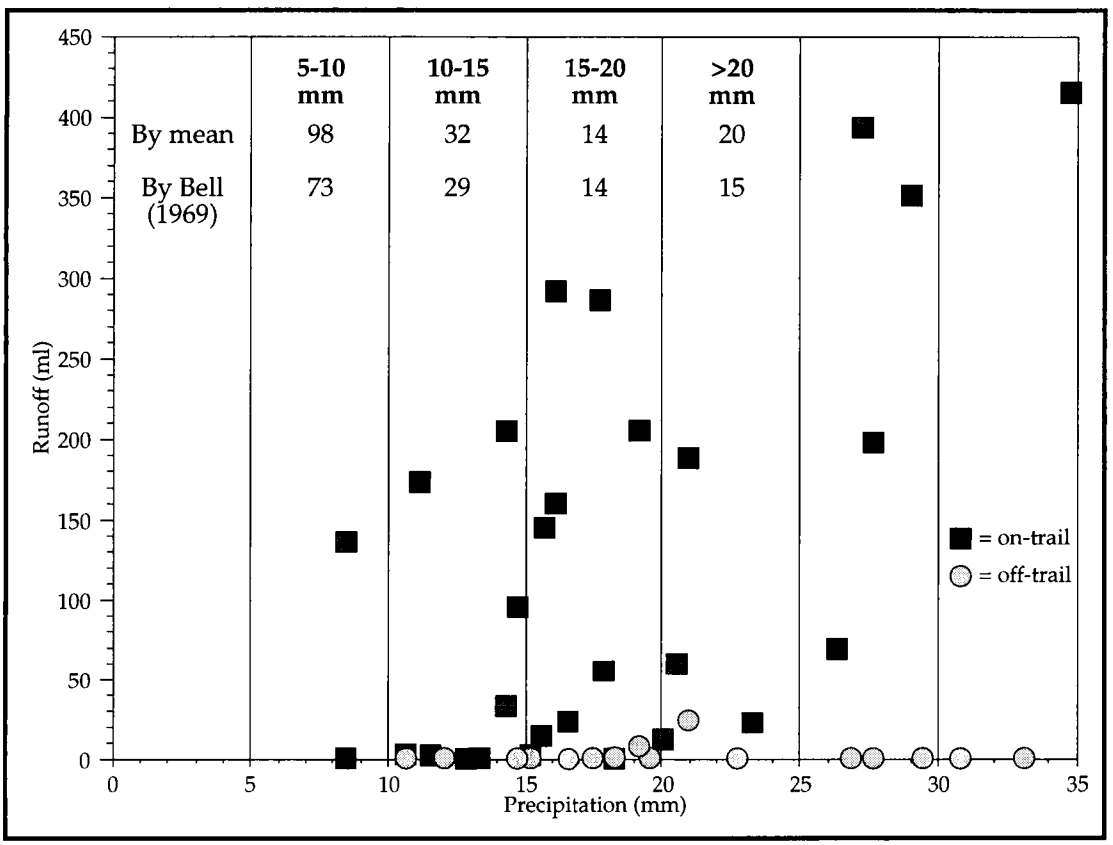


Figure 6.1 Relationship of simulated rain events to actual 30-minute rain events at La Selva. Number of events estimated from 1993 La Selva hourly data.

This figure of 5 mm, however, does represent rain that *actually reaches* the ground. Interception by forest canopy was discounted in this study for two main reasons. First, natural runoff was detected under canopy at La Selva after a 2 hour duration rain event that was measured at 1.0 mm by the La Selva Meteorological Station. Second, the inherent dependency of interception and throughfall on variables such as intensity of rain, vegetation type, and time since last rain makes the determination of a throughfall threshold in a tropical wet forest quite difficult (Lloyd and Marques, 1988) and of minimal practical use in this study.

Do soil bulk densities differ between on-trail and off-trail sites within the same immediate area?

The differences between on and off-trail paired bulk density samples at both Jatun Sacha and La Selva are distinct and fairly consistent. At Jatun Sacha, the on-trail average bulk density is 127% and 128% of off-trail values for residual and alluvial soils, respectively. At La Selva, the pattern is similar, though the differences are somewhat smaller -- La Selva on-trail residual soil bulk densities average 114% of the off-trail values, while on-trail alluvial soil sites average 119% of the off-trail values. These results, which show a definite rise in bulk density on trails, are comparable (though the differences are somewhat smaller) to those of Harden (1992), and Weaver and Dale (1978). This similarity is further evidence that the same basic set of erosion-inducing processes outlined by Manning (1979) are at work in both temperate and humid tropical environments.

The striking visual differences shown in Figures 5.1, 5.2 and 5.3, lead me to believe that statistical analysis of a larger data set would confirm significant differences between on and off-trail sites as a whole, within each reserve, and split by soil type.

I suggest that differences in bulk density between trail and off-trail sites are solely caused by compaction and vegetation loss due to trail use, as there is no other available mechanism to account for the large differences in bulk density over small distances in similar soils. Differences in the average degree of compaction of on and off-trail sites between Jatun

Sacha and La Selva suggest that differences in the mineralogy and/or textural makeup of soils between the two reserves causes a difference in their degree of compressibility.

Do Jatun Sacha and La Selva bulk density values differ in general?

Figures 5.2 and 5.3 show that bulk density values differ considerably between Jatun Sacha and La Selva, with Jatun Sacha values higher both on-trail and off. There is very little overlap between the on and off-trail samples, with the exception of one very high value in the Jatun Sacha off-trail category and one very low value on-trail at Jatun Sacha.

Off-trail bulk density should represent natural conditions. Differences between the two reserves -- 0.77 g/cm^3 for Jatun Sacha versus 0.59 g/cm^3 for La Selva -- may well be attributable to the larger percentage (Uehara and Gillman, 1981; Brady, 1984) and different type of clay in La Selva soils, and to their highly microaggregated state (Radulovich et al., 1992). It is also possible that these differences are due in part to the effects of recent human disturbance at Jatun Sacha. However, the tendency for Jatun Sacha soils to be more readily compressible with trail use (27-28% greater bulk density with use at Jatun Sacha and 14-19% greater bulk density with use at La Selva) was unexpected given the general tendency of higher clay content (i. e. La Selva) soils to be more readily compressible. Again, this might hinge on the particular types of clay and microaggregates found at La Selva.

Are the differences in measures of infiltration between rainfall simulator sites attributable to differences in bulk density or soil penetration resistance?

Regressions computed for coefficient of runoff and time to runoff on bulk density show no statistically significant relationship between bulk density and either of these measures of infiltration. There is probably an indirect relationship between the two, however, as compacted (higher bulk density) on-trail sites produce far more runoff than off-trail sites. It is probably not apparent as a direct effect on infiltration due to very localized effects of other soil variables, such as macroporosity, soil texture, percentage of organic material, and rainfall

effects such as the formation of soil crusts. Previous studies have found bulk density to be a contributing, but not a defining, factor in runoff generation (Harden, 1992). In this study, even a role for bulk density as a minor contributing factor to runoff generation is in serious doubt. Bulk density shared no statistically significant relationship with any measure of infiltration.

The regression of time to runoff and coefficient of runoff onto penetrometer measurements produced weak to moderate (r-square = .19 to .35) relationships for on-trail sites at Jatun Sacha. The lack of relationships at any other sites, however, casts doubt on the utility of penetrometer readings as a predictive measure of infiltration. The penetrometer *is* useful, however, for determining the degree of compaction a soil has undergone. For example, La Selva site group L had the highest penetrometer values recorded at either reserve. These high values were no surprise, as this trail was at one time a tractor road. At this site, the penetrometer recorded two peaks in resistance on-trail about 1.5 m apart -- roughly the distance between the wheels of a small farm tractor. This high penetration resistance for a highly compacted site underscores the fact that the penetrometer can function as a relative measure of soil compaction. Its utility as an absolute measure of compaction, however, is severely limited due to the fact that point-to-point variability in readings can be caused by numerous and sometimes subtle error factors (small roots, pebbles, etc.) that usually cannot be controlled for by the operator. The best way to de-emphasize these unavoidable errors, in my opinion, is to make a large number of measurements and then average them.

How accurately do static cone penetrometer measurements predict soil bulk density values? Is use of the penetrometer a viable alternative to bulk density measurement?

Except for the weak (r-square = .27) relationship between off-trail penetrometer readings and bulk density values, no linear relationship between the two measurements was detected in this study. This probably results from the fact that penetrometer readings are greatly affected

by water content and other basic soil characteristics (Brainard-Kilman, n.d.), while bulk density simply relies on the amount of pore space in the soil and the average density of soil particles (Hammitt and Cole, 1987). The effects of soil water content may be borne out in the data as a result of the malfunction, repair, and reuse of the penetrometer. Despite the fact that the gauges were identical in construction and were both calibrated, there may have been some difference in penetrometer readings due to different soil moisture conditions, as the first sampling was in June 1993, during the wet season, and the second was in February 1994, in the middle of the dry season.

As a result of the observed lack of predictive success, the penetrometer should not be used as a substitute measurement for bulk density. However, this does not mean that the penetrometer is not useful for characterizing compaction. A more applicable use for the penetrometer in the field would be to serve as a rapid, semi-quantitative measure of compaction over a site area that could then be used to accurately place sites in spots that are representative of the surrounding area.

Conclusions

As ecotourism likely will continue to increase in popularity, so will the erosional impact of trails in ecotourism areas. More visitor pressure will further compact trail soils, detach more sediment by the mechanical action of footsteps, and will almost certainly result in the widening of existing trails and more frequent use of outlying trails. How can the erosional impacts of trails in ecotourism centers in tropical wet forests be minimized? La Selva has installed 60 cm wide concrete paths on some of the most heavily traveled trails close to the main station area. This represents a fairly expensive, but probably effective mechanism to combat trail-related soil erosion. The concrete paths are wide enough that balance is not a problem (as it is on boardwalks), and they present a distinct trail edge that is psychologically harder for visitors to cross (i.e., they will likely no longer walk right on the edge of a trail,

compacting forest soil, damaging trail edge vegetation, and eventually widening the trail). A less expensive strategy to combat sediment transport is to construct angled narrow drains or place angled logs with their tops protruding 4 to 5 cm above the surface to act as shunts to remove runoff water from the trail and place it onto the more readily infiltrable forest floor. A much simpler solution is available for new ecotourism areas that are just beginning to develop trail systems and well-established stations that desire to revamp parts of their trail network -- construction of trails that avoid steep slopes when possible or use switchbacks, drains, or some other means of minimizing the flow of runoff water when steep slopes cannot be avoided.

With the exception of the unusually high infiltration capacities of some La Selva soils, the erosional behavior of trails in these two tropical wet forest areas seems to be comparable to that described in the literature focused on trails in temperate areas. The factors that lead to erosion on trails in temperate areas -- soil compaction, vegetation loss, and decreased infiltration capacity -- appear to operate in much the same fashion in the tropics. As in temperate areas, trails in the humid tropics act as partial area sediment sources, producing far more runoff and detached sediment than off-trail areas.

Further research that would be beneficial in quantifying the erosional contribution of trails in tropical wet forest areas includes the following -- the establishment of long-term programs of collection of hourly or 30-minute precipitation totals; studies of the hydraulic properties of disturbed (i.e. compacted) tropical soils; studies of the relationships between slopes and the movement of runoff and sediment; and studies of the actual amount of sediment delivered by trails to streams. Such studies would further understanding of the interaction of hydrology and sediment dynamics with trail use in humid tropical forests. This knowledge would provide a scientific basis for long-term management of ecotourism sites.

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APPENDICES

APPENDIX A

SAMPLE BAG WEIGHT ADJUSTMENT PROCEDURE

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SAMPLE BAG WEIGHT ADJUSTMENT PROCEDURE

To account for the change in weight of sample bags due to the slight scorching that some received from a malfunctioning oven, I conducted a test to determine the effects of various degrees of scorching on individual empty bags.

All sample bags (those used in the field as well as those used in scorch testing) were weighed on a digital balance prior to the beginning of field work. The bags were weighed empty without an initial oven drying period, but, due to the fact that they were all weighed within a three hour period, the amount of uptake of atmospheric moisture by the cotton fabric was virtually constant from bag to bag, as is explained more fully in the following paragraphs.

Following their use in the field, the sample bags were allowed to air dry, and were then oven dried for 12 to 24 hours at a thermostat setting of 105° C. Most came through this oven drying stage unscathed -- 75 of the 104 bags used showed no signs of scorching. The other 29 that were adversely effected by the high temperatures fell into four well-defined categories of scorching based on their outward appearance (the amount of scorching seems to have varied closely with the position of the bag within the malfunctioning drying oven.) I developed a classification system of five categories based on the degree of scorching for use during testing; group 0 consisted of the 75 bags that had no visible scorching; group 1 contained 13 bags that showed a very slight brownish tinge along the drawstring top; group 2 contained 4 bags that had a visible light brown tint over up to 20% of their surface; group 3 encompassed 9 bags that had a light brown tint over 30-50% of their surface; and group 4 consisted of 3 bags that had areas that were truly scorched and were dark brownish-gray in color.

In tests to determine the weight loss due to progressively greater degrees of scorching, I used 5 empty bags, and oven dried them 17 times at temperatures that began at 104° C and were

increased incrementally to 207° C. After each oven drying session, I removed the test bags, allowed them to cool, weighed them, compared their appearance to the bags in each category (0-4), and then placed them back into a slightly hotter oven for the next test session. In this manner, I was able to approximate the amount of weight lost by each bag at each different stage in their outward appearance.

After the first drying session, at 104° C, the weight of each test bag was reduced by an average of .065 g (.060 minimum, .074 maximum). As there was no visible change in the condition of the bags, I believe that atmospheric moisture taken up by the cotton cloth of the bags is responsible for this change. Since all the bags we used in the field were weighed at the same time as the test bags, this .065 g correction should apply to all bags that showed no signs of having been adversely affected by oven drying. Therefore, .065 g was added to the weight of the 75 bags in group 0. When the test bags reached a stage where they exhibited the very slight top-edge browning shown by the group 1 bags (most reached this point in the sixth oven drying period, at 141° C), they had only lost an average of an additional .003 g from their weight after the initial oven drying period at 104° C. Thus, the 13 bags in category 1 were given an upward correction of .068 g. When the test bags reached a condition comparable to the 4 bags of group 2 either after the sixth, seventh (144° C), or eighth (149° C) drying period, their weight had further decreased by an average of .006 g. Therefore, the bags of group 2 were given an upward correction of .074 g. I found the test bags to have a similar outward appearance to the group 3 bags after either the seventh or eighth drying period. At this point, they exhibited an average reduction in weight of .020 g. As a result, the 9 bags of group 3 were given an added .094 g. The three bags of category 4 were scorched to a point that they each had to be considered individually. Based on comparisons with the test bags during subsequent oven drying periods, I estimate that sample bags 194 and 195 should be corrected by .172 g and bag 183 should be corrected by .352 g.

Correction factors for all bags are listed in the complete database in Appendix B.

APPENDIX B

JATUN SACHA AND LA SELVA DATABASES

JATUN SACHA DATABASE

Site Group	Site Number	Pairs for Paired Database	Outliers-Deleted for Unpaired Database	1=on-trail 0=off-trail	Bulk Density (g/cc)	Rain in mm	Runoff in ml	Coefficient of Runoff (ro/rain)	Time to Runoff in minutes	Runoff bag number	Bag Condition	Correction Factor	Runoff Sediment Weight in g	Splash bag number	Bag Condition	Correction Factor	Splash Sediment Weight in g	Total Sediment Weight in g	Penetrometer on-3 highest readings off-average	Penetrometer on-1 meter average off-average
A	3.0	1		0	**0.72**	**18.8**	0	**0.00**	5				**0**				**0**	**0**		
A	1.0			1	**1.11**	**34.4**	503	**0.80**	5	195	4	0.172	**1.526**				**0**	**1.526**	10.7	9
A	2.0	1		1	**1.11**	**19.6**	124	**0.35**	10	196	1	0.068	**0.403**	197	0	0.065	**5.33**	**5.733**	10.7	9
B	5.2	2,3		0	**0.71**	**23.3**	0	**0.00**	35				**0**				**0**	**0**	11.3	11.3
B	5.3			0	**0.71**	**18.2**	0	**0.00**	35				**0**				**0**	**0**	11.3	11.3
B	5.4	4		0	**0.71**	**16.1**	0	**0.00**	35				**0**				**0**	**0**	11.3	11.3
B	5.5			0	**0.71**	**24.0**	0	**0.00**	35				**0**				**0**	**0**	11.3	11.3
B	4.0	2		1	**0.89**	**21.0**	280	**0.73**	5	198	0	0.065	**0.668**				**0**	**0.668**	11.3	9.3
B	5.1	4		1	**0.56**	**11.6**	130	**0.61**	5	199	2	0.074	**1.341**	100	3	0.094	**2.407**	**3.748**	11.3	9.3
B	6.0	3		1	**0.56**	**21.0**	368	**0.96**	5	107	2	0.074	**2.764**	108	0	0.065	**1.132**	**3.896**	11.3	9.3
C	7.2	5		0	**1.03**	**9.1**	0	**0.00**	35				**0**				**0**	**0**	9	9
C	7.3	6		0	**1.03**	**21.9**	4	**0.01**	10	105	2	0.074	**0.189**				**0**	**0.189**	9	9
C	7.1	5		1	**1.04**	**10.7**	28	**0.14**	5	109	3	0.094	**1.066**				**0**	**1.066**	8.7	8
C	8.0	6		1	**1.04**	**17.9**	309	**0.95**	5	110	3	0.094	**1.04**	111	3	0.094	**0.952**	**1.992**	8.7	8
D	9.2	7		0	**0.89**	**11.5**	0	**0.00**	35				**0**				**0**	**0**	8	8
D	9.3	8		0	**0.89**	**23.7**	0	**0.00**	35				**0**				**0**	**0**	8	8
D	9.1	7		1	**1.18**	**10.7**	171	**0.87**	5	112	3	0.094	**1.414**				**0**	**1.414**	10.7	10.3
D	10.0	8		1	**1.18**	**21.0**	373	**0.97**	5	113	3	0.094	**2.421**	114	3	0.094	**1.987**	**4.408**	10.7	10.3
E	11.2	9		0	**0.77**	**8.9**	10	**0.06**	25	117	2	0.074	**0.091**				**0**	**0.091**	7.7	7.7
E	11.3	10		0	**0.77**	**18.8**	63	**0.18**	5	180	0	0.065	**0.459**	181	0	0.065	**0.473**	**0.932**	7.7	7.7
E	11.1	9		1	**0.91**	**11.6**	125	**0.59**	5	115	0	0.065	**1.057**	116	3	0.094	**0.934**	**1.991**	6.3	5.5
E	12.0	10		1	**0.91**	**18.8**	197	**0.57**	5	118	1	0.068	**1.972**	119	1	0.068	**0.61**	**2.582**	6.3	5.5
F	13.1			0	**0.63**	**9.4**	0	**0.00**	35				**0**				**0**	**0**	4	4
F	13.2	12		0	**0.63**	**21.5**	0	**0.00**	35				**0**				**0**	**0**	4	4
F	14.2			0	**0.63**	**9.4**	0.1	**0.00**	35				**0**				**0**	**0**	4	4
F	14.3	11		0	**0.63**	**17.4**	7	**0.02**	15	182	1	0.068	**0.198**	184	1	0.068	**0.442**	**0.64**	4	4
F	13.3	11		1	**0.72**	**12.5**	23	**0.10**	10	183	4	0.352	**0.287**	185	1	0.068	**0.564**	**0.851**	6.3	5.2
F	14.1	12		1	**0.72**	**22.8**	50	**0.12**	10	194	4	0.172	**0.197**	186	3	0.094	**0.828**	**1.025**	6.3	5.2
G	15.2	13		0	**0.71**	**11.2**	0.1	**0.00**	35				**0**				**0**	**0**	5.7	5.7
G	15.3			0	**0.71**	**25.0**	178	**0.39**	5	191	1	0.068	**0.133**				**0**	**0.133**	5.7	5.7
G	15.4	14		0	**0.71**	**18.8**	119	**0.35**	5	192	1	0.068	**0.141**				**0**	**0.141**	5.7	5.7
G	15.1	13		1	**1.07**	**6.5**	13	**0.11**	10	187	1	0.068	**0.54**	188	1	0.068	**1.475**	**2.015**	7.3	6.2
G	16.0	14		1	**1.07**	**17.7**	170	**0.53**	10	189	1	0.068	**1.018**	190	0	0.065	**0.402**	**1.42**	7.3	6.2
H	17.0			1		**9.8**	84	**0.47**	5	193	0	0.065	**0.305**	106	0	0.065	**0.737**	**1.042**	9	7.7
H	18.0			1		**22.4**	262	**0.64**	5	101	0	0.065	**1.303**	102	0	0.065	**0.649**	**1.952**	9	7.7
I	19.2	15		0	**0.78**	**22.3**	0	**0.00**	35				**0**				**0**	**0**	5.3	5.3
I	19.3	16		0	**0.78**	**5.4**	0	**0.00**	35				**0**				**0**	**0**	5.3	5.3
I	19.4			0	**0.78**	**14.8**	0	**0.00**	35				**0**				**0**	**0**	5.3	5.3
I	19.1	16		1	**1.11**	**5.8**	47	**0.44**	10	104	1	0.068	**0.46**	201	0	0.065	**0.694**	**1.154**	6	5.5
I	20.0	15		1	**1.26**	**21.9**	284	**0.71**	5	103	1	0.068	**2.212**	200	0	0.065	**1.943**	**4.155**	6	5.5

LA SELVA DATABASE

Site Group	Site Number	Pairs for Paired Database	Outliers-Deleted for Unpaired Database	1=on-trail 0=off-trail	Bulk Density (g/cc)	Rain in mm	Runoff in ml	Coefficient of Runoff (ro/rain)	Time to Runoff in minutes	Runoff bag number	Bag Condition	Correction Factor in g	Runoff Sediment Weight in g	Splash bag number	Bag Condition	Correction Factor in g	Splash Sediment Weight in g	Total Sediment Weight in g	Penetrometer on-3 highest readings off-average	Penetrometer on-1 meter average off-average
J	102.1	17		0	**0.65**	**29.5**	0	**0.00**	35				**0**				**0**	**0**	10.6	10.6
J	102.2		**DELETED**	0	**0.65**	**49.2**	0.1	**0.00**	35				**0**	122	0	0.065	**0.317**	**0.317**	10.6	10.6
J	104.1	18		0	**0.65**	**30.9**	0	**0.00**	35				**0**				**0**	**0**	10.6	10.6
J	104.2		**DELETED**	0	**0.65**	**50.1**	0	**0.00**	35				**0**				**0**	**0**	10.6	10.6
J	104.3		**DELETED**	0	**0.65**	**93.1**	69	**0.04**	5	178	0	0.065	**0.177**	179	0	0.065	**0.341**	**0.518**	10.6	10.6
J	101.0	17		1	**0.76**	**14.3**	33	**0.13**	5	120	0	0.065	**0.259**	121	0	0.065	**0.902**	**1.161**	6.3	5.6
J	103.1			1	**0.76**	**34.8**	415	**0.65**	5	123	0	0.065	**0.822**				**0**	**0.822**	6.3	5.6
J	103.2	18		1	**0.76**	**11.2**	173	**0.85**	5	124	0	0.065	**0.316**	125	0	0.065	**0.755**	**1.071**	6.3	5.6
K	106.0	19,20,21,23		0	**0.63**	**17.5**	0	**0.00**	35				**0**				**0**	**0**	6.6	6.6
K	107.0	22,24		0	**0.63**	**33.1**	0	**0.00**	35				**0**				**0**	**0**	6.6	6.6
K	105.1	19		1	**0.71**	**13.4**	0	**0.00**	35				**0**				**0**	**0**	10	8
K	105.2	20		1	**0.71**	**18.3**	0.1	**0.00**	35				**0**	177	0	0.065	**0.355**	**0.355**	10	8
K	108.0	21		1	**0.71**	**15.6**	14	**0.05**	20	126	0	0.065	**0.122**	127	0	0.065	**0.34**	**0.462**	10	8
K	109.1	22		1	**0.61**	**20.6**	60	**0.16**	5	128/129	0/0	0.13	**1.34**	176	0	0.065	**1.114**	**2.454**	10	8
K	109.2	23		1	**0.61**	**17.9**	55	**0.17**	5	130	0	0.065	**0.142**	175/131	0/0	0.13	**2.346**	**2.488**	10	8
K	110.0	24		1	**0.71**	**20.1**	12	**0.03**	15	132	0	0.065	**0.111**	133	0	0.065	**0.761**	**0.872**	10	8
L	112.1	26,27,28,29		0	**0.71**	**16.6**	0	**0.00**	35				**0**				**0**	**0**	10.1	10.1
L	112.2	25		0	**0.71**	**22.8**	0	**0.00**	35				**0**				**0**	**0**	10.1	10.1
L	111.1	26		1	**0.94**	**11.6**	2	**0.01**	30				**0**				**0**	**0**	19	14.5
L	111.2	27		1	**0.94**	**8.5**	0	**0.00**	5				**0**				**0**	**0**	19	14.5
L	111.3	28		1	**0.94**	**14.7**	95	**0.35**	5	134	0	0.065	**0.148**	135	0	0.065	**0.474**	**0.622**	19	14.5
L	113.0	29		1	**0.94**	**14.3**	205	**0.78**	5	136	0	0.065	**0.231**	137	0	0.065	**1.175**	**1.406**	19	14.5
L	114.0	25		1	**0.94**	**18.3**	0	**0.00**	5				**0**	139	0	0.065	**0.339**	**0.339**	19	14.5
M	116.1	30		0	**0.60**	**10.7**	0	**0.00**	35				**0**				**0**	**0**	6.9	6.9
M	116.2	31		0	**0.60**	**19.6**	0.1	**0.00**	5				**0**				**0**	**0**	6.9	6.9
M	115.1	31		1	**0.81**	**17.7**	286	**0.88**	5	138	0	0.065	**3.209**	140	0	0.065	**1.645**	**4.854**	10.7	9.5
M	115.2			1	**0.81**	**27.3**	393	**0.79**	5	173	0	0.065	**2.591**	174	0	0.065	**1.57**	**4.161**	10.7	9.5
M	117.0	30		1	**0.81**	**8.5**	136	**0.88**	5	172	0	0.065	**1.165**	171	0	0.065	**0.808**	**1.973**	10.7	9.5
N	119.1	32		0	**0.51**	**14.7**	0.1	**0.00**	35				**0**	168	0	0.065	**0.771**	**0.771**	2.3	2.3
N	119.2			0	**0.51**	**21.0**	24	**0.06**	10	165	0	0.065	**1.468**	164	0	0.065	**2.464**	**3.932**	2.3	2.3
N	120.0	33		0	**0.51**	**18.3**	0	**0.00**	35				**0**	163	0	0.065	**0.364**	**0.364**	2.3	2.3
N	118.1	32,33		1	**0.59**	**15.7**	145	**0.51**	5	169	0	0.065	**0.435**	170	0	0.065	**1.39**	**1.825**	5.3	3.5
N	118.2			1	**0.59**	**29.1**	351	**0.66**	5	167	0	0.065	**0.844**	166	0	0.065	**1.137**	**1.981**	5.3	3.5
O	122.1	34		0	**0.56**	**15.2**	0	**0.00**	35				**0**				**0**	**0**	7	7
O	122.2	35,36		0	**0.56**	**26.9**	0	**0.00**	35				**0**				**0**	**0**	7	7
O	121.0	34		1	**0.74**	**10.7**	3	**0.02**	15	162	0	0.065	**0.283**	161	0	0.065	**1.222**	**1.505**	10	7.5
O	123.0	35		1	**0.74**	**19.2**	205	**0.59**	5	160	0	0.065	**2.947**	159	0	0.065	**0.926**	**3.873**	10	7.5
O	124.0	36		1	**0.74**	**16.1**	292	**0.99**	5	141	0	0.065	**0.406**	142	0	0.065	**0.697**	**1.103**	10	7.5
P	127.0	37, 38, 39		0	**0.58**	**26.9**	0	**0.00**	35				**0**				**0**	**0**	5.7	5.7
P	125.0	38		1	**0.63**	**16.1**	160	**0.54**	5	202/204	0/0	0.13	**0.375**	203	0	0.065	**1.427**	**1.802**	10.7	9
P	126.1	39		1	**0.65**	**16.6**	23	**0.08**	15	205	0	0.065	**0.062**				**0**	**0.062**	10.7	9
P	126.2	37		1	**0.65**	**23.3**	22	**0.05**	5	206	0	0.065	**0.067**				**0**	**0.067**	10.7	9
Q	131.0	40,41,42,43		0	**0.51**	**27.7**	0.1	**0.00**	35				**0**				**0**	**0**	0.4	0.4
Q	128.0	40		1	**0.64**	**26.4**	69	**0.14**	5	207	0	0.065	**0.877**	208	0	0.065	**0.762**	**1.639**	5.7	4.7
Q	129.0	41		1	**0.65**	**27.7**	198	**0.39**	10	209	0	0.065	**0.597**	210	0	0.065	**0.468**	**1.065**	5.7	4.7
Q	130.0	42		1	**0.65**	**15.2**	2.5	**0.01**	25	149	0	0.065	**0.239**	150	0	0.065	**0.38**	**0.619**	5.7	4.7
Q	132.0	43		1	**0.65**	**12.9**	0	**0.00**	35				**0**	151	0	0.065	**0.22**	**0.22**	5.7	4.7
R	133.1	44		0		**12.1**	0.1	**0.00**	35				**0**				**0**	**0**	13.4	13.4
R	133.2	45		0		**19.2**	7	**0.02**	15	143	0	0.065	**0.437**	144	0	0.065	**0.898**	**1.335**	13.4	13.4
R	134.0	44		1		**10.7**	3	**0.02**	10	145	0	0.065	**0.218**	146	0	0.065	**1.125**	**1.343**	12	8.7
R	135.0	45		1		**21.0**	188	**0.49**	5	147	0	0.065	**1.502**	148	0	0.065	**1.406**	**2.908**	12	8.7

VITA

Thomas Ryan Wallin was born in Knoxville, Tennessee on March 9, 1970. He attended Knoxville City schools -- Pond Gap Elementary, Tyson Middle, and West High -- and graduated in May 1987. He entered the University of Tennessee, Knoxville the following fall and graduated with the degree of Bachelor of Arts in Geography in December, 1991. From January until August 1992, he worked for the Cartographic and Educational Media Divisions of the National Geographic Society as a cartographic intern and freelance cartographer. In August 1992, he reentered the University of Tennessee, Knoxville, where he served for two semesters as a laboratory teaching assistant and three semesters as a lecturer in Introductory Physical Geography. In May 1995, he received a Master of Science degree in Geography.