

# Impact on a Changing World

PROGRAM



REPORT

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INTERNATIONAL POTATO CENTER

# A Process-Based Model (WEPP) for Simulating Soil Erosion in the Andes

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Soil erosion by water represents a major threat to the long-term productivity of hillside agriculture in the Andes. To help combat this threat, researchers need a quantitative understanding of the hydrologic and physical processes that drive soil loss. They also need to understand how these processes interact with land use and management to either diminish or increase soil loss. This understanding, however, is not easily obtained in a cultural and physical environment as diverse and complex as the Andes, particularly given the paucity of experiments and data needed to quantify soil erosion for the myriad land-use systems in the region.

To better understand soil erosion and its impact in the Andes, we have begun a multi-institutional and multidisciplinary effort based on a systems research approach. This approach is designed to take advantage of existing simulation models, using existing experimental data to the extent possible for model calibration and model testing. New experiments and other data collection activities will be pursued as this approach helps us to identify gaps in available data sets and possibly inaccuracies in process descriptions incorporated in present models. With time, we expect the iterative process of experimentation and model evaluation to increase our understanding of the major processes that cause soil erosion. We also expect the systems research approach to result in improved simulation models that can be used to help predict how conservation measures—or the

lack of them—might affect soil productivity on a site-specific basis.

A process-based simulation model we have begun to evaluate under Andean conditions is one recently developed by the Water Erosion Prediction Project (WEPP) of the U.S. Department of Agriculture (Flanangan and Nearing, 1995). The WEPP model mathematically describes the processes of soil particle detachment, transport, and deposition due to hydrologic and mechanical forces acting on a hillslope profile. It is considered to possess state-of-the-art knowledge of erosion science, and has become an important analytical tool for global change studies (Favis-Mortlock et al., 1996).

The purpose of this study is to provide a first approximation of the capability of the WEPP model for simulating soil loss in an Andean environment. We will do this by comparing model predictions of runoff and soil loss to data measured from fallow runoff plots during a 154-d study in the eastern Andes of Peru.

## Materials and Methods

### Model description

The WEPP erosion model is a continuous simulation computer program that calculates runoff and erosion on a daily basis. Erosion processes may be simulated at the level of a hillslope profile or at the level of a small watershed. Our evaluation, however, is restricted to the hillslope profile version (v 98.4). The major inputs for running the hillslope profile version need to be specified in four data files: weather, slope, soil, and management.

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The weather file requires daily values for precipitation, maximum and minimum temperature, and solar radiation. In addition to rainfall amount, the model requires three variables related to rainfall intensity that are used to compute rainfall excess rates and thus runoff. These are (1) rainfall duration, (2) the ratio of time to peak rainfall intensity to rainfall duration, and (3) the ratio of maximum peak intensity to average intensity.

With the WEPP model, a user can simulate differences in soil types or management along the length of a hillslope through the use of overland flow elements (OFE). An OFE is a specified section of the hillslope with a region of homogeneous soils and management. Up to 10 OFEs can be defined for one hillslope of a given width. The number of OFEs to include in a simulation is specified in the slope file, along with the length and slope characteristics of each OFE.

The soil file contains information on the physical characteristics of the surface soil and subsoil for each OFE. The surface soil parameters required are the effective hydraulic conductivity (Green and Ampt effective conductivity), interrill erodibility (sheet erosion mostly caused by raindrop impact), rill erodibility (small eroded channels), critical shear stress (rill detachment threshold parameter), and albedo (fraction of solar radiation reflected back to the atmosphere). For each soil layer, the inputs required are cation exchange capacity (CEC) and percentages of sand, clay, organic matter (OM), and rock fragments. Up to eight soil layers to a maximum profile depth of 1.8 m may be defined in the soil file.

The management file contains information needed to define initial conditions, tillage practices, plant growth parameters, and residue management and crop management. It is the file with the largest number of parameters.

### Runoff plot study

Measurements of runoff and soil loss were obtained from a runoff plot study conducted during the first 6 mo of 1991 in San Ramon, Peru (Pastor, 1992). In this study, 30 runoff plots, each 10 m long and 4 m wide, were set up on slopes of 30, 35, 40, 45, 50, and 60%. At each of the six slope sites, five plots with the following management systems were installed: (1) clean fallow, (2) natural grass vegetation, (3) sweetpotato (*Ipomoea batatas*) planted in rows along the contour with hilling, (4) sweetpotato planted in rows along the contour without hilling, and (5) sweetpotato planted up and down the slope with hilling. Treatments were not replicated, meaning there was only one set of observations for each unique combination of slope and management system. There were also fairly large differences in the infiltration properties of the soils (Entisols) across slope sites. Infiltration measurements in the field showed infiltration was 21.0 mm/hr on the 30-35% slopes, 12.4 mm/hr on the 40-45% slopes, 215.0 mm/hr on the 50% slope, and 104.7 mm/hr on the 60% slope.

Runoff and soil losses were measured after each rainfall from 21 Jan to 24 Jun 1991. There were 62 rainfall events during this 154-d period, each producing measurable runoff and soil loss. The total rainfall for the period was 1,053 mm. Total runoff and soil loss measured for all treatments and slopes are shown in Table 1 (note the sweetpotato contour treatment represents the mean of plots with and without hilling). The greatest runoff and soil loss occurred from the clean fallow plots. Any discernible impact of slope on runoff and soil loss apparently was masked by the differences in soil infiltration properties across slopes. The 50% slope, because of more rapid infiltration, actually produced less runoff and soil loss than the 30-45% slopes.

### Model analysis

Our analysis of the WEPP model in this initial study focuses on measured and simulated data obtained from the clean fallow plots only. Soil is often left bare

**Table 1.** Runoff and soil loss measured for four different management systems at six locations with different slopes in San Ramon, Peru, from 21 January to 24 June 1991 (Pastor, 1992).

Treatments	Slope (%)						Treatment mean
	30	35	40	45	50	60	
<b>Runoff (mm)</b>							
Natural vegetation	42.18	41.57	38.25	52.84	25.77	27.77	38.06
Sweetpotato/contour <sup>a</sup>	30.95	26.24	26.29	29.36	21.83	29.67	27.39
Sweetpotato/up-down <sup>b</sup>	59.10	44.69	38.52	33.53	23.39	34.58	38.97
Clean fallow	62.85	50.99	43.40	60.05	48.38	41.30	51.16
<b>Slope mean</b>	<b>48.77</b>	<b>40.87</b>	<b>36.62</b>	<b>43.95</b>	<b>29.84</b>	<b>33.33</b>	<b>38.90</b>
<b>Soil loss (mg ha<sup>-1</sup>)</b>							
Natural vegetation	0.44	0.48	1.10	0.86	0.45	0.79	0.69
Sweetpotato/contour <sup>a</sup>	0.61	0.80	0.98	1.42	0.65	1.06	0.92
Sweetpotato/up-down <sup>b</sup>	2.42	3.33	3.21	4.01	1.82	3.96	3.13
Clean fallow	14.88	13.03	11.38	7.74	3.12	8.39	9.76
<b>Slope mean</b>	<b>4.58</b>	<b>4.41</b>	<b>4.17</b>	<b>3.51</b>	<b>1.51</b>	<b>3.55</b>	<b>3.62</b>

<sup>a</sup> Sweetpotato planted in rows along the contour.  
<sup>b</sup> Sweetpotato planted in rows up and down the slope.

between crops, thus it is important to quantify the vulnerability of exposed soil to the erosive forces of natural rainfall. Also, we thought it better to first parameterize and evaluate the performance of the model for bare soil where there would be no expected interaction between residue cover and plant growth. If the model cannot be shown to simulate soil loss realistically from bare soil, then it would not be expected to do so for other management systems.

Our analysis of WEPP in this study is also restricted to results averaged across slopes. There was insufficient information about the on-site soil properties to parameterize the WEPP model for each slope site. Therefore, we evaluate the performance of the model by averaging both measured and simulated data across slopes. That is, WEPP model input files were set up to simulate by slope, but the simulated output values were averaged across slopes before comparing them to measured data, which were also averaged across slopes.

For evaluating model performance, we followed the suggestion of Nearing et al. (1994) to compare the frequency distributions of the measured and simulated events rather than make event-by-event comparisons. Although the WEPP model should eventually be evaluated by comparing outcomes on an event-by-event basis, such a comparison is not valid in this study. The reason is that critical input parameters for soil properties and rainfall intensity were not measured on site and could only be approximated.

#### Model inputs

The weather file for simulating erosion from the clean fallow plots was assembled using daily rainfall recorded in pluviometers at the experimental site. Daily temperature and solar radiation values were obtained from the CIP-San Ramon weather station located about 1 km from the experimental site. Rainfall intensity was not recorded at the site, so we estimated values for the duration and intensity parameters



using statistical relations derived from recorded values at the CIP-San Ramon weather station.

Slope input files were assembled for each of the six slopes by specifying one OFE with a slope length of 10 m and a plot width of 4 m. Soil input files were made identical for each of the slope sites. Soil profile parameters for soil depth, texture, OM, CEC, and rock fragments were based on measurements taken from a nearby site (La Torre, 1985). Surface soil parameters were estimated using either empirical relations described in the WEPP User Summary (Flanagan and Livingston, 1995) or by calibrating simulated runoff and soil loss to measured data from only the 30% slope. Input values for surface soil parameters were 7.0 mm/h for effective hydraulic conductivity,  $2.0 \times 10^6$  kg s/m<sup>4</sup> interrill erodibility, 0.002 s/m for rill erodibility, and 4.0 N/m<sup>2</sup> for critical shear stress. The management input files were also made identical for each slope with parameters set to simulate bare soil.

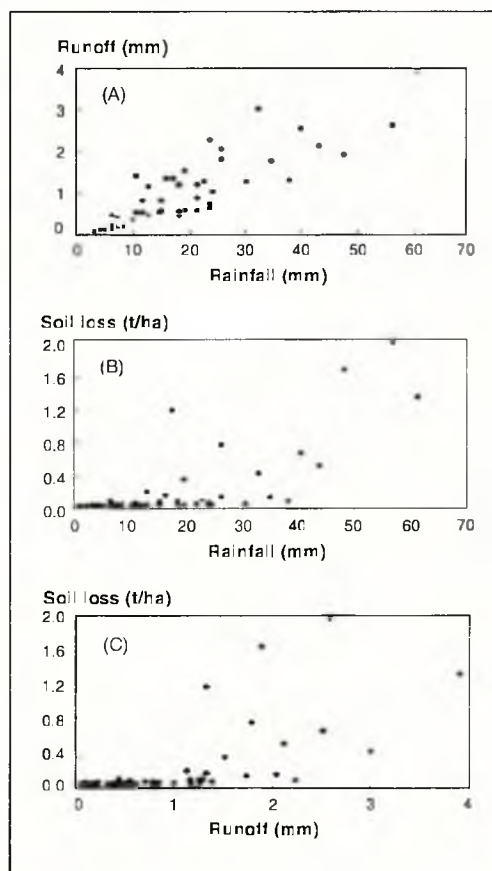
### Results and Discussion

One of the most notable discrepancies between WEPP model simulations and measured data was in the number of rainfall events that resulted in runoff and soil loss. Whereas field measurements showed that each of the 62 rainfall events produced some runoff and soil loss, although often in only small amounts (Figures 1A and 1B), the WEPP model produced runoff and soil loss values for only 16 of the events. Closer analysis revealed that the model failed to pick up the less intense or smaller rainfall events that produced measured runoff values of less than 1 mm or soil loss values of < .1 t/ha.

The failure of the model to simulate the smaller events was judged not significant as the measured data clearly showed that any substantial soil loss only occurred when rainfall exceeded 10 mm (Figure 1B) or runoff exceeded 1 mm (Figure 1C). Furthermore, we were able to demonstrate in a

sensitivity analysis that the model would reproduce more of the measured runoff and soil loss events by adjusting the rainfall intensity parameters of specific rainfall events. Thus, if the on-site rainfall duration and intensity parameters had been known with more certainty, the model output may have more accurately reflected the observed number of events.

The cumulative frequency distributions for runoff and soil loss measured during all 62 events are provided in Figure 2, expressed as the probability that any one event will exceed a given runoff or soil loss



**Figure 1.** Measured data from fallow plots showing the relations between (A) rainfall and runoff, (B) rainfall and soil loss, and (C) runoff and soil loss. Runoff and soil loss values represent the mean across slopes for each event.

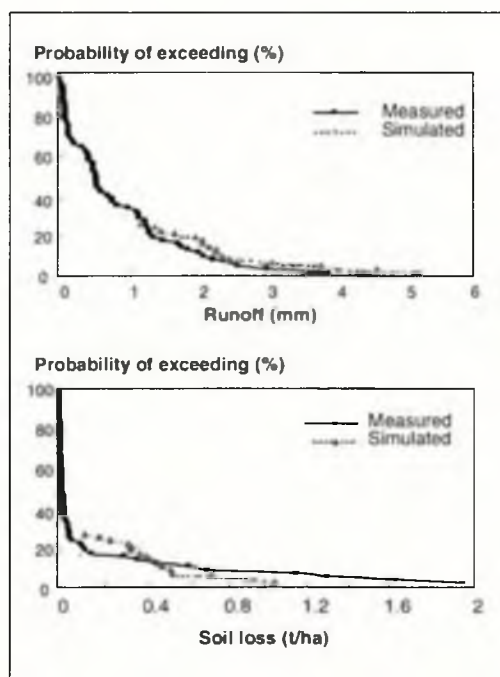
amount. These distributions represent the same data presented in Figure 1. Here, however, the highly skewed nature of the data is more apparent; relatively few events produced most of the runoff and soil loss. For example, only 4 of the 62 events resulted in a combined soil loss of 6.0 t/ha, whereas the cumulative soil loss from all events amounted to 9.8 t/ha.

The cumulative frequency distributions for simulated runoff and soil loss are also shown in Figure 2. These were calculated using the simulated output for the 16 events reproduced by the model together with zero values for the other 46 events not reproduced by the model. For that reason the simulated distributions indicate that most of the events would not have produced runoff exceeding 1 mm or soil loss exceeding 0.1 t/ha, values similar to those indicated by the measured distributions. When these values were exceeded, the

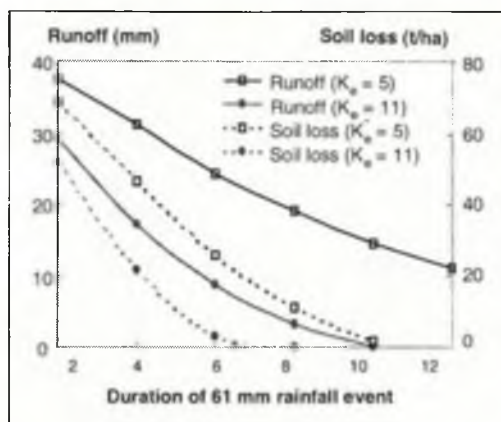
simulated distribution of events similarly reflected the measured distribution.

For runoff, the simulated distribution was shifted to the right of the measured distribution, indicating the model tended to overpredict runoff. For soil loss, the model tended to overpredict small values (distribution shifted to the right), but underpredict large values (distribution shifted to the left). This same trend in overpredicting small values and underpredicting large values is common when evaluating many erosion models with measured data. Nearing (1998) attributes the trend to limitations in capturing the random component of measured erosion data with a deterministic model. Although measured and simulated distributions were somewhat similar, the model underestimated the 154-d totals for runoff and soil loss. We attribute that to the failure of the model to reproduce all events. The total measured runoff was 51.2 mm compared with 40.4 mm for the simulation. The total measured soil loss was 9.8 t/ha compared with 7.6 t/ha for the simulation.

In addressing some of the uncertainty regarding input parameters, we found both runoff and soil loss to be quite sensitive to rainfall and surface soil parameters. To illustrate, Figure 3 shows how runoff and soil loss would vary with the duration or intensity of a 61-mm rainfall event for two soils with different effective hydraulic conductivity values. The 61-mm rainfall was the largest recorded during the runoff plot study. In general terms, the model indicates that the difference in soil loss between a 4- or 6-h event could be as much as 20 t/ha. Likewise, an 8-h event might result in no soil loss on a soil with good infiltration properties, but erode more than 10 t/ha if infiltration is poor. The measured soil loss for this event was 1.3 t/ha. Clearly, it is important to have reliable estimates of parameters like rainfall intensity and effective hydraulic conductivity if the model is to provide realistic estimates of runoff and soil loss.



**Figure 2.** Measured and simulated cumulative frequency distributions showing the probability of exceeding a given runoff or soil loss from fallow plots.



**Figure 3.** Sensitivity of simulated runoff and soil loss due to variation in the duration of a 61 mm rainfall event for two soils with different effective hydraulic conductivity values ( $K_s$ ).

### Conclusions

This initial analysis of the WEPP erosion model has shown that it can be an effective tool for studying the hydrologic and erosion processes that drive soil loss in the Andes. The model should be particularly valuable for focusing on the quantitative relations and interactions between soil, weather, topography, slope, and management factors that determine runoff, soil loss, and deposition on a site-specific basis. Nevertheless, we must caution that this study should not be seen as a validation of the WEPP model for Andean conditions. More rigorous testing of model assumptions is needed. That will require more complete experimental data sets than the one used in this study.

The results presented in this study represent our first attempt at working with the WEPP model and collating the type of measured data needed to parameterize and evaluate the model. The runoff plot study used in this analysis was certainly not ideal for model testing as shown by the lack of some on-site measurements needed to parameterize the model. It did at least start us on the road toward a better understanding of model assumptions and data input

needs. As part of an ongoing regional effort, we are gathering experimental data from other historical runoff plot studies in the Andes. We will continue to evaluate the WEPP model with these data. As the need and opportunity arise, we will also conduct new experiments using the WEPP model to help us focus on improved understanding of processes.

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## Ecoregional Research: A Vision from the Andes

In response to growing interest among scientists and donors in natural resource management and sustainable development, the CGIAR initiated ecoregional research programs beginning in 1992. The CGIAR defines the ecoregional approach as:

“The main role of the ecoregional approach is to contribute to the goal of increasing sustainability of agricultural production by providing: first, a process that identifies the **right research content** due to its holistic and forward looking approaches to research; second, a **mechanism for partnership**, among relevant actors with complementary functions, that contributes to achieving their common and individual institutional goals through applied and strategic research on the foundations of sustainable production systems; and, third, a mechanism that develops, tests, and supports **effective research paradigms** for the sustainable improvement of productivity.” (The eco-regional approach to research in the CIGAR. TAC, CGIAR, Rome Italy. 1993, p. 4.)

### Ecoregional Research Agenda in the Andes

CONDESAN, the Consortium for the Sustainable Development of the Andean Ecoregion, carries out ecoregional research in the Andes in the context of the CGIAR approach. Operating under the umbrella of CIP, CONDESAN is a consortium of more than 75 associated groups, including universities, NGOs, communities, and local government agencies. CIP's natural resource management program develops methodological tools for use in meeting the research and development objectives of CONDESAN whose ecoregional approach contains three objectives.

- Sustainable natural resource management.
- Improved rural incomes and employment.
- Increased community input and control of the landscape.

To meet these objectives, energy is invested in both research programs and benchmark integrated research/development programs. The former are developing much needed tools for improved natural resource management and monitoring, participatory methodologies, and productive technologies, whereas the latter are working at the frontier of increasing agricultural productivity, resource use, and community control. In almost all cases, the activities are inter-disciplinary, multi-institutional, and strive to develop a participatory agenda.

The research agenda for the Andes is a work in progress, initiated with a series of Andean-wide project planning by objective (PPO) exercises. In the broadest terms, the Consortium is focusing on four “cross-Andean” research components.

**1. Soil and water management.** Methodologies for the evaluation and rehabilitation of natural resource —GIS, remote sensing, ex-ante and ex-post watershed modeling, and promoting community management of natural resources.

**2. Agrobiodiversity in Andean roots and tubers and pasture species.** Identifying micro-centers of genetic diversity; characterizing clones; improving agronomic and postharvest technologies; and understanding marketing pathways.



### **3. Improved farming systems for the Andes: From producer to consumer**

- **Production systems research.** Modeling (crop and animal production, chemical leaching, soil erosion, and water run-off); resource management (soil biology, drip/sprinkle irrigation, pesticides/health); commodity research.

- **Agroindustries and Marketing research.** Development of new products; identifying bottlenecks and new opportunities.

**4. Policy research.** Modeling trade-offs between productivity, profit, and environmental impact; using government policy to promote Andean development; and promoting private investment in the rural Andes.

These research activities primarily take place in the field at “research sites,” where both the energy and funding originates from the research agenda. Several examples are:

- San Gabriel (Ecuador): Tradeoffs project.
- Lake Titicaca fringe (Peru/Bolivia): Remote sensing project.
- San Antonio/Rio Recio/Rio Guadalajara (Colombia): Ex-ante analysis of watershed management project.
- Pensilvania (Colombia): Joining entrepreneurs and local and national government authorities in investing in the hillsides.
- San Jose de Minas (Ecuador), Sucse (Peru), and San Juan de Miel (Bolivia): Developing the local arracacha industry: methodologies for working with cottage industries.

Two companion themes are part of the cross-Andean portfolio: developing human resources and communications. In addition to conducting workshops, in the case of human resources, CONDESAN is working to improve postgraduate education in agricultural production and natural resource management. With respect to communication, INFOANDINA is the Consortium’s information network with nearly 500 participants. It is focusing on improving communications between Consortium members, providing access to the “gray literature,” and conducting forums on key development issues.

#### **Research and Development Agenda: Work at the Benchmark Sites**

A crucial component of the ecoregional approach is “effective research paradigms” and the concept of the benchmark site. For us, a benchmark site is neither a pilot, “integrated rural development program,” nor a point along some heroic Andean transect, but rather, a place where sustainable development becomes operational. It is here where the three goals of the Andean Program come together: (1) sustainable natural resource management; (2) rural poverty alleviation; and (3) community empowerment. Each benchmark site represents a small number of communities that share a common resource base and have an interrelated set of management and development challenges (usually 10,000-100,000 ha). These benchmark sites have been selected based on three criteria.

1. The site selected represents a “typical” location within an important Andean ecology (e.g., the green Andes, semi-arid inter-Andean valleys, the high plains). A good database already exists at the site.
2. Local organizations are willing to collaborate to address an important productivity/natural resource management issue. This normally requires building a multi-disciplinary and multi-institutional team, with a shared research/development agenda.
3. The benchmark sites are in different stages of development. Some have solidified teams with a second round of funding; others are still forming and debating their research agenda. Ideally, the team develops an integrated funding proposal, funding from one or several sources are secured, and the research/development activities begin. Over time, the “round table” of team members is strengthened and new research and development activities are designed. Descriptive titles and themes for the benchmark site projects are shown below.

**Benchmark site projects.**

Location	Themes	Comments
Pueblo Llano and Gavindia, Merida, Venezuela	Intensifying potato production	Motor for and menace to sustainable development in Alto Merida
La Selva de Florencia, Manizales, Colombia	Managing the Florencia bioserve and buffer zone	Developing profitable alternatives in the humid cloud forest
Rio El Angel, Carchi, Ecuador	Phase 1: Characterizing the watershed with special emphasis on the potato-pasture zone Phase 2: Building a sense of commonwealth in the watershed and promoting rural prosperity	Managing a new irrigation canal in Rio El Angel
La Encanada, Cajamarca, Peru	Phase 1: Using GIS tools to help characterize the watershed Phase 2: Building a micro-watershed management plan	From landscape interventions to increasing incomes
Manazo, Puno, Peru	Intensifying production in a new irrigation district	From water management to marketing Andean products
Aroma, La Paz, Bolivia	Intensifying livestock production in the semi-arid Andes	Landscape and risk management
Cochabamba, Bolivia	- Andean roots and tubers in Candelaria - Cochabambina water forum	From prospecting to profit Clarifying the debate

### **The Future**

Although not yet fully realized, the expectation is that the cross-Andean methodologies, research findings, and discussions will increase the effectiveness of the benchmark teams, and that the benchmark successes will serve to focus the cross-Andean themes. The future has a threefold thrust.

- Research activities will result in new and user-friendly tools for natural resource management, better participatory methodologies, and improved technologies.
- The Consortium will grow stronger as the model of shared-risk, shared-benefit, multi-institutional teams has greater success.
- The ability to have a real impact on sustainable rural development in the Andes will increase as the synergism of the cross-Andean methodology and in-depth benchmark site research activities take off.

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A cultivated mountainside near Cusco, Peru.