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Current Programs, Problems, and Strategies for Land Clearing and Development on Volcanic Ash Soils

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Abstract

Soils derived from volcanic ash are quite varied, owing to the diversity of climates in regions of volcanic activity and to differences in age and rates of weathering of the parent material. Most volcanic soils are fertile. Although there are few virgin soils left to be exploited, large areas in which the soil has deteriorated exist as a result of poor agricultural practices, but these soils can be recovered and reestablished. Techniques for management, fertilization, and protection against erosion of volcanic soils are generally known; however, to effectively extrapolate recommendations for use of these extremely diverse soils, it is useful to map the soils at a suitable scale and delineate their potential applications.

The author has directed the preparation of 1200 maps at a scale of 1:50,000 in the Sierra of Ecuador. These maps include the zoning potential for wheat, maize, potato, coffee, pasture, forest, and suitable forest species. Recommendations for the optimal use of new soils and those already under permanent cultivation are also provided. A similar program, in progress in the Precordillera of southern Argentina and Chile, is principally concerned with reforestation and soil conservation. The maps, based on climo-toposequences of soils, are well adapted to such mountainous regions, where radical changes of climate occur over short distances.

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DESCRIPTION OF VOLCANIC ASH SOILS

Soils derived from volcanic ash are quite variable. The parent material may be very fine or very coarse (pumice) and vary from a few millimeters to a few centimeters. Soils may be very young or exhibit all degrees of evolution to the oldest soils, such as Oxisols. Various types of volcanic ash–derived soils are described below.

Very Young Soils

Soils derived from volcanic ash are most often built up by successive thin layers of ash produced by eruptions over a period of time. Near volcanos, however, the ash deposit resulting from a single eruption can be several meters deep.

Fine ash. A few years may be sufficient to transform fine ash into excellent soil for cultivation if the climate is sufficiently humid. Water is retained in micropores of the ash and in the numerous cavities of the pumitic aggregates. Roots can penetrate deeply in this friable soil, in search of water. The organic-matter content of the soil increases quickly, both at the surface and at depth.

On the island of Martinique, 20 years were enough to erase the damage caused by the eruption of Mount Pelée in 1902 and to change the ash deposits into new, very fertile soil for sugarcane production. Soil moisture is an important factor leading to the cohesion of ash and protects the soil from erosion by wind. In certain cases, the granulometric composition of ash allows very rapid compaction within a few months of deposition; a small amount of free silica is enough to cement the particles and obtain a duripan.

Coarse ash. In coarse ash, water is less well retained, the growth of vegetation is slower, and the organic-matter content increases more slowly, especially at depth. The humidity does not ensure good cohesion of the ash material and wind erosion often occurs, particularly in the dry topsoils. Ash deposits are remodelled by the wind: significant quantities of ash are transported and deposited elsewhere.

Pumice. In pumice (very coarse ash), erosion risks are great. Surface-water runoff produces deep ravines, and wind action produces dunes. A few years may be sufficient to irrevocably transform a beautiful forest into a sterile desert landscape. Native vegetation should be retained and not cleared because its surface roots form a dense, protective layer against erosion.

Slightly Old Soils

Volcanic ash soils are rich in useful mineral elements and, with sufficient rain and water supply, the organic-matter content increases quickly. At the

beginning, organic matter is the main active element of the soil. Surface weathering is important, however, and minerals produced by neoformation appear more quickly than in many other nonsedimentary geological formations.

Mollisols. In areas with successive wet and dry periods of some weeks or months, formations of halloysite appear. If the dry periods are longer, interstratificate clays of halloysite and smectite materials are produced. These are the best soils in many regions of the world: deep, aerated, very fertile, and permitting deep, dense root development. Organic matter plays an important role in determining the properties of soil, but neoformed mineral substances—halloysite 10 Å, imogolite, etc.—also have exceptionally good water-retention characteristics, allowing extra water storage after dry periods.

Since they are found everywhere, except on steep slopes, these Mollisols must, of course, be cleared to be used for agriculture or pasture. Few soils of this type that have not already been exploited remain in the world. The high fertility of these deep soils justifies expensive antierosion work, such as terracing and soil transport. Erosion risks due to water runoff are great, but can usually be overcome by good agricultural antierosion practices, provided the slope is not too steep. In Hapludolls in wet areas, the humidity allows a cohesion of aggregates, which protects the soil against wind erosion. In Haplustolls, during very long, dry periods, wind erosion can be severe after plowing; the very fine aggregates are carried by the wind and form dunes.

Allophanic soils: Andisols. In areas having a short dry period or none at all, allophanic substances with good water-retention capacity appear in the soil. Soils containing these substances have a high level of available water and strong cohesion of aggregates. The elementary particles (small aggregates) are very stable, and ultrasonic vibration is needed to obtain dispersion; consequently, these soils are potentially resistant to erosion. They have very stable aggregates, cohesion among peds, good permeability, high fertility, and quasi-permanent vegetal growth. Allophanic soils cover vast areas of hilly ground in uniform deposits, even on very steep slopes.

When the soil moisture content is less than 100% (100 parts of water for 100 parts of dry soil), Andisols are suitable for growing a range of crops. Land must be cleared to provide for agriculture or grazing. Normal antierosion agricultural practices for the preparation of the soils are sufficient: steep slopes (more than 60 or 70%) should not be cleared, even if the existence of deep, virgin soil makes this tempting—unless the slope is to be terraced.

Andisols are also excellent for forests, providing a good year-round supply of water and minerals to the trees and allowing good root penetration, thus assuring optimal and regular growth. These soils may have the disadvantage of high P fixation.

Old Soils

Mollisols, Alfisols, Ultisols. In areas of successive dry and wet periods, clay content, mostly halloysite, increases progressively. There are many different soils in this category:

- Mollisols with argillic layers, often very evident and with shiny coatings;
- Alfisols and Ultisols, with 30 to 50% clay content, are good soils but subject to erosion by runoff on steep slopes;
- Vertisols or vertic soils in drier areas are usually fertile soils.

It is more difficult or impossible to carry out antierosion work such as terracing on these old soils since, after removal of surface layers, it may take many years for the soil to regain its initial fertility.

Hydrated Andisols: Hydrudands. In areas with a short dry period or none at all, allophane content increases year by year. These allophanic materials are responsible for the very special properties of the Hydrudands:

- High water retention, often more than 100 parts of water for 100 parts of dry soil and sometimes 200% when the bulk density is very low. The soil possesses very stable aggregates and good cohesion, but landslides on the cultivated slopes are frequent. In the Caribbean, banana fields which have "slipped" onto lower slopes are frequently seen.
- When the soil is truncated or reworked, a few years are sufficient to renew the fertility of the soil. It is therefore possible with these soils to undertake extensive antierosion terracing work.
- Soils have good permeability, but in wet areas with abundant rain, temporary excesses of water may occur in the surface layers. A drainage system consisting of shallow ditches close together is necessary, particularly after deforestation and the consequent disappearance of leaf transpiration, which contributes to the drying of surface layers.
- In allophanic material, phosphorus is strongly retained. Phosphate fertilization is necessary after clearing. The new method used in New Zealand for determining P fixation by the soil is suitable for these soils and is used as a classification criterion.
- Cation- and anion-exchange properties vary with the pH of the soil. The consequences for retention of the calcium, potassium, and magnesium in fertilizers are not well understood.
- These soils are good for forestry and agriculture, provided that heavy fertilization is economically possible. For example, in the pineapple and banana plantations of the Caribbean and in the coffee, palm tree, and rubber plantations of Ecuador, magnesium deficiencies are frequently noticed some years after clearing, and heavy phosphate fertilization is needed.

Clearing of the soils is not recommended for food crops if it is not possible to fertilize artificially, since leaching causes the natural fertility of the surface layers to quickly decrease. Mechanization of these soils presents some problems due to the low bulk density and the low capacity of the soil to support heavy tractors. The softness of the soil also makes road construction expensive.

Very Old Soils

After long weathering periods, with formation of halloysite clay or transformation of allophanic material, the final products of these transformations appear as very old soils.

Oxisols. In wet areas, we observe the presence of tubular halloysitic clay, but with properties closer to kaolinite than to young halloysite. Precautions are necessary when clearing these soils to avoid eliminating the upper humus-bearing layer. Oxisols are fragile soils when found on steep slopes. After elimination of the upper layer, a long period is necessary to restore the initial fertility.

Ultisols and Alfisols. In Ultisols and Alfisols we often find a mixture of kaolinitic clay with halloysitic clay and irregular interstratification of several clays, which are responsible for the heavy structure not typical of kaolinitic soils. These are good soils for cropping, but surface drainage is often necessary, even on steep slopes.

Identification of interstratificate clays is difficult. Extractible aluminum content, sometimes in large quantity, is a good indication of the existence of types of clay other than kaolinite. Erosion risk is limited by using recommended cultivation practices. In the West Indies and Ecuador, these soils are plowed and cultivated on slopes sometimes greater than 40 or 50%. In pastures, paths made by livestock may take the form of very narrow terraces (*terracetas*); this is unavoidable, but not always important.

Vertisols and Vertic soils. Vertisols and vertic soils are formed in areas with a long dry season. The appearance of montmorillonite clay is enhanced by the presence of magnesium in the volcanic ash; the magnesium often provides more than 50% of the exchangeable cations. The structure of the upper humus-bearing layer is coarser and less granular than the fine aggregate layer of calcic Vertisols (Grumosols).

In Vertisols and vertic soils, we often observed very low pH in KCl, frequently around 4 or 4.5, and pH in water of 6.0 with high magnesium and calcium exchangeable contents. We find all stages of evolution of the vertic soils toward Alfisols, with progressive decrease in the proportion of montmorillonite as it is transformed into other clays. Vertisols and vertic soils are eroded on steep slopes. Very large areas of relatively shallow vertic Grumosols on slopes disappear by erosion in volcanic areas after clearing of bush.

PARTICULAR OBSERVATIONS

Deposition of Ash in the Seas

Eruptions of volcanos may throw ash into the sea. After emergence of these deposits, successive layers of clays and compacted volcanic ash are found, reflecting the succession of calm periods of sedimentation and the periods of eruption. Contact of ash with sea water seems to enhance the formation of montmorillonite clay, probably due to the high magnesium content.

In dry areas, Vertisols with high magnesium content are formed. In wet areas, we find brown and red soils with high cation content and high total cation-exchange capacity, but often with low pH in potassium chloride. We have noted on several hundred soil samples that a pH-KCl lower than 4.0 always signals the presence of extractable aluminum in the normal KCl. Levels can reach 30 meq of Al for 100 g of soil, sometimes with similar levels of exchangeable magnesium and calcium.

Aluminum levels are greater at depth where the montmorillonite forms and degrades into other clays. It would be interesting to know the process by which aluminum appears in the surface layer after forest clearing. The appearance of aluminum at the surface is very localized: soils high and low in aluminum content may coexist within a few hundred meters of each other.

Soil containing extractable aluminum in the presence of montmorillonitic and interstratificate clay can be found in the Caribbean, where it is toxic to certain crops, and also in Ecuador, where it is responsible for the failure of many forest plantations of *Pinus radiata*, *Eucalyptus globulus*, etc. Extractable aluminum is also found in several soils of the southern part of Chile and Argentina, arising from deep montmorillonitic deposits of which the origin is probably volcanic, at least in part, and in soils in Martinique, Nicaragua, Rwanda, and Venezuela. Andean areas seem well-suited to a study of the spatial repartition of extractable aluminum in order to determine the main factors effecting its appearance in the soil: truncation by erosion of the surface layers, clearing, and heavy fertilization for very intensive cropping. Soils which appear to be very fertile before clearing can afterward become very poor soils for certain crops and some species of trees.

Phosphorus Deficiency

All allophanic soils reveal a certain amount of phosphatic retention. There have been many studies of this subject; three particular cases are described below.

Example 1. In the French West Indies we find climo-toposequences of allophanic soils without gibbsite and others, associated with older ash deposits and containing large quantities of it. About 25 years ago, during soil mapping at a scale of 1:20,000, I noticed that all banana fields on allophanic soils without gibbsite were rich in total Truog-available phosphorus. On the

other hand, soils with high gibbsite content were rich in total P but very poor in available P. All the banana plantations had received the same fertilizers. It was therefore necessary to map soils with and without gibbsite. Gibbsite is an index of older and aluminous allophanic material and high P-fixation capacity. After some years of strong phosphatic fertilization, the differences disappeared. Also, the gibbsitic soils were rich in total and available phosphate. This investment was possible in banana fields, but not economical for pastureland, food crops, or wheat cultivation in other countries.

Example 2. On the gibbsitic allophanic soils, factorial experiments with two levels of P and lime gave the following results (in tons of sugarcane per hectare):

P (1) Ca (1) : 10
P (2) Ca (1) : 40
P (1) Ca (2) : 40
P (2) Ca (2) : 80
(1 = without fertilizer; 2 = with fertilizer)

We observed the same increase in yield and in leaf phosphorus content with lime or phosphate fertilization and also the cumulative effect of the two. Lime increases phosphorus level in the leaves by blocking aluminum at root level.

Example 3. Forest clearing on Oxisols formed from volcanic ash material (Haplorthox) was authorized in Guadaloupe 20 years ago, on land given to smallholders. Phosphate fertilizers were distributed by the sugar factory: the bags were stacked in the fields. First-year yields were good: about 100 t ha^{-1}, except in one case in which there was no crop at all, except for a clump of sugarcane around the burst fertilizer bags. The owner of this field had forgotten to spread the fertilizer. Here was a clear demonstration of phosphate response in virgin Oxisols.

GENERAL RECOMMENDATIONS

It is possible to make some remarks and to draw some conclusions:

1. Volcanic ash soils are generally fertile. Land clearing is not a very important problem because most of these soils are already cultivated.
2. Regions of volcanic ash soils are often densely populated. The presence of towns offers the possibility of selling crops and, thus, of buying fertilizer. Shifting cultivation can then be replaced by permanent agriculture.
3. Erosion is the most serious problem associated with land clearing, especially in mountainous areas. Runoff and lamellar, solifluxion erosion could be controlled by suitable agricultural practices or anti-

erosion works or reforestation. Owing to the high initial fertility of these soils, the necessity to adopt anti-erosion measures may not always be obvious. This is a problem, since erosion continues slowly, year after year.

Wind erosion after plowing during dry periods is often difficult to counteract; it is not possible to delay the plowing and preparation of the soil until the arrival of the rain, which renders the soil resistant.

4. Phosphate retention in allophanic soils has been studied by many soil scientists in Japan, New Zealand, Chile, etc. I have given three examples from my own experience. In aluminous allophanic soils and Oxisols, it is impossible to obtain any crops without application of fertilizer after clearing. However, between the soils having a very high phosphate retention and the Mollisols, there are more siliceous allophanic soils in which phosphate retention is less marked.
5. The maintenance or increase of organic matter merits study only in the case of young soils.
6. The increase of aluminum in soils with montmorillonitic and interstratificate clays can have a detrimental effect on crops or certain trees. It seems useful to obtain more information on the processes involved.
7. With few exceptions, we have sufficient knowledge of volcanic ash soils to be able to make recommendations for their management. However, the soils are extremely varied, with different types sometimes found close together. So, in order to make recommendations adapted to each soil, soil maps and interpretive maps are necessary.

MAPPING SOILS

It is very useful to know the spatial distribution of the different soils, correlated with the factors responsible for their variations (climate, slope, etc). The basis of volcanic soil cartography is defining climo-toposequences of the soils.

Sierra of Ecuador

In the Sierra of Ecuador, working with Ecuadorian technicians and scientists, I have established 1200 soil and interpretive maps covering practically the whole surface from Peru to Colombia: about 140 maps at a scale of 1:50,000, 65 x 45 cm in size. The scale of 1:50,000 was used since this provides a good impression of morphology and slopes, and the maps are easy to use. The precision is not uniform in all parts of the 7 million ha mapped. Soils or cartographic units are designated by letters and grouped into relatively coherent sets, although this is not essential. Some cartographic units or sets are quite like those in Soil Taxonomy, while others are rather different. It is important to know to what the cartographic unit corresponds; this will not

change, regardless of eventual modifications of Soil Taxonomy. Any difference that might modify a soil's suitability for agriculture, and therefore be indicated on the aptitude maps, was taken into consideration and duly noted.

For the Mollisols and Andisols, the legend corresponds to the new proposition of Andisol classification proposed by Guy Smith following his visit to Ecuador, and partially motivated by our soil map legends. For each soil unit, we have indications of the moisture and temperature regimes. Temperature of the soil at the 50-cm depth is relatively constant throughout the year in Ecuador. The limits 10°–13°–21°C were chosen (no cropping is possible at less than 10°C). Several auxiliary maps were obtained from the original soil maps at the same scale, 1:50,000. The following supplementary information was added.

The auxillary maps include:

- *Erosion and risk of erosion*: Erosion depends on the type of soil, but also on slope, parent material, and moisture regime. We identify several types of erosion by water runoff. Solifluxion erosion is dramatic in many soils with argillic montmorillonitic layers (Mollisols, etc).
- *Zoning for potential forests and suitable species*: Forest aptitude maps can easily be derived from the soil and erosion maps. The aim of these maps is to provide an answer to the following questions:
  - Where is it prohibited to clear the forest, or where is it recommended to reforest?
  - Where is it best to reforest when we do not wish to carry out soil conservation work?
  - Which forest species are suited to various areas or are to be tried?

  For the legend we have 4 main categories:
  1. No possibility of cultivation (except for coffee). Reforestation is necessary for protection and wood production. Clearing to be avoided.
  2. Preferable to reforest. Possibility of cultivation and pasture, but only if very expensive anti-erosion work is undertaken.
  3. Generally suitable for agriculture and stock raising, but, in certain areas, reforestation or anti-erosion work is needed.
  4. Region of agriculture and pasture (normal anti-erosion practices) with, in addition, the possibility of wood production in some places.
- *Cartographic representation*: One map is superimposed on the soil maps; this is the basic document which will be used for the modifications and to explain the concept of the map. Another map is created by superimposing the same masks on the topographic map; this is handed to the agents of the Forest Development Program and any other interested organizations. Native or cultivated forests are identified by shade on a third map. Generally, there are 3 x 140 maps for the zoning potential of the forest, including indication of suitable species.

- *Zoning for potential crops*: The crop zoning that we did in the Sierra would not be necessary were the climate and soils more uniform, as is the case in other regions. We made these maps because the Sierra regions are rugged and have diverse climates. All crops do not have the same needs: what is detrimental for one is not necessarily for another and can, in fact, be advantageous. The disadvantage in making a synthesis map for all crops is that serious distortions occur. If, on the other hand, only one crop is chosen, it is possible to select from the 1:50,000 soil map the factors relevant to that one crop. Other plants which might be rotated or planted (mixed) at the same time are also indicated. If there is any distortion, it concerns these other crops and not the main crop in question.

By studying each crop individually, additional data can be included on the maps, such as species and disease zoning, as well as parasites. Farming techniques or irrigation adapted to each mapped sector can also be shown and, in addition, the fertilizers or soil improvements which are needed. It is also possible on these individual maps to register all useful information that pertains to the particular crop. This means that written or oral information and the fruits of experiment or experience will not be lost. Much information from former studies is ignored because no one knows where it is kept or even if it still exists. Therefore, it is important to carefully research everything relevant to the crop in question and then to correctly extrapolate the results.

Potatoes. The purpose of these maps is to provide answers to the following questions:

- Where is it possible to cultivate potatoes and what are:
  - the ecological areas more likely to give better yield and better quality?
  - the risks of disease or parisitism in each area (in relation to the moisture and temperature regime of the soil)?
  - the number and nature of necessary treatments?
  - the risk of drought?
  - the risk of excessive rain?
  - the risk of frost?
  - the risk of erosion?
- Where is it possible to mechanize plowing and cropping? Which kind of anti-erosion precautions must be taken?
- What are the fertilizer needs in the different zones?
- What rotations with other crops are possible?
- Which are the areas sufficiently homogeneous to justify field experiments for fertilizer variety and to obtain available results for large areas?

Cartographic representation is achieved by superimposing on the soil maps. This constitutes the basic document which will be used for modification. Another map is created by superimposing the same masks on the topographic map; this gives information about agrarian structures and irrigation, and is given to the agents of the Agricultural Development Program. For example:

- Very small properties (minifundia), or medium or large farms;
- The total soil surface can be irrigated without limitation; soils can be irrigated, but only on part of the surface and sometimes with an inadequate water supply.

Wheat. These maps are similar to those described above, but include supplementary problems of mechanization by combine harvester, where this is possible. Flat cultivation is more susceptible to erosion by runoff than the furrow practice of potato fields. Tentative zoning of local varieties of wheat was done. All varietal experiments over a 10-year time period were correlated with mapping units.

Pastureland. In wet areas, it is possible to have good intensive pasture. In each ecological area, we have recommendations for modern farms and simpler, less progressive farms. Indications are given concerning mechanization, fertilization, cut grass, rotation with other crops, number of cattle per ha, etc.; and at lower altitudes, irrigation needs, types of agriculture, and pastureland. In many areas with an intense dry season, overgrazing and degradation of the soil by erosion has been observed; we have not mapped these areas. Zoning potential of pasture only concerns areas where actual practice or recommended practice, indicated in the legend, is suitable to ensure soil maintenance in accordance with normal soil conservation practice.

Similar zoning maps are obtained for corn, coffee, plantation crops, and vegetables.

All the zoning maps for crops and forests (1200) are distributed and widely used in the Sierra of Ecuador. The completion of this zoning for crops and potential agricultural use has recently become one of the priority objectives of the Minister of Agriculture of Ecuador.

Argentina

We are starting similar cartographic work in a 1500-km stretch of the Precordillera and the Cordillera of Patagonia. The maps are based on the climotoposequences of the soils for zoning on potential forest and transhumance pastureland. The predominant winds are from the Pacific; rain is abundant on the peaks (Andisols) but decreases very rapidly toward the east (Mollisols, then Aridisols). Vast areas of native forests of nothofagus and araucaria have been destroyed by burning in the last 50 years; in order to clear a few hectares, thousands of hectares have gone up in smoke. The purpose of the maps at the scale of 1:50,000, which are to be produced, is the establishment of forests, with a view to production of either native species or exotic species adapted to each site, and also the creation and conservation of the transhumance pastureland and the restoration of deteriorated areas or areas unsuitable for reforestation.

Numerous factors concerning the soils are taken into consideration—moisture and thermal regimes, and external factors such as frost, wind, and slope.

Martinique and Guadaloupe

The maps at a scale of 1:20,000 show the deforested areas and the zones of degraded soils which could possibly be recovered for pastureland and also the areas where reforestation is preferable.

SUMMARY

There are many different volcanic ash soils. Some are very fertile and have not been affected by erosion, even on steep slopes. Others are extremely fragile and unstable, and land clearing can provoke irrevocable destruction within a few years.

The fertility and depth of some soils can hide different effects of erosion, despite progressive elimination of soil. The necessity to take essential anti-erosion measures may not be readily apparent, but destruction of the soils increases annually.

The chemical fertility of some soils is very high and is maintained for a long time. In other soils, the fertility decreases very quickly after land clearing, and fertilizers are required.

The great variety of soils, the often hilly relief of mountains, and variations of hydric and thermic regimes of soils, require the establishment of soil maps and interpretive maps. Maps show all kinds of information in an easily available form.

The author took part in the production of various maps in the Sierra of Ecuador (1200), and in Antilles (500). At present, he is working in Argentina on volcanic ash soils.

Examples of maps are given concerning the soils, risks of erosion, potential of native or cultivated forests and species to be adopted, and zoning of various crops, pastures . . . some areas being clearing native forest, bush, or grassland.