

**Solving Agricultural Problems Related to Soil Acidity  
in Central Africa's Great Lakes Region**

**CATALIST Project Report**

by

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## Acronyms and Abbreviations

Al	aluminum
C	carbon
Ca	calcium
CAGLR	Central Africa's Great Lakes Region
CaCO <sub>3</sub>	calcium carbonate, calcite or calcitic limestone
CaO	calcium oxide
Ca(OH) <sub>2</sub>	calcium hydroxide
CaMg(CO <sub>3</sub> ) <sub>2</sub>	calcium-magnesium carbonate or dolomitic limestone/dolomite
CAN	calcium ammonium nitrate
CAS	critical Al saturation
CATALIST	Catalyze Accelerated Agricultural Intensification for Social and Environmental Stability
CCE	calcium carbonate equivalent
CEC	cation exchange complex
CO <sub>2</sub>	carbon dioxide
DAP	diammonium phosphate
DRC	Democratic Republic of Congo
ECC	effective calcium carbonate rating of a liming material (= CCE × FF)
ECEC	effective cation exchange capacity
Fe	iron
FF	fineness factor
H	hydrogen
H <sub>2</sub> O	water
HCO	bicarbonate
ICRAF	World AgroForestry Centre
IITA	International Institute of Tropical Agriculture
ISAM	integrated soil acidity management
ISAR	Rwanda Institute of Agronomic Sciences (Institut des Sciences Agronomiques du Rwanda)
ISFM	integrated soil fertility management
K	potassium
LR	lime requirement(s)
Mg	magnesium
Mn	manganese
N	nitrogen
NGOs	non-governmental organizations
NUANCES	Nutrient Use in Animal and Cropping Systems—Efficiency and Scales
O	oxygen
OH	hydroxide
OM	organic matter
P	phosphorus
PR	phosphate rock
RAS	required percentage Al saturation
S	sulfur

SO <sub>2</sub>	sulfur dioxide
SOM	soil organic matter
TLU	tropical livestock unit(s)
TSP	triple superphosphate
VCR	value:cost ratio
WARDA	Africa Rice Center

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# **Solving Agricultural Problems Related to Soil Acidity in Central Africa's Great Lakes Region**

## **CATALIST Project Report**

### **I. Introduction**

IFDC, an International Center for Soil Fertility and Agricultural Development headquartered in the United States, is currently implementing a project to intensify agricultural production in the Great Lakes Region of Africa. The Catalyze Accelerated Agricultural Intensification for Social and Environmental Stability (CATALIST) project is a 5-year regional activity funded by the Dutch Government. The project began in October 2006 and will run through September 2011. Field headquarters are located in Kigali. In addition to Rwanda, the project will mainly work in Burundi and eastern Democratic Republic of Congo (DRC) and, to a lesser degree, in southern Uganda and western Tanzania. CATALIST's overarching goal is to contribute to regional peace and security through intensified, sustainable agricultural production and improved product marketing. The linkage between peace and productivity highlights a core belief that a *sine qua non* for regional stability is increased productivity to improve food security and rural incomes.

CATALIST focuses on staple crops rather than high-value commodities as intensification of staple production holds the greatest potential impact on poverty reduction and increased producer revenue.

The following is partially based on a report of a 2-week consultancy by T. W. Crawford, Jr., additional information from communication with experts (see acknowledgments), and literature. Basic information is presented about soil acidity and the often inherent Al toxicity and about diagnosis and correction of Al toxicity and soil acidity through liming. The document also treats other related information regarding soil and crop management, including fertilizer. It also treats partial alternatives for expensive liming in VII: "Living With Acid Soils."

Because there is little regional data regarding the yield effects of suppressing or decreasing Al toxicity, only a rough estimate has been made of the economic feasibility of liming under different sets of conditions in Central Africa's Great Lakes Region (CAGLR). The last chapter presents the results.

The appendices present the (A) terms of the Scope of Work of the short-term consultant, (B) several maps, (C) information about Rwandan sources of lime, (D) crop calendars of Rwanda, Tanzania, and Uganda, (E) a literature review, and (F) a bibliography. The maps present the presence of acid soils in CAGLR, against the background of a general map of soils and climate (agroclimatic zone map) for the entire CATALIST region (only part of CAGLR). F. Rey de Castro composed most of these maps, based on Internet information, etc.

The document is written for agronomists from projects such as CATALIST, research and extension services and organizations, farmers' organizations, non-governmental organizations (NGOs), etc. It focuses on tropical soils, which differ significantly from soils in temperate regions regarding soil acidity, Al toxicity, and correction concern (see II.2). The presented recommendations regarding soil analyses and treatments are for the indicated agronomists; at present, farmers do not yet have the means for the analyses (see the introduction of III), and the economic feasibility of correcting Al toxicity in most of the CAGLR still has to be proven. The report will show that governments and donors should help ensure that good quality lime becomes available for reasonable prices (VIII).

Agronomists should use the document for deriving recommendations for farmers. Projects, services, and organizations should derive recommendations for policymakers and donors for improving the economic feasibility of controlling Al acidity.

## **II. Soil Acidity**

### **II.1. Basic Information on Soil and Soil Acidity**

“Food comes from the earth. The land with its waters gives us nourishment. The earth rewards richly the knowing and diligent but punishes inexorably the ignorant and slothful. This

partnership of land and farmer is the rock foundation of our complex social structure,” W. C. Lowermilk (Soil Improvement Committee, 1985).

The soil, a medium for plant growth of field crops, is a complex natural material derived from disintegrated and decomposed rocks and organic materials, which provide essential nutrients and anchorage for land plants. The following information about soil acidity is mainly from a practically oriented publication, *The Western Fertilizer Handbook* (Soil Improvement Committee, 1985). Of 17 essential plant nutrients, only carbon (C) is obtained by the plant primarily from the air with the fixation of carbon dioxide in photosynthesis. All of the other 16 essential nutrients that plants need in adequate amounts to complete their life cycle and reach their full genetic potential are absorbed through the roots.

The roots of field crops are the entry point of plant nutrients from the soil, and the absorption of plant nutrients from the soil is affected by many soil characteristics. A key characteristic of the chemical environment of plant roots in all soils is the soil reaction, which is measured as pH. The pH value is the negative logarithm of the hydrogen ion activity and is, therefore, also an indicator of the relative amounts of hydrogen ions ( $H^+$ ) and hydroxyl ions ( $OH^-$ ) in the soil solution (the water in the soil). The sum of the pH and the P ( $OH^-$ ) values equals 14. Values of pH are characterized as acid, neutral, or alkaline on a scale of 0 to 14. In the middle of the scale (7.0), the soil is neutral in reaction; below 7.0, the soil is acid; and above 7.0, the soil is alkaline. The lower the pH value, the more acidic the soil, and conversely, the higher the pH value, the more alkaline is the soil. Because pH is a logarithmic function, the difference between one pH unit and the next represents a tenfold increase or decrease in relative acidity or alkalinity. For example, a soil with pH 4.0 is 100 times more acidic than a soil with pH 6.0.

Soil reaction is important to plant growth, because it (1) affects nutrient availability to the roots; (2) has a direct effect on uptake of nutrients by roots; (3) affects the solubility of toxic substances, such as aluminum;<sup>1</sup> and (4) affects micro-organisms in the soil. As a consequence of these factors, (5) root development is influenced, which in turn influences factors (1) and (2) as well as water uptake, plant growth, and development. Between pH 6.0 and 8.0, most plant

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<sup>1</sup>Aluminum toxicity, manganese toxicity, or nutrient deficiencies that are common in untreated acid soils can severely depress crop yield even when NPK fertilizer is applied.

nutrients are soluble and are available unless the soil has been “mined” of them by taking out more nutrients from cropping than are returned. Most agricultural crops show optimal root development and produce well in the range of pH 6.0–8.0 if all plant nutrients (including hydrogen and oxygen as water) are available in the soil.

There are many sources of soil acidity (Havlin et al., 2005): (1) precipitation; (2) soil organic matter; (3) nutrient transformations and uptake; (4) leaching; (5) clay minerals, aluminum (Al) oxides, iron (Fe) oxides, and organic matter (OM); (6) Al and Fe hydrolysis; (7) soluble salts; (8) fertilizers; and (9) other long-term effects. *Precipitation*, or rainfall, introduces acidity to soils, because gaseous carbon dioxide (CO<sub>2</sub>) and water (H<sub>2</sub>O) in the rain react to form a solution that is about pH 5.7. The pH of rainwater can vary, depending upon contributions to acidity of the precipitation by gases such as sulfur dioxide (SO<sub>2</sub>), ammonia (NH<sub>3</sub>), and gaseous oxides of nitrogen (NO<sub>x</sub>), such as nitric oxide (NO) and nitrous oxide (N<sub>2</sub>O), products of industrialization.

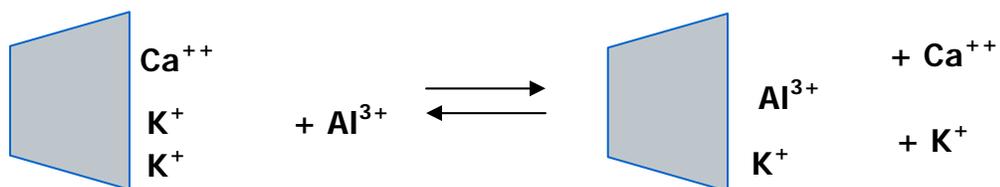
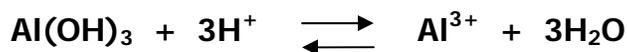
*Soil organic matter (SOM)* is a source of CO<sub>2</sub>; as micro-organisms in the soil decompose organic matter in the soil, CO<sub>2</sub> gas released from the decomposition combines with water in the soil to produce H<sup>+</sup> and bicarbonate (HCO<sub>3</sub><sup>-</sup>). Because the CO<sub>2</sub> produced by decomposition of organic residues and by root respiration is about ten times the concentration of atmospheric CO<sub>2</sub> above the surface of the soil, acidity produced from soil CO<sub>2</sub> is greater than that produced in the atmosphere. SOM also contains organic acids and reactive carboxylic and phenolic groups that are sources of acidity (H<sup>+</sup>). In peat and muck soils, as well as in mineral soils with high organic matter content, organic acids contribute significantly to soil acidity.

*Nutrient transformation and uptake* by plants is a source of soil acidity. Because most plants take up more cations than anions, H<sup>+</sup> is extruded by plants, resulting in an ionic balance, but a decrease in pH, of the soil solution. One study has shown that the pH of the soil solution next to the root decreased from about 7.5 to about 5.5 when ammonium ions were supplied as a nitrogen source. Hydroxyl ions are extruded by plant roots when anions are taken up, so the net

effect of nutrient uptake on soil pH will depend upon many factors of plant uptake of nutrients from the soil solution.<sup>2</sup>

*Leaching*, which is the movement of water downward through the soil, moves both cations and anions downward. Electrical neutrality (the balance of positive and negative charges in the soil solution) must be maintained, so if cations such as sodium (Na<sup>+</sup>), potassium (K<sup>+</sup>), calcium (Ca<sup>+2</sup>), and magnesium (Mg<sup>+2</sup>) move downward at a greater rate than anions such as nitrate (NO<sub>3</sub><sup>-</sup>), chloride (Cl<sup>-</sup>), and bicarbonate (HCO<sub>3</sub><sup>-</sup>), the pH in the root zone will decrease, because a net increase in H<sup>+</sup> will occur, maintaining electrical neutrality of the soil solution.

*Clay minerals, Al and Fe oxides, and OM* all are sources of H<sup>+</sup> in the soil solution resulting from the dissociation of the H<sup>+</sup> from these materials. Buffering, or the tendency to minimize the pH change of the soil solution, is also provided by these materials, which have functional groups that can accept and lose H<sup>+</sup>. Soils with high clay, SOM, or oxides of Al or Fe have greater capacity to buffer soil pH than sandy soils or soils low in OM. *Al and Fe hydrolysis* are sources of soil acidity, because as soil pH decreases, aluminum hydroxide [Al(OH)<sub>3</sub>] reacts with H<sup>+</sup> in a reversible reaction, which brings an increasingly large proportion of Al in the soil solution as Al<sup>+3</sup>, which is toxic to plants. It reduces root growth and development.



The soluble Al<sup>3+</sup> ions enter into exchange reactions with cations on the soil cation exchange complex (CEC) phase (bound to negatively charged clay particles), displacing essential plant nutrient cations such as Ca<sup>+2</sup>, Mg<sup>+2</sup>, K<sup>+</sup>, and cationic micronutrient metals such as copper,

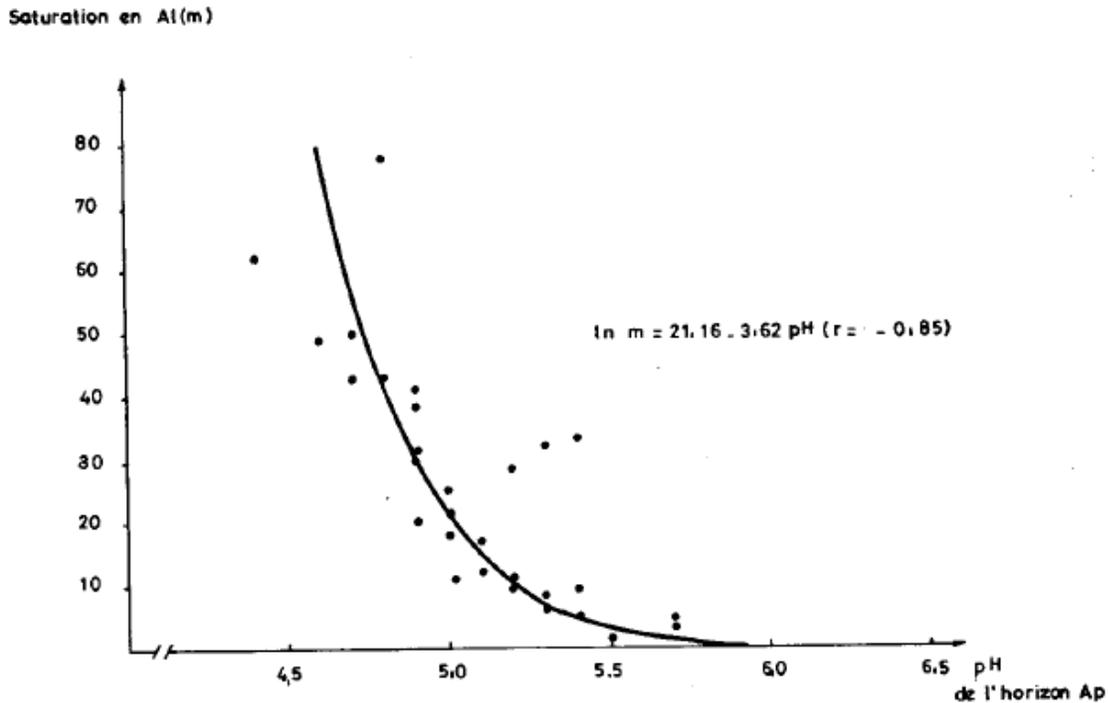
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<sup>2</sup>One may wonder why both plant growth and the mineralization of the product (organic matter; see above) cause soil acidification. V.3 and VII.3 formulate a partial answer; they also treat the “liming effect” of OM. Also see information on the buffering capacity of SOM.

iron, and zinc from the cation exchange complex. This results in high Al saturation—higher proportion of exchange sites occupied by Al.

Figure 1 illustrates the relationship between Al saturation of the CEC and the soil pH for a soil in Burundi. The graph varies between soils and their mineralogy, Al content, CEC levels, etc.

Oxides of Fe can undergo hydrolysis like those of Al, but because soil acidity is buffered by Al hydrolysis reactions,  $\text{Fe}^{+3}$  and soluble hydroxides of Fe are not produced until most of the soil Al has reacted. Al and Fe hydroxides occur as colloids, both amorphous and crystalline, and they coat the surfaces of clays and other minerals.



**Figure 1. Relationship Between Aluminum Saturation of the CEC and pH of the Ap Horizon of Moist Kaolisols in the Mugamba Region of Burundi (Schalbroeck and Opedecamp, 1985)**

*Soluble salts* from the dissolution of soil minerals, from addition of fertilizers or manures, or from the decomposition of OM can result in decrease of soil pH with the production of  $\text{H}^+$ . High rates of band-applied fertilizers in soils with  $<5.0$  can result in higher soluble  $\text{Al}^{+3}$ , which is toxic to plants, decreasing plant growth. *Fertilizers* differ in their effects on soil pH. Fertilizers

containing nitrogen (N) or sulfur (S) can decrease soil pH as the N or S is oxidized by soil microorganisms. The calcium carbonate equivalent of fertilizers containing N or S is the weight of calcium carbonate ( $\text{CaCO}_3$ ) required to neutralize acidity in the fertilizer. Rated from lowest (least acidifying) to highest (most acidifying) calcium carbonate equivalent, the following fertilizers acidify soils: anhydrous ammonia (3.6), urea (3.6), ammonium nitrate (3.6), diammonium phosphate (5.4), ammonium thiosulfate (5.4), ammonium sulfate (7.2), monoammonium phosphate (7.2), and elemental sulfur (7.2) (Adams, 1984; VII.1.3). On the other hand, calcium ammonium nitrate (CAN) has much less or no acidifying effect depending on the ammonium nitrate: $\text{CaCO}_3$  ratio in CAN. Hence, it may be a preferred N source in areas where lime is not available. *Long-term effects* of soil acidification will be most severe on sandy soils and generally less, other factors being equal, on medium-textured soils such as loams. Heavy-textured soils that generally have higher CEC (the capacity of solids in the soil to loosely hold by electrostatic charged cations in equilibrium with the cations in the soil solution) are better buffered and will generally suffer less from long-term effects of acidification.

## II.2. Tropical Versus Temperate Soils

A significant nuance regarding the end of the previous paragraph concerns the difference between soils in the tropics and those in temperate regions. In the tropics, soil pH is usually lower than in the temperate regions. Among the adsorbed cations, Al takes a large portion. Because of this and the presence of Al and Fe (hydr)oxides, the structure (stability) is good. The most important aim of liming in the tropics is mitigation of Al toxicity. At pH ( $\text{H}_2\text{O}$ ) above 5.0–5.2, the concentration of Al ions in the soil is so low that crops are not (seriously) hindered by Al. In the tropics, soil acidity is mainly linked to old, heavily weathered soils (rainfall > evapotranspiration), existing for a large part out of Al and Fe oxides and hydroxides; these are red or yellow-brown soils with a relatively high texture. When the pH of temperate soils is increased by liming to levels above 6–6.5, the soil structure improves. However, in the case of tropical soils with high levels of Al and Fe oxides, liming to increase the pH to such levels leads to degradation of structure and progressive increase of erodibility; the slowly soluble  $\text{Al}(\text{OH})_3$  is formed. A second risk is the distortion of the soil cation balance (in particular Mg, K, and  $\text{NH}_4$ ) through high amounts of Ca. Even when trying to achieve pH levels of 5.2–5.5, risks exist for smallholder farmers who do not have the equipment to mix lime homogeneously in the first 30 cm or more of the soil; locally, the pH of the topsoil may reach levels that are too high and favor soil erosion.

The most serious problem of acid soils concerns Al toxicity (see II.3);  $\text{Al}^{3+}$  becomes soluble and progressively occupies the CEC at lower pH levels. This fact and the peculiarity of tropical soils described above imply that in the tropics, it is wiser to focus on lime application for the correction of Al toxicity instead of trying to bring the soil pH close to neutral. This is why this document focuses on the decrease or suppression of the Al toxicity.<sup>3</sup>

Another important difference between soils from temperate and tropical regions is the nature of soil surface charge. The most common source of surface charge on soil colloids is from structural imperfections in the crystal structure. These imperfections result in a permanent negative charge on soil colloids, because lower valence (charge) elements substitute for higher ones (e.g.,  $\text{Al}^{3+}$  for  $\text{Si}^{4+}$  and  $\text{Mg}^{2+}$  or  $\text{Fe}^{2+}$  for  $\text{Al}^{3+}$ ). The less weathered soils from temperate regions have such a surface charge—mostly a fixed negative charge. Soils with oxides and hydroxides of Al, Fe, Mn, Si, and Ti, and kaolinites—commonly soils of the tropics—can assume either a positive or negative surface charge, hence a variable charge. The sign and magnitude of surface charge are determined solely by the ion that is adsorbed in excess on the hydroxylated surface. It is possible to increase the cation retention capacity (negative surface charge) of variable-charged soils by lowering the pH at zero point of charge ( $\text{pH}_0$ ). At zero point of charge, the soil has a net charge of zero. The  $\text{pH}_0$  can be lowered by application of silicates and phosphates (option for phosphate rock as P source and soil amendment). Al, on the other hand, has the opposite effect (Singh and Uehara, 1998).

$$\text{Surface Charge}_{\text{variable}} = \text{Constant} (\text{pH}_0 - \text{pH})$$

More importantly, the equation shows that soil pH in variable-charged soils determines the magnitude of net charge as well as the sign. Thus, the increase in soil pH due to liming results in lower Al saturation due to precipitation of  $\text{Al}(\text{OH})_3$  and also higher CEC. The pH buffering capacity of variable-charged soils also increases exponentially as the absolute difference between  $\text{pH}_0$  and pH increases. The  $\text{pH}_0$  of most variable-charged soils is between 4.8 and 5.5; thus, it is impractical (excessive lime requirement) to raise soil pH above 6.

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<sup>3</sup>For stronger pH increases, which may be required on acid soils of temperate regions, available guides should be used. Examples are *The Western Fertilizer Handbook* (Soil Improvement Committee, 1985) and *Nutrients in Soil Plant Relationships* (Janssen, 1999).

A significant percentage of soils of the CAGLR are acidic. Partially as a consequence, deficiencies in nitrogen (N) and phosphorus (P) are widespread and potassium (K) and magnesium (Mg) deficiencies are also observed.

### **II.3. Problems of Plant Nutrition in Acid Soils**

The effects of soil acidity, acidification, and liming can be classified into three main categories that cannot always be sharply distinguished: the availability of nutrients and toxic elements, biological activity,<sup>4</sup> and soil structure. The first category will be treated here.

The availability of essential plant nutrients is affected by soil pH. In acid soils, there are problems of both plant nutrient deficiencies and toxicities of three elements (Al, Mn, and H).<sup>5</sup> Water is essential for plant life as soil solution because it carries all plant nutrients through mass flow and/or diffusion to the roots. N, after hydrogen and oxygen, is the element needed in greatest quantity from the soil for plant growth. Plants absorb most N in the nitrate ( $\text{NO}_3^-$ ) form, but they also absorb N in the ammonium form ( $\text{NH}_4^+$ ). The latter is preferentially absorbed at high pH (Adams, 1984). Nitrate-N can be more available than ammonium-N, because  $\text{NO}_3^-$ -N is mobile in soils and can move to plant roots with soil water, since it is negatively charged. Ammonium-N, on the other hand, is relatively immobile, being attracted to negatively charged surfaces of the soil's CEC. In the process of nitrification, nitrogen is converted by microbial activity from ammonium-N to nitrate-N in temperature-dependent and pH-dependent reactions catalyzed by micro-organisms. The optimum range of oxidation of  $\text{NH}_4^+$  nitrogen to  $\text{NO}_3^-$  is between pH 5 and 8. In acid soils below pH 5, nitrification is severely reduced. The result is that N in the soil becomes less available to plants. At soil pH <5, both nitrification and mineralization (conversion of N from organic molecules into inorganic forms by microbial activity) are diminished, making N less available to plants. Liming of soils of pH less than 5 results in increased heterotrophic microbial activity, resulting in greater availability of mineral forms of N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) for uptake by plants.

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<sup>4</sup>Soil micro and macro flora and fauna, SOM mineralization, nitrification, biological nitrogen fixation, etc. Micro-organisms form cementing agents, like polysaccharides, by which soil particles are stuck to each other. As the development of roots increases, it further stimulates the cohesion of soil particles and increases the porosity and organic matter content of the soil.

<sup>5</sup>Fe is a fourth possible toxic element. It may play a role in the anaerobic environment of irrigated crops.

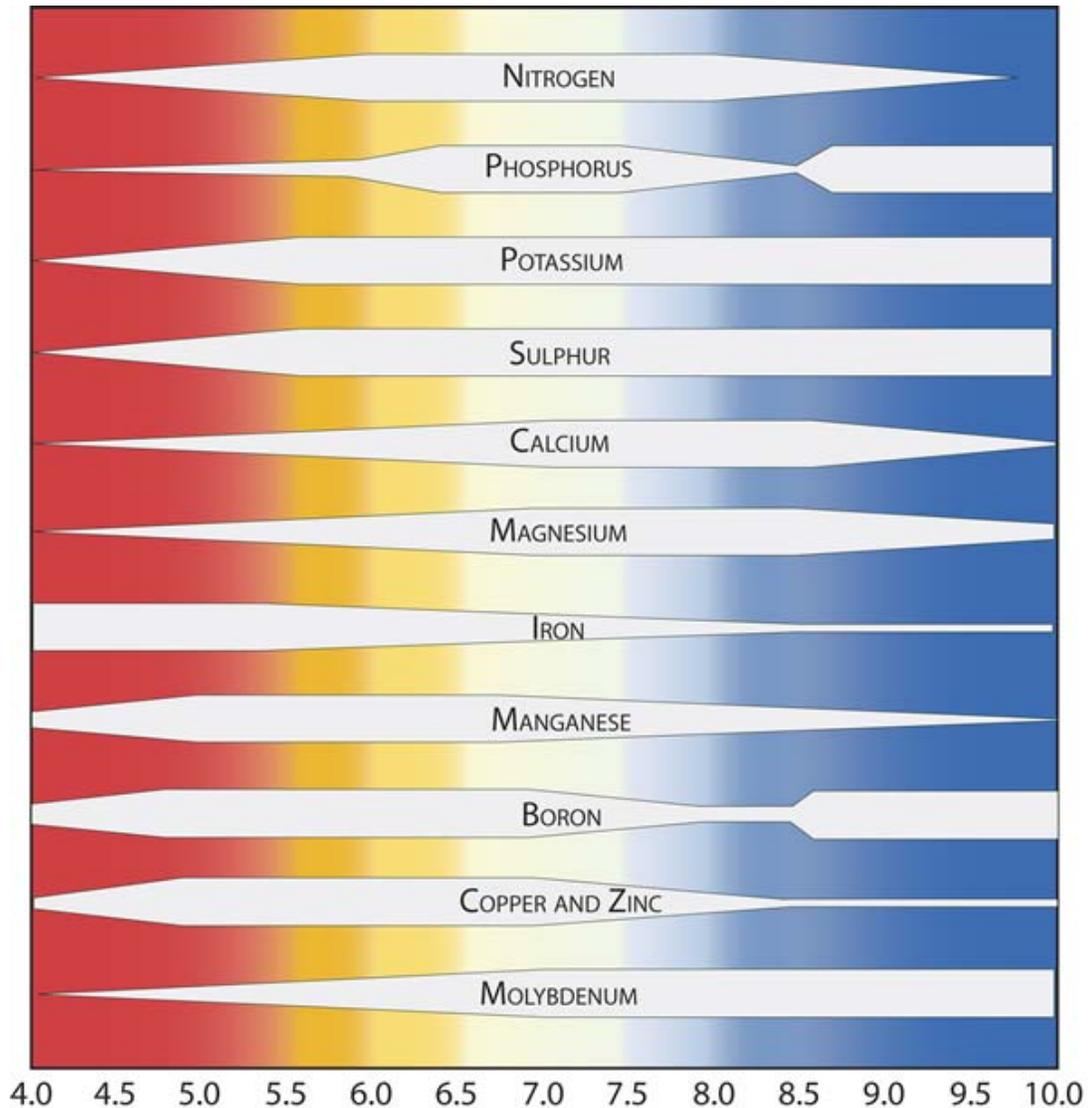
In soils of low pH (pH <5) that contain high amounts of Al and Fe oxides, P (an essential plant nutrient that occurs in anionic compounds) is deficient in the soil solution because it is precipitated or surface adsorbed with Al and Fe as insoluble Fe/Al-P compounds on the surface of Fe/Al oxide minerals. Liming of such soils precipitates Al as Al(OH)<sub>3</sub> and Fe as Fe(OH)<sub>3</sub> and thus eliminates Al toxicity. However, the availability of P may not increase because both Al(OH)<sub>3</sub> and Fe(OH)<sub>3</sub> can adsorb P. Liming increases surface negative charges of variable-charged Fe/Al oxide minerals, which results in a reduction of P adsorption. *(Note: The ionic form of the P nutrient depends on the P source; e.g., H<sub>2</sub>PO<sub>4</sub><sup>-1</sup> is in water-soluble P fertilizers, HPO<sub>4</sub><sup>-2</sup> is in dicalcium phosphate, and PO<sub>4</sub><sup>-3</sup> is in apatite).*

Several other essential plant nutrients, which are present in the soil as cations, are deficient in acid soils with pH <5.0 and low-percentage base saturation; the percentage of CEC that is attributed to exchangeable Ca<sup>+2</sup>, Mg<sup>+2</sup>, K<sup>+</sup>, and Na<sup>+</sup>. They include potassium, calcium, magnesium, and molybdenum. Correction of nutrient deficiencies in acid soils can be achieved by several means: liming, addition of organic matter, and fertilization with mineral fertilizers.

Plant growth, and especially root growth, in acid soils is retarded by toxicities of Al, manganese (Mn), and H<sup>+</sup>. The degree of toxicity depends upon how high the concentration of soluble or exchangeable Al<sup>3+</sup> is (including its contribution to the CEC saturation) and how low the pH is. Toxicities of Al and Mn become evident in reduced plant growth when pH is less than 5.0. Exchangeable Al and the concentrations of Al and Mn in solution increase as pH decreases. At pH <4.0, toxicity of H<sup>+</sup> has been observed. The toxicities of Al, Mn, and H<sup>+</sup> must be corrected by removing Al (and Mn) from the CEC and from the soil solution. This involves a combination of replacing Al<sup>3+</sup> occupying the CEC by Ca<sup>2+</sup> (Mg<sup>2+</sup>, K<sup>+</sup>) and raising the soil pH, leading to precipitation and to neutralizing excess H<sup>+</sup> by the formation of water and other means. Selection of crop varieties and crop species that are relatively tolerant of acid soils, such as potatoes, can be used to produce crops in mildly acid soils, where sensitive plant species will not grow normally. Acid-tolerant crops and varieties can tolerate higher concentrations of aluminum and lower concentrations of essential plant nutrients than most crop species can (see VII.2). They succeed in (rather) good rooting in spite of soil acidity, making them also more drought tolerant. The retarded, limited, and shallow root development of other sensitive crops and varieties causes a serious decrease of accessible soil water (especially for acidic subsoils).

#### II.4. Availability of Plant Nutrients as a Function of Soil pH

Because many complex chemical and biological phenomena in soils depend, in part, upon soil pH, the availability of essential plant nutrients varies with soil pH. Figure 2 presents a rough overview.



**Figure 2. The Availability of Essential Plant Nutrients Varies With Soil pH**

Source: National Sustainable Agriculture Information Service  
([http://attra.ncat.org/attra-pub/organic\\_soil.html](http://attra.ncat.org/attra-pub/organic_soil.html))

One should realize the difference between the availability of soil nutrients in relation with soil pH and the availability of fertilizer nutrients. It is possible that a crop growing at low pH will absorb a (much) higher fraction of, for example, N, P, and K from timely fertilizer gifts, than

indicated by Figure 2 for pH values below 5. Crop growth depends, however, on both fertilizer nutrients and soil nutrients, and fertilizer gifts are often far from optimal regarding the time and method of application. Particularly when Al toxicity leads to bad root development, the chance of absorbing enough nutrients (and water; see above) for maximum growth is extremely limited. In order to increase the availability of essential plant nutrients in acid soils, it is necessary to correct Al toxicity by increasing the soil pH.

### **III. The Extent of Soil Acidity and Management of Acid Soils in the African Great Lakes Region**

The CATALIST project is being implemented in selected areas within the CAGLR. The first map in Appendix B shows administrative boundaries of Rwanda, Burundi, and parts of the DRC, Tanzania, and Uganda where CATALIST will implement agronomic work. The second map presents an overall impression of the presence of different pH classes of acid soils, and the third concerns the major soil types of the region. The generalized pH associated with large areas of land in Burundi, DRC, Rwanda, Tanzania, and Uganda is indicated by soil pH maps in Appendix B. The maps should be used carefully; a difference exists between the sources of the maps and the methods and precision of the products. Comparing the southern part of Rwanda with the northern part of Burundi clearly shows that something is wrong; the border appears to determine pH changes. But, for example, in the west, soil and landscape do not change significantly.

While the soil pH maps in Appendix B present the spatial extent of soils within ranges of pH, they are merely generalizations. The pH ranges of the mapping units described in the legend of each map are generalizations at low resolution. Because of local differences among soils within a mapping unit, the maps are not adequate to determine whether the pH of the soil of any particular parcel of land is actually within the range of pH indicated on the map. Sampling and testing the soil reaction (pH) and Al toxicity are needed to determine whether soil acidity is a problem and to what extent Al toxicity or soil acidity should be corrected. However, only projects such as CATALIST can realize this for now. In the region, no systems exist for regular and general soil sampling or for measuring Al toxicity and pH. Also, it will take time to convince farmers that spending money for these systems is worthwhile. It is not yet known if sampling,

analyses, and liming should be promoted as long as the economic feasibility is not known (see VIII).

In contradiction to these maps that have limited precision, one may expect that a strong correlation exists between soil acidity and agroecological zones, which are combinations of soil and climate. This will be one of the tools for advising farmers who do not have access to systems of soil sampling and soil analyses. The tool will exploit knowledge and experience obtained for a similar combination of soil and climate.

Literature information about soil acidity in Burundi, Rwanda, eastern DRC, western Tanzania, and southwestern Uganda follows. VIII explains when and where to promote the correction of Al toxicity with external inputs such as lime, and when and where it should not be done. These recommendations will be based on the above-mentioned first impressions of the economic feasibility to use such inputs and the information from literature; they will take into account factors such as soil type, climate, typical crops, and weeds in certain regions, and the available knowledge, experience, and behavior of farmers.

### **III.1. Burundi**

Approximately 1 million ha are acidic (pH <5.0) of the 3 million ha of cultivated soils in Burundi; these acid soils require treatment to increase crop yields (Ntiburumusi, 1989). The soils of the Mugamba region are toxic in both aluminum and manganese and are deficient in bases, namely  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$ , and  $\text{K}^{+}$ , and in micronutrients such as Cu and Zn. Fe deficiency is seldom in acid soils because of the significant presence of Fe oxides. The soils are also deficient in P due to its adsorption with aluminum and iron oxides in the acid soils; some acid soils are low in total P, not just available P. Sulfur deficiency may occur in shallow sandy soils with low organic matter content.

In zones of the Mugamba region, where acidic, infertile kaolisols predominate, triticale was found to be more tolerant of soil acidity and Al toxicity than was wheat. Wheat and maize are grown in the relatively cool and rainy zone of Burundi between 1,400 and 2,200 m in altitude; here, the most important factor limiting agricultural intensification is soil acidity. Because of human pressure on the land, pastures are being changed to cultivated land, and

manure is becoming less available; therefore, a treatment of 4 tons (t)/ha of manure and 2 t/ha of lime was tested. In the manure-and-lime treatment, to approximate situations in which less manure is available, the 2 t/ha of lime is to partially correct Al toxicity.

On an Oxisol at Karuzi (1,600 m) in Burundi, maize and bean crops were given adequate fertilizer and applications of 3 and 6 t/ha of the pruned shrub and tree material; the increased yield was attributed to amelioration of soil acidity and lowered Al saturation of the CEC. These rates of addition appear feasible in agroforestry systems.

Al is toxic to crops, and Al saturation of many soils in Burundi is a serious impediment to achieving crop growth and increased yields. Scientists at the Faculty of Agricultural Sciences at Bujumbura conducted research to determine whether locally available materials (i.e., farmyard manure, lime, and partially acidulated phosphate rock [PR]) could be used to increase the yield of maize in strongly acid soils (pH 4.0). Farmyard manure and lime reduced the amount of exchangeable Al, and soluble P sources (triple and single superphosphate) were replaceable by partially acidulated PR from the Matongo PR deposits in Burundi (Rwigema et al., 1993).

In Burundi, commercial agricultural lime ( $\text{CaCO}_3$ ) is scarce and costly—more than US \$100/t in 1999,<sup>6</sup> which is about a fifth of the annual income of an average local farmer (see VIII for more recent prices). This necessitates the use of other locally available materials to ameliorate acidity of Oxisols used to cultivate crops (Van den Berghe and Hue, 1999). Experiments with sorghum showed that application of Verrundi lime reduced exchangeable Al, increased plant growth, and, by increasing pH, increased available phosphorus. Application of composts had similar results; composts were more effective in correcting soil acidity when fresh and enriched with some nutrients during composting. Equivalent yield of sorghum was achieved with about 20 t of compost per hectare, compared with sorghum in acid soil treated with  $\text{CaCO}_3$  applied at a rate of 0.6–1.7 t/ha. Most farmers will not be able to afford to apply 20 t/ha of compost, because the sources for compost are limited. Also, the labor requirement is high compared with the labor necessary to apply about 1 t/ha of lime.

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<sup>6</sup>Present price is \$160/t.

### **III.2. Democratic Republic of Congo**

The chronic deficit of food in South Kivu is due to two factors: (1) the soils are exhausted (low fertility) and (2) there are few opportunities for members of rural households to find employment (Faily, 2000). There is a vivid memory of the famines of 1920–1940 and 1945 in this part of the DRC. High population density has transformed the countryside into a patchwork of small parcels where soils are no longer left fallow. In addition, a feudal land tenure system persists, which dictates ownership and use of the land. In a development project entitled the Kabare Project, for about 30 years, the mean size of a parcel of land cultivated per family was about 0.86 ha (mode: 0.63 ha), and the parcels of land cultivated by women were about 40% smaller than those cultivated by men. Of 176 households, 80% shared 50% of the arable land, and 2% of the households controlled 16% of the total land cultivated. Control of most of the land in South Kivu is hereditary, which favors the customary power of the “modern” authorities of the state. This situation discourages soil conservation, encourages manual labor, and results in severe soil erosion. The lack of availability of chemical fertilizers, improved varieties, and crop protection products means that the only method available to most farmers in South Kivu to improve acid soils is the use of organic matter. Widespread Al toxicity of the acid soils is a severe impediment to increased crop production. For many years, those in the hinterland of South Kivu were able to make up their food deficit by purchasing beans from the Valley of Sake and maize in the territory of Lubero in the southern part of North Kivu. However, small producers in South Kivu are becoming marginalized, because the concentration of commerce is moving more and more to just a few traders who buy large quantities and take them to Bukavu by the lake. Bukavu has begun relying on food produced on the island of Idjwi and the riverine agricultural production areas of Kalehe where manioc (cassava) and bananas are the main crops. Due to civil unrest, animal husbandry has suffered; meat from livestock and poultry has disappeared from the diets of many in South Kivu. The situation in North Kivu is not much different; fallow land has disappeared, and overexploitation caused by overpopulation and land use rights has limited land available for smallholder farmers. The fraction of land in North Kivu that has acid soils is somewhat lower than in South Kivu, because the distribution of better soils is more favorable (see maps in Appendix B).

There are many opportunities to improve management of acid soils in South Kivu. The most important lime deposits are in Katana, north of Bukavu, and in Mushinga, south of Bukavu;

these lime deposits are not used for agriculture but are used principally in the construction industry and for production of pharmaceuticals by Pharmakina. In North Kivu, lime deposits are in Kasugho, southwest of Lubero, and in Katana.

### **III.3. Rwanda**

It is estimated that acid soils comprise two-thirds of the cultivated soils of Rwanda; serious problems occur on about half of these soils having the lowest pH (Roose et al., 1988). The effectiveness of alley cropping with leguminous shrubs in acid soils was investigated in Rwanda between 1983 and 1989. Yield increases of common bean (*Phaseolus vulgaris* L.) and sorghum (*Sorghum bicolor* L.) were greatest with *Cassia spectabilis*, but those on maize (*Zea mays* L.) were weak; the yields of sweet potato (*Ipomoea batatas* [L.] Lam) were less with the alley cropping treatments than with the control. Agroforestry was examined by field experimentation as a means of restoring eroding, acid soils in the central plateau (Rubona station of ISAR near Butaré) and in savannahs in the east (Karama station of ISAR) at lower altitudes in Rwanda. To achieve higher production of maize and bean grains (2,300 kg/ha per year) and sorghum grain (1,500 kg/ha per year), it was necessary to correct the pH (3 t/ha per 3 years of lime) and add 3–10 t/ha per 2 years of manure and fertilizer (40–100 kg/ha per year of N, 30–80 kg/ha per year of P<sub>2</sub>O<sub>5</sub>, and 20–200 kg/ha of K<sub>2</sub>O, depending upon plant needs and soil deficiencies). Results show that besides manure, addition of lime and fertilizers is necessary to raise yields significantly in acid soils of the central plateau and lowlands of Rwanda. Combined with agroforestry, soil erosion becomes as low as in the case of natural vegetations.

### **III.4. Tanzania**

Based on systems analysis of soils and agriculture for a 30-year period in Tanzania, it is predicted that the productivity of Tanzanian soils will decline unless steps are taken to reverse several processes. The main factor causing decline in productivity is the reduction in nutrient availability through soil mining and erosion. A buildup of soil acidity is also a threat to agricultural productivity, especially if strongly acidifying fertilizers are used. It has been observed that application of fertilizers has already contributed to the acidification of some soils in Tanzania.

### **III.5. Uganda**

Some soils in the Southern Province of Uganda have less than pH 6.0 (see maps in Appendix B). Some, but not all, soils in the districts of Bushenyi, Kiruhura, Lyantonde, Mbarara, Rukungiri, Kanungu, Ntungamo, Kisoro, Kabale, Isingiro, and Rakai are acid soils requiring amelioration. Small limestone resources are located near Ndorwa, Kitumba, Bubale, Kigata, and Kigararma (all in the vicinity of Kabale) and Kisiizi, Rubabo, and Rwonye in Rukungiri District.

In Uganda, it has been shown that phosphorus availability can be increased when acid soils are limed, resulting in higher yields of beans and seed cotton. The ratio of Ca:K is important in cotton, and potassium fertilization should be considered when liming soils used to grow cotton, such as ferralitic soils in Uganda.

Much of the soil information discussed above for the CAGLR was obtained during the 1980s and 1990s. During the last 20 years, increased population pressures have led to crop intensification without nutrient input or with inadequate nutrient input resulting in soil nutrient mining and increased soil acidity. Hence, the current soil acidity and soil fertility conditions are worse than reported.

## IV. Diagnosis of Soil Acidity and Al Toxicity

Final recommendations concern the correction of Al toxicity, since the CAGLR is located in the tropics. Because Al toxicity is a derivative from soil acidity, IV and V will discuss both soil acidity and Al toxicity.

### IV.1. How to Sample and Test Soil

Soil should be sampled from several places (three to five) in the field, and the samples should be taken to a depth of 30 cm. Once the samples have been taken, they should be mixed; a composite sample should be analyzed with a “soil kit” or sent to a laboratory to determine the pH (1:1 of soil:water suspension), the Al toxicity, and the CEC saturation by Al.

### IV.2. How to Determine Soil pH

There are many ways to determine soil pH. Buffer pH is most often used to estimate lime requirement, and it is a measure of both the soil’s active and reserve acidity. Gavlak et al. (2003) describe four laboratory procedures and calculations that can be used to recommend lime application rates. These methods are:

1. **SMP Single Buffer pH Lime Requirement**—Standard calibration curves are established for liming based on an SMP value to a desired pH for soil groups in a geographic area. Local calibration of the method is desirable if the SMP method is to be used in the CAGLR.
2. **Woodruff Buffer pH Lime Requirement**—The Woodruff method is better suited to soils low in exchangeable aluminum with acidity associated with ammoniacal nitrogen applications.
3. **Adams and Evans Buffer pH Lime Requirement**—The Adams and Evans method can detect small differences in lime requirement that may elicit large changes in pH. The procedure is generally reproducible within 0.10 pH units.
4. **Mehlich Buffer pH Lime Requirement**—The Mehlich Buffer method is particularly well suited to determine the lime requirement for neutralizing very acid soils that may be harmful to crop productivity.

However, the simpler, 1:1 of soil:water suspension to measure soil reaction (pH) is recommended for projects, such as CATALIST, that do not focus on research. Although this method of measuring soil reaction includes the soil’s active acidity and not the reserve acidity

( $\text{Al}^{3+}$  and  $\text{H}^+$  on the CEC), it does measure acidity of the soil solution and can be used to estimate lime requirement. This is a simple and cost-effective method of estimating soil acidity. It is not as accurate as the more complicated methods above measuring buffering capacity that include both active and reserve acidity, which require a chemical laboratory. However, it can be used as a basis to estimate the need to correct soil acidity and, with appropriate data and calculations, a basis to estimate lime requirement.

### **IV.3. How to Determine Al Toxicity**

Soil acidity limits nutrient uptake and plant growth through soluble and exchangeable  $\text{Al}^{3+}$ ,  $\text{Fe}^{2+}$ ,  $\text{H}^+$ , and  $\text{Mn}^{2+}$  (II.3), and shortages of Ca, Mg, and P. This document limits itself to the soil acidity as such ( $\text{H}^+$ ) and to Al toxicity.  $\text{Fe}^{2+}$  does not receive attention, because  $\text{Al}^{3+}$  has a much stronger affinity for the CEC. When Al toxicity is suppressed, the toxicity of Mn and Fe will also have been treated. Irrigated (flooded) rice on acid soils could form an exception; Fe toxicity may hinder crop growth.

The Al toxicity is caused by both exchangeable  $\text{Al}^{3+}$  (replacing other cations on the CEC) and soluble  $\text{Al}^{3+}$  that is in equilibrium with the CEC-absorbed  $\text{Al}^{3+}$ . The total amount is related to the degree of soil acidity (the concentration of  $\text{H}^+$ ). The degree of Al toxicity is quantified by extraction of  $\text{Al}^{3+} + \text{H}^+$  with neutral unbuffered salt. A soil sample should be extracted with 1M KCl, and the amount of  $\text{Al}^{3+} + \text{H}^+$  will be determined through titration. In acid tropical soils, most of the soil acidity is attributed to  $\text{Al}^{3+}$ . The procedure now used in most labs is atomic absorption, which will analyze only  $\text{Al}^{3+}$ , neglecting the  $\text{H}^+$ .

## V. Correction of Al Toxicity and Soil Acidity

Before treating the correction of Al toxicity and soil acidity, products that can be used for correction and their relative “liming efficiencies” will be discussed (V.1). The variation in liming efficiency in locally available liming resources is shown in V.2, which gives the results of analyses from samples obtained mainly in Rwanda. Some Burundian samples are also treated.

In spite of the fact that the CAGLR lies in the tropics, soil acidity correction will be treated in combination with the presentation of liming materials, even before treating the correction of the Al toxicity (V.3). This is done because it is often easier and cheaper to measure soil pH than to measure Al toxicity in the region; this allows agronomists to develop rough recommendations first. Al toxicity disappears when the soil pH reaches 5.0–5.5. The amounts of lime required for increasing a given pH to the level of pH 5.2 are presented in V.1 and V.3.3. They will also be used to estimate the upper limit of liming costs (VIII.2).

### V.1. Materials to Correct Al Toxicity and Soil Acidity

Liming materials have an alkaline effect: the anion is either  $\text{OH}^-$ ,  $\text{CO}_3^{2-}$ , or  $\text{SiO}_4^{4-}$ . These are anions that form non-dissociated or hardly dissociated combinations with  $\text{H}^+$  (in other words, anions that eliminate protons). In fact, the cation is not of interest for the pH increase<sup>7</sup>. In practice, mostly Ca is the cation; sometimes it is combined with Mg and in a few cases with K. Several factors influence the effectiveness of liming materials to correct Al toxicity and soil acidity, and several materials can be used for it. The following recommendations enable the agricultural producer to choose among alternatives to manage Al toxicity and soil acidity in an economical manner.

#### V.1.1. How to Calculate a Lime Requirement for Calcite or $\text{CaCO}_3$

There are several methods of estimating lime requirement. Yamoah et al. (1990) used chemical analyses of soils and mathematical models to estimate lime requirement. They found that there was a very high level of confidence in predicting lime requirement as a linear function of extractable aluminum (exchangeable aluminum on the cation exchange complex of the soil + soluble aluminum). Such a method requires a chemical laboratory and special reagents and procedures to determine extractable aluminum (V.3). They found that a less clear relationship

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<sup>7</sup>Groupe Chaulage du COMIFER, 2000.

exists between soil pH and lime requirement. Comparing their results with those of other researchers, Yamoah and his colleagues found that their methods, which yielded equations of the relationships between lime requirement and either exchangeable aluminum or soil pH, were similar, but on average, less than estimates of lime requirements from other researchers' more complicated methods (IV.2). Because of its simplicity and the region's lack of systematic soil sampling and analyses practices, it is suggested that soil pH (1:1 of soil:water) and an equation derived from the one Yamoah and his colleagues (1990) established should be used in CAGLR. They estimated the lime requirement for correcting soil acidity using 110 Rwandan soil samples<sup>8</sup> and the ACID4 model. Their formula,  $Y = 16.988 - 2.727 X$ , where Y = lime requirement in tons per hectare of CaCO<sub>3</sub> and X = water pH, has two weaknesses. Accepting the model ACID4, their formula describes a straight line where an S-form shape should be more logical (Figure 10 in Yamoah et al., 1990), and the formula calculates lime requirements for pH corrections to the level of pH 6.2.

It is proposed that pH (H<sub>2</sub>O) 5.2–5.5 be used as a maximum (Al saturation 0%–30%, making it possible for sensitive crops to grow without soil acidity problems). Thus, the formula needs to be adapted for lime recommendations up to pH 5.2–5.5. The precision of the formula and approximations also imply that anticipated pH will have an error of at least  $\pm 0.2$  pH units. As expected, this would result in a  $\pm 0.5$  t lime/ha difference.

The formula of Yamoah et al. (1990) and the adapted formula (see V.3.3) determine the lime requirement (LR) for changing the pH for the first 15 cm of topsoil. Factors such as the soil texture and the pH buffering capacity are neglected. For example, a sandy soil and clay soil with the initial pH 4.8 would require the same amount of lime according to the equation; however, the two limed soils would result in different pH values, with the limed sandy soil having much higher soil pH than the limed clay soil.

The relative “liming efficiencies” of materials treated below in V.1 and V.2 concern both the correction of soil acidity and Al toxicity. The liming effect of pure calcite or CaCO<sub>3</sub> is used as a standard and is 100%. The liming effect of other materials is expressed in relation to this

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<sup>8</sup>Samples from the Central Plateau and the Buberuka Highlands, at altitudes of 1,500 to 2,600 m and annual rainfall between 1,100 and 1,600 mm.

standard, or in Calcium Carbonate Equivalent (CCE). The relative CCE values are included with the descriptions of liming materials below (Havlin et al., 2005).

### ***V.1.2. Inorganic Materials for Liming***

Calcium oxide is the only material to which the term “lime” may be correctly applied (Havlin et al., 2005), but “lime” and “liming” have become generic terms. “Lime” refers to inorganic materials that can be added to an acid soil to increase the reaction (pH) of the soil. “Liming” is the addition of inorganic materials to the soil to increase the pH of an acid soil. Common liming materials include Ca and Mg oxides, hydroxides, carbonates, and silicates. “Limestone” is a generic term that refers to calcite and dolomite (see below). Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and other neutral salts cannot neutralize  $\text{H}^+$ , so they are not liming materials. In fact, neutral salts such as gypsum lower the soil pH of acid soils, because  $\text{Ca}^{+2}$  from dissolved gypsum can displace  $\text{H}^+$  from the cation exchange complex, thereby increasing active acidity of the soil solution and lowering soil pH. Application of gypsum on tropical soils can also result in lower surface charge and hence lower CEC. The effectiveness of liming materials will be expressed as CCE; some use, however, the calcium oxide equivalent (see Table 1). Phosphate rock (PR) can be used as liming material, because dissolution of PR consumes protons and adsorption of phosphate results in increased surface charge and CEC. The relative agronomic effectiveness of PR sources is also higher in acidic soils. Given the above and the low P status of the soils in the region, the use of PR as an amendment and the source of P should be explored further.

#### *Calcium Oxide*

Calcium oxide is a white powder made by roasting calcite ( $\text{CaCO}_3$ ) in a furnace, driving off carbon dioxide ( $\text{CO}_2$ ). Calcium oxide is the most effective of all liming materials, but it is caustic and must be shipped in paper bags. Pure calcium oxide has a calcium carbonate equivalent of 179% (CCE = 179%), compared with pure  $\text{CaCO}_3$  (CCE = 100%). Calcium oxide is also known as unslaked lime, burned lime, or quicklime. In Rwanda, it is disadvantageous to use CaO to correct soil acidity for several reasons (Beernaert, 1999).

### *Calcium Hydroxide*

Calcium hydroxide [Ca(OH)<sub>2</sub>], also known as slaked lime, hydrated lime, or builder's lime, is a white powder and difficult to handle. Calcium hydroxide rapidly neutralizes acid. CCE = 136%.

### *Calcium and Calcium-Magnesium Carbonates*

CaCO<sub>3</sub> or calcite (the standard), and calcium-magnesium carbonate [CaMg(CO<sub>3</sub>)<sub>2</sub>] or dolomite, are also called calcitic limestone or dolomitic limestone. They are grouped together as "limestone." From the standpoint of plant nutrition, when using limestone to correct soil acidity, it is important to know whether it is calcite or dolomite, because dolomite adds both Ca and Mg to the soil, whereas calcite adds only Ca. Dolomites are found in Rwanda, but at present only calcitic limestone and travertine (see below) are exploited. CCE of pure calcite is theoretically 100% (the standard); CCE of pure dolomite is 109%; however, the CCE of most agricultural lime, which has impurities, is 80%–95% or less. Limited dolomite mining occurs in Butare in southern Burundi.

### *Marl*

Soft, unconsolidated deposits of calcium carbonate are known as marl. Marl is moist and often mixed with impurities. CCE = 70%–90%.

### *Calcium Silicates*

Calcium silicates occur in slag byproducts of iron manufacturing and are found in some natural deposits. CCE = 86%.

### *Travertine*

Rwanda has several deposits of travertines, which are recent formations of the Pleistocene Age. They are compact, soft rocks that are easily extractable, and they have a Ca<sup>+2</sup>/Mg<sup>+2</sup> ratio much higher than the "optimal" 4–5 (Beernaert, 1999). Fertilization with Mg was found to be necessary when acid soils were reclaimed using travertine as a liming material in Rwanda. Because Rwanda has dolomite deposits, Beernaert recommended that mixtures of 65%–80% ground travertine with 20%–35% dolomite be used to neutralize soil acidity and provide adequate amounts of Ca and Mg in Rwanda. Beernaert suggests that ground volcanic rocks of Virunga could be used with travertine, as an alternative to dolomite, to neutralize soil

acidity and supply the necessary Mg for plant nutrition. Beernaert recommends that travertine be applied with either dolomite or ground volcanic rocks and fertilizers containing phosphorus and potassium, rather than applying volcanic rock alone. The chemical composition of travertine allows it to be used to neutralize acidity in soils; the travertines in Rwanda, while neutralizing the soil, are apparently adequate sources of Ca, but are inadequate sources of Mg,<sup>9</sup> for plant nutrition once soil acidity has been neutralized. CCE = 52%–78%.

The neutralizing capacity of some Rwandan travertines, expressed as CaO and CaCO<sub>3</sub> equivalence, varies both within the mine and among mines (Table 1).

**Table 1. The Neutralizing Capacity of Some Rwandan Travertines, Expressed as CaO and CaCO<sub>3</sub>**

Deposits	Number analyses used	Neutralizing Value						
		% CaCO <sub>3</sub> **	54	63	72	81	89	98
		% CaO	30	35	40	45	50	55
Mpenge II-IV	95			60% <sup>†</sup>				
Mpasti	85			50% <sup>†*</sup>				
Ruhundo	32			50% <sup>†*</sup>				
Mashyuza	23					30% <sup>†*</sup>		

Source: SOFRECO, 1999

\*Percentage of chemical analyses within the range of CaO content indicated 35 = minimum CaO content required by norms.

\*\*CaCO<sub>3</sub> equivalent of CaO neutralizing values reported by SOFRECO, 1999, are based on neutralizing value of CaCO<sub>3</sub> = 100 and neutralizing value of CaO = 179 (Tisdale and Nelson, 1966).

All of the data in Table 1 indicate that the travertines have less than the neutralizing value of pure calcium carbonate. The CaO equivalent values, indicated by Beernaert, are calculated and do not indicate that there is any CaO in the travertines listed in the table. Travertines may be calcined by treating them with heat to partially or completely drive off carbon dioxide from the

<sup>9</sup>When liming soils and when using superphosphate, the offered Ca is fixed strongly by the Al and Fe oxides of clays while eliminating other cations from the CEC (K<sup>+</sup>, Mg<sup>2+</sup>, and NH<sub>4</sub><sup>+</sup>). The latter are easily lost through leaching. Therefore, limited liming with dolomite in combination with ammonium phosphate instead of superphosphate is recommended for heavily weathered tropical soils.

calcium carbonate, which is the component of the travertines that can neutralize soil acidity.<sup>10</sup> Production of CaO by sufficiently heating calcium carbonate would increase the neutralizing capacity of the travertines per unit weight.

### ***V.1.3. Miscellaneous Liming Materials***

Some of the many miscellaneous liming materials include sludge from water treatment plants, lime or flue dust from cement manufacturing, pulp mill lime, carbide lime, packinghouse lime, acetylene lime, fly ash from coal-generating power plants, and wood ashes.<sup>11</sup> Some of these miscellaneous liming materials could be useful to correct acidity of some soils in the CAGLR. Wood ashes have a CCE of 40%–80%. Since biomass composes 94% of all energy sources; ashes are not negligible as liming material.

## **V.2. Chemical and Physical Properties of Lime and Travertine Samples**

In 2007, 25 samples of Rwandan lime and travertine were collected by CATALIST staff in Rwanda and sent to IFDC Headquarters where they were analyzed for the following (range of values in parentheses):

- Moisture as received at the laboratory (0.3%–32.5%, dry weight basis)
- Fineness factor (as described in the section on the fineness factor below, 28.4–97.7)
- CCE (59.7%–126% CaCO<sub>3</sub>)
- Calcium (24.3%–50.9%)
- Magnesium (0%–0.89%)
- Copper (0–8 ppm)
- Iron (6–1,800 ppm)
- Manganese (0.003%–0.111%)
- Zinc (6–38 ppm)

In 2008, 27 additional samples including 3 from Burundi were collected and analyzed at IFDC with the following results:

- Moisture content (0.2%–20.4%)

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<sup>10</sup>Rwanda has traditional furnaces that are still functioning.

<sup>11</sup>An additional advantage of using wood ashes is the contribution of charcoal (rests) to the CEC of the soil (Glaser et al., 2002).

- Fineness factor (28.4–97.0)
- CCE (73.8%–127% CaCO<sub>3</sub>)
- Calcium (19.9%–49.2%)
- Magnesium (0.2%–12.2%)

The data are presented in the tables in Appendix C. Reagent-grade calcium carbonate was used as the standard for determining the CCE, the moisture, and the fineness factor. The data reveal several factors that should be taken into account by purchasers of the lime or travertine to treat acid soils. For example, the material that contains 20%–30% water has less neutralizing value per unit weight than if the material were dry. All calculations of the liming rates below are on a dry-weight basis. Determinations of the fineness factor, calcium carbonate equivalent, and contents of the chemical constituents of all the materials reported in Appendix C were on dry material obtained by drying in an oven after the moisture determinations were made. Costs of transport per CCE will be higher for liming materials with lower CCE values. Materials with a high fineness factor will react more quickly in the soil and neutralize soil acidity more rapidly than materials with a lower fineness factor. Lime or travertine can also be considered sources of essential plant nutrients, because they contain the six cations and dissolve in the soil, neutralizing soil acidity. Liming would be expected to release such micronutrients for interaction with the cation exchange complex of the soil and for uptake by plants. Because it is an essential plant nutrient for plant growth, fertilization with magnesium would be required once soil acidity is controlled when liming materials are used that do not contain magnesium. Fertilization following the application of lime and neutralization of soil acidity should take into account the capability of the liming material to provide essential plant nutrients such as those in Appendix C.

In reviewing the data in Appendix C, IFDC's geologist<sup>12</sup> concludes that any samples with more than 40% calcium have been calcined (burned) and probably slaked (treated with water after burning). Pure calcium carbonate (limestone) contains 40% Ca, and increasing the Ca content of limestone requires driving off carbon as gaseous compounds. Of the 25 liming materials sampled in 2007 (Appendix C), those that have probably been calcined (and possibly slaked) are Nos. 1, 2, 12, 13, 18, 19, 20, 22, and 23. These samples, as expected, have CCE >

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<sup>12</sup>Van Kauwenbergh, S. J., personal communication, October 16, 2007.

100%. Seven additional samples (No. 5, 6, 8, 14, 21a, 24, and 25), which have relatively high CCE, may have been calcined, but it is not possible to determine with only the CCE data—although the Ca content is < 40%.

Of the 27 liming materials sampled in 2008, the following samples were probably calcined: No. 12, 13, 18, 19, 20, 22, and 23. In addition, the following samples from 2008 with CCE of 90% may have been calcined: No. 8, 14, 21a, 21b, 21c, 24, 25, and 26. The samples that were collected from the same sources in 2007 and 2008 gave similar results in both years. The three samples from Burundi collected in 2008 are dolomite containing both CaCO<sub>3</sub> and MgCO<sub>3</sub> (Appendix C).

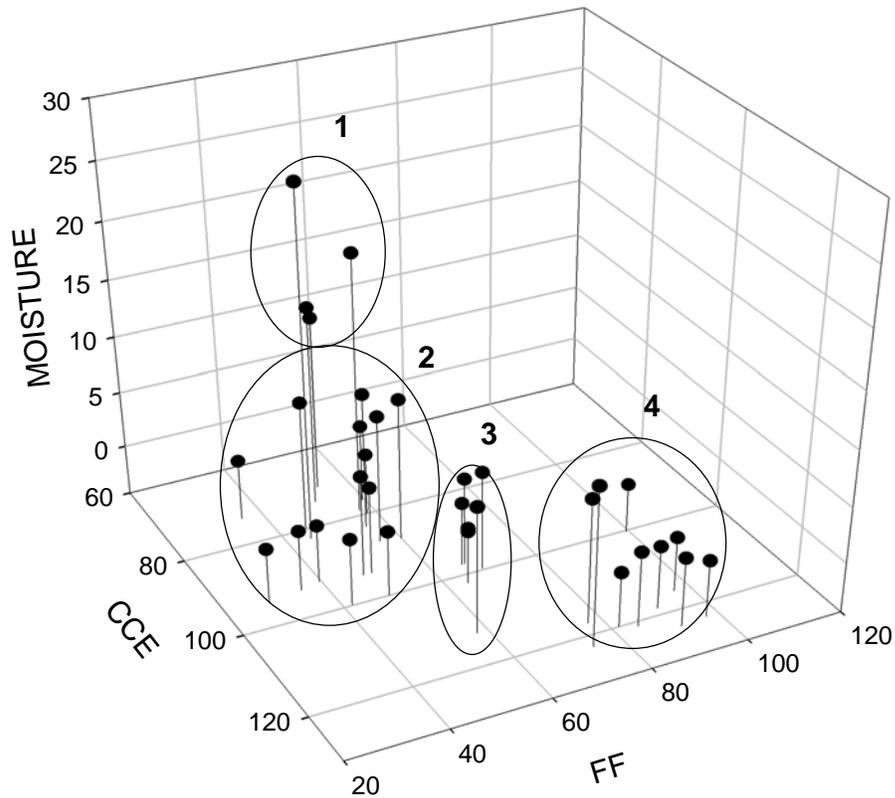
### ***V.2.1. Classification of Liming Materials by Statistical Method***

A statistical method was used to group the liming materials—25 samples from 2007 and 27 samples from 2008—whose properties are presented in Appendix C. The analysis was done in two steps. First, the lime characteristics with higher discriminatory power were identified using Multivariate Factor Analysis. Those characteristics are, in order of importance: % CaCO<sub>3</sub>, moisture content, fineness factor, % Ca, % Mg, ppm Fe, and % Mn. Next, the samples of liming materials were classified using only the characteristics identified in the first step. Cluster analysis was used for the classification that resulted in four ranking groups for the liming materials. Micronutrients were not analyzed for the samples that were collected in 2008. The group rankings and their characteristic means are presented in Table 2.

**Table 2. The Means of a Series of 52 Samples of Liming Materials Collected in 2007 and 2008**

Ranking Group	Group Size	Mean		
		Calcium Carbonate Equivalent	Moisture Content	Fineness Factor
		(%)	(%)	
1	8	76	17.4	52
2	20	88	3.4	47
3	10	102	2.5	65
4	14	120	2.9	87

Ranking Group 3 also includes three dolomite samples from Burundi. Due to its high Mg content, dolomite will be preferred over other members of Group 3. Rankings and cluster means for the three most important characteristics—calcium carbonate equivalence (CCE), moisture content, and fineness factor—are also shown in Figure 3.



**Figure 3. Distribution of Lime Samples as Function of Calcium Carbonate Equivalent (CCE), Moisture Content, and Fineness Factor (FF)**

Tables 3 and 4 present the separate cluster analyses for liming material collected in 2007 and 2008, respectively. As is evident from the most significant characteristics of the four groups in Tables 2–4, many samples of liming materials available in Rwanda have lower neutralizing capacity than pure calcium carbonate (Groups 1 and 2, mean CCE < 100%). Samples with CCE > 100% (Groups 3 and 4) have greater neutralizing capacity than calcium carbonate. The groups of samples with CCE < 100% generally have a lower fineness factor than the groups with CCE > 100%. This indicates that the sampled liming materials of Groups 1 and 2, which have a

neutralizing capacity less than 100% CCE, will also take longer to react in the soil to reduce soil acidity than the samples of the liming materials of Groups 3 and 4. Because of these differences, the liming materials of Groups 3 and 4 are considered to be of higher quality than those of Groups 1 and 2. Considering only the CCE and fineness factor, the quality increases from Group 1 to 4. Moreover, liming materials in Group 1 have much higher moisture content, implying more lime will be required to control soil acidity when these liming materials are used.

**Table 3. The Means of a Series of 25 Samples of Liming Materials Collected in 2007**

Ranking Group	Group Size	Mean						
		Calcium Carbonate Equivalent	Moisture Content	Fineness Factor	Ca	Mg	Fe	Mn
		(%)	(%)		(%)	(%)	(ppm)	(%)
1	4	75	18.3	56	29	0.6	472	0.09
2	9	88	3.9	52	34	1.1	612	0.05
3	4	99	4.6	65	38	1.1	308	0.06
4	8	120	2.1	86	45	1.5	148	0.03
CaCO <sub>3</sub> reagent		100		99				

**Table 4. The Means of a Series of 27 Samples of Liming Materials Collected in 2008**

Ranking Group	Group Size	Mean				
		Calcium Carbonate Equivalent	Moisture Content	Fineness Factor	Ca	Mg
		(%)	(%)		(%)	(%)
1	4	78	16.6	47	30	0.9
2	11	89	3.5	47	35	1.3
3	6	105	1.9	64	32	6.6
4	6	121	4.9	87	44	1.9
Calcium carbonate reagent		100		99		

The samples of liming material with less than 100% CCE generally have substantially higher iron content than the samples with CCE > 100% (Table 3). Likewise, the low quality lime (Group 1) also has high Mn content.

All the lime samples in Group 4 are produced for industrial use (e.g., water purification) or construction. All lime sources in Groups 1 and 2 are agricultural lime (Appendix C). In addition, at least three out of five liming materials in Group 3 are available for agricultural use. However, how widely this higher quality lime (Group 3) is used by farmers is not known. For example, the dolomite from Butare mines in Burundi is used for liming mostly by externally funded projects.

In Groups 1 and 2, in which all samples are for agricultural use, the original travertine may be as effective as heated lime or lime sold for agricultural use. The production of agricultural lime (or calcined or heated liming materials in general) requires energy. One would expect to see a more general effective improvement of the original travertine due to heating. Given the rapid and slowly reversible deforestation of Rwanda, there is a significant ecological price to pay to produce lime with neutralizing capacity greater than that of calcium carbonate (i.e., with CCE > 100%). The fineness factor of the lime and travertine of all the sample clusters could be increased by additional grinding of the materials. Such treatment would increase the rate of reaction of those materials when used as a soil amendment to increase soil pH, but also requires additional energy.

Among the samples above, 8 out of 25 samples in 2007 and 11 out of 27 in 2008 were the original travertine, representing three of the four sources presented in Table 1, the small Ruhundo reserve not being sampled. In spite of the small number, the average quality of characteristics are in line with the data in Table 1: Mpasti (Kibuye) travertine has a somewhat higher CCE than that of Mpenge (Ruhengeri); the CCE of 94% for Mashyuza (Bugarama) is significantly higher than the two others (Appendix C). The average moisture content of travertine from Mashyuza is also low at 2%. The average fineness factor of samples from this deposit is only 40%. Additional grinding will greatly improve liming effectiveness in the field. Grinding to fineness of 60% will be more beneficial than calcination. The travertine from Ruhengeri not only has low CCE (Table 1; Appendix C) but high moisture content (15%). The Bugarama (Mashyuza) travertine also has significantly higher Mg (1.74%) compared with 0.99% for Ruhengeri and 0.25% for Mpasti (Appendix C). Use of Bugarama travertine or dolomite will also provide Mg—an essential plant nutrient—and provide soil cation balance.

### V.3. Correcting Al Toxicity<sup>13</sup>

#### V.3.1. The Approach

The aim of liming in the tropics is to render aluminum harmless. To calculate the quantity of lime that has to be applied, the following data are required:

- a. Actual quantity of exchangeable Al (IV.3).
- b. Desired (see below) ratio 100 x Al/ECEC (ECEC = effective cation exchange capacity).
- c. Quantity of lime that is required per unit of Al.
- d. Calcium carbonate equivalent of the liming material that is used (V.1 and V.2).

Cochrane et al. (1980) derived an equation to calculate the required amount of lime. For this, the number of required analyses has been kept as small as possible. Concentrations of Al, Ca, and Mg are measured in a 1 M KCl extract, and the results are expressed in mmol (p<sup>+</sup>) per 100 g of soil. The sum of these three cations nearly equals the ECEC, because the quantities of exchangeable K and Na are very small (0.01–0.05 mmol per 100 g of soil). The required ratio 100 x Al/ECEC is indicated by RAS (required percentage Al saturation), hence

$$\text{RAS} = \frac{100 \text{ desired Al}}{\text{Al} + \text{Ca} + \text{Mg}}, \text{ or}$$

desired Al = RAS (Al+Ca+Mg)/100, where Al, Ca, Mg, and desired Al are expressed in mmol (p<sup>+</sup>) per 100 g of soil.

One would expect that the lime application has to be sufficiently high to neutralize a quantity of Al that corresponds with the difference between the actual and desired quantity: mmol (p<sup>+</sup>) Ca<sup>2+</sup>CO<sub>3</sub><sup>2-</sup> = mmol (p<sup>+</sup>) actual Al<sup>3+</sup> - mmol (p<sup>+</sup>) desired Al<sup>3+</sup>. It has been shown, however, empirically that per mmol (p<sup>+</sup>) Al<sup>3+</sup>, not 1 but 1.5 mmol (p<sup>+</sup>) CaCO<sub>3</sub> is required. As a result of the pH increase brought about by the lime, the ECEC increases (further dissociation of -OH and -COOH groups) and this increase in ECEC comes down to about .5 mmol (p<sup>+</sup>) per exchanged mmol (p<sup>+</sup>) Al. The quantity of lime required thus equals:

$$1.5 (\text{mmol (p}^+) \text{ actual Al}^{3+} - \text{mmol (p}^+) \text{ desired Al}^{3+}).$$

If mmol (p<sup>+</sup>) actual Al<sup>3+</sup> is substituted by Al (= determined in 1 M KCl), and desired Al<sup>3+</sup> by the above expression, it holds:

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<sup>13</sup>The information presented is mainly based on data and documentation from and obtained through Bert Janssen, WUR, Wageningen.

$$1 \text{ mmol (p}^+) \text{ Ca}^{2+}\text{CO}_3^{2-} = 1.5 (\text{Al} - \text{RAS} (\text{Al}+\text{Ca}+\text{Mg})/100)$$

This equation can be worked out a little more for practice. The topsoil (15 cm) of 1 ha has a mass of about  $2 \cdot 10^6$  kg.<sup>14</sup> So, 1 mmol (p<sup>+</sup>) Ca<sup>2+</sup>CO<sub>3</sub><sup>2-</sup> per 100 g of soil corresponds with  $2 \cdot 10^7$  mmol (p<sup>+</sup>) Ca<sup>2+</sup>CO<sub>3</sub><sup>2-</sup> per hectare. As 1 mmol (p<sup>+</sup>) Ca<sup>2+</sup>CO<sub>3</sub><sup>2-</sup> corresponds with .50 mmol CaCO<sub>3</sub>,  $2 \cdot 10^7$  mmol (p<sup>+</sup>) Ca<sup>2+</sup>CO<sub>3</sub><sup>2-</sup> corresponds with  $10^7$  mmol CaCO<sub>3</sub> =  $10^9$  mg CaCO<sub>3</sub> = 1 t CaCO<sub>3</sub> (rel. mol. mass of CaCO<sub>3</sub> equals 100: 40 + 12 + 16 x 3). So, the lime application expressed in tonnes CaCO<sub>3</sub> per hectare also equals:  $1.5 (\text{Al} - \text{RAS} (\text{Al}+\text{Ca}+\text{Mg})/ 100)$ , with the ions expressed in mmol (p<sup>+</sup>) per 100 g of soil.

$$\text{LR (t CaCO}_3\text{/ha)} = 1.5 (\text{Al} - \text{RAS} (\text{Al}+\text{Ca}+\text{Mg})/100)$$

**Equation V.3-1**

Where LR = lime requirement expressed in tons CaCO<sub>3</sub> per hectare

RAS = required (or desired) aluminium saturation (%)

Al = extractable Al (exchangeable + soluble Al) mmol/100 g soil

Al + Ca + Mg is an approximation for the effective CEC (ECEC)

### V.3.2. The Desired Al Saturation

Several reasons exist for not entirely correcting the Al toxicity; instead of determining the required liming on the elimination of all exchangeable Al, one may decide to accept a certain percentage of Al saturation of the ECEC:

- The various agricultural and horticultural crops make different demands on soil reaction. The optimum pH is a compromise for which production systems, the availability of different nutrients, soil life, soil structure, and risks of pests and diseases have to be taken into account.
- It appears that crops and even crop varieties differ in Al sensitivity (VII.2); the total extractable Al as determined in IV.3 should be corrected for production systems based on sensitive crops.
- A desired percentage of Al saturation could be chosen in areas where liming is expensive and farmers grow crops that are more tolerant to Al (VII.2).

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<sup>14</sup>Correcting Al toxicity or pH in the first 15 cm of topsoil implies only that crop rooting will be superficial for (relatively) sensitive crops; the subsoil will be poorly accessible by roots. If profitable, the first 30 cm should be treated.

Thus, Equation V3-1 could be used to achieve the recommended lime rate. For the sensitive crops, the ratio  $100 \times \text{Al/ECEC}$  must be brought back to about 30 (RAS = 30%), which agrees with a pH (H<sub>2</sub>O) of about 5.1 and an Al concentration in the soil solution of 40 micro-mol ( $\mu\text{mol}$ ;  $\text{p}^+$ )  $\text{Al}^{3+}$  per liter or  $40 \times 9/1000 = 0.36$  mg/l. For the acid-tolerant crops, values as high as: 70 (RAS = 705) for  $100 \times \text{Al/ECEC}$ ; 4.6 for pH(H<sub>2</sub>O); and 190  $\mu\text{mol}$  or 1.7 mg  $\text{Al}^{3+}$  per liter soil solution are sufficient.

An easier and more rough approach calculates the lime requirement (pure CaCO<sub>3</sub>) in direct relation to the total amount of toxic Al, with or without the H<sup>+</sup> ions (depending on the procedure used in the laboratory; see IV.3):

$$\text{LR (t-CaCO}_3 \text{ ha}^{-1}) = \text{factor} \times \text{mmol (Al + H}^+) / 100 \text{ g soil} \quad \text{Equation V.3-2}$$

**or** = factor x mmol Al/100 g soil (see IV.3)

To avoid overliming, an adaptation factor is proposed that takes the Al sensitivity of crops into account:

- Factor = <1 for Al-tolerant crops
- = 1.0 for moderately Al-tolerant crops
- = 1.5 for Al-sensitive crops

The above equation assumes that Al toxicity is eliminated and, for Al-sensitive crops, it assumes that Al saturation is close to 0%. The approach also does not take into account the effect of actual soil Al saturation; it considers only extractable Al. However, soil with the same extractable Al may have very different Al saturation values and thus a different impact on crop performance.

### ***V.3.3. Alternative in Case Only pH (H<sub>2</sub>O) Can Be Measured***

Some farmers and agronomists in the region do not have access to laboratory analyses of Al toxicity and Al saturation of the ECEC, but they can execute the simple and cheap determination of pH (H<sub>2</sub>O). They could apply the method for correcting soil acidity that is presented in V.1.1, for soils with a pH (H<sub>2</sub>O) < 5.5.

Lime requirement for correcting soil acidity is estimated using data from ACID4 (Yamoah et al., 1990), NuMaSS Expert System (Osmond et al., 2002), and PRDSS database. The equation was developed using only the lime amounts needed to bring soil pH to 5.2–5.5.

$$\mathbf{LR (t-CaCO_3 \text{ ha}^{-1}) = 16.0 - 2.87(\text{pH})} \qquad \mathbf{\text{Equation V.3-3}}$$

Equation V.3-3 reflects higher slope, less pH buffering, and hence less lime requirement than the original ACID4 (Yamoah et al., 1990) recommendation, which was based on liming to pH 6.2.

## VI. How to Calculate Liming Rates for Calcite (CaCO<sub>3</sub>), Calcium Oxide (CaO), and Rwandan Agricultural Lime

First, the three methods (VI.1) will be compared, calculating the liming rates for pure CaCO<sub>3</sub> based on the desirable Al<sup>+</sup> (Equation V.3-1), the exchangeable Al<sup>+</sup> (V.3-2), and the pH (H<sub>2</sub>O) (V.3-3). In the following paragraphs, only the last and most simple formula will be used as an illustration. First, the LR for CaO and for a relatively high and relatively low quality Rwandan agricultural lime are derived (VI.2). VI.3 shows how the fineness factor should be taken into account, and VI.4 answers practical questions such as how and when to apply lime, to which depth, and with which frequency.

### VI.1. Comparison of the LR Using the Three Formulas

For this comparison, the most acid soils observed by Yamoah et al. (1990) have been used and the LR for sensitive crops have been estimated. The most acid soils occur in what is called the agroecological zone 3 (altitude 1,500–1,800 m; rainfall > 1,400 mm/year). These soils have, on average, pH of 4.9, exchangeable Al of 3.0 mmol/100 g soil, ECEC (Al<sup>+</sup>+Ca<sup>+</sup>+Mg<sup>+</sup>) of (3.0+1.8+0.6) = 5.4, and Al saturation of 50%.

#### *Desired Al Saturation*

For sensitive crops, the desired Al saturation has to be ≤ 30%. The value of 30% is used for RAS in view of the costs of liming, the poverty of smallholders, and assuming a moderately Al-tolerant crop. Using Equation V.3-1 the lime requirement (LR), expressed in tons CaCO<sub>3</sub> per hectare and with the ions expressed in mmol (p<sup>+</sup>) per 100 g of soil, is:

$$\begin{aligned}\text{LR} &= 1.5 [\text{Al} - \text{RAS} (\text{Al}+\text{Ca}+\text{Mg})/100], \\ &= 1.5 [3.0 - 30 (3.0+1.8+0.6)/100] = 2.1 \text{ t/ha CaCO}_3.\end{aligned}$$

#### *Extractable Al<sup>3+</sup>*

The lime requirement here is determined based on extractable Al using Equation V.3-2.

$$\begin{aligned}\text{LR (t-CaCO}_3 \text{ ha}^{-1}) &= \text{factor x mmol Al/100 g soil} \\ &= 1.5 \times (3) = 4.5 \text{ t CaCO}_3/\text{ha}\end{aligned}$$

The equation assumes that for Al-sensitive crops, the Al saturation is brought down to 0, i.e., all of the extractable Al is neutralized. Even for a moderately tolerant crop (factor = 1), the lime recommendation will be 3 t CaCO<sub>3</sub>/ha. Thus, the extractable Al approach will lead to higher rates of lime than the desired Al saturation approach. If Al saturation of a soil is known, then the LR to achieve 30% RAS implies that only 1.38 out of 3 mmol of Al is neutralized. Hence, the LR to achieve 30% Al saturation is:

$$\text{LR (t-CaCO}_3 \text{ ha}^{-1}) = 1.5 \times 1.38 \text{ Al/100 g soil} = 2.1 \text{ t/ha}$$

If the information needed to use the desired Al saturation approach (Equation V.3-1) is known, then it is more appropriate to use it than the extractable Al approach (Equation V.3-2) to predict LR.

*pH (H<sub>2</sub>O)*

$$\text{LR} = 16.0 - 2.87 \text{ pH}$$

$$\text{LR} = 16.0 - 2.87 \times 4.9 = 1.9 \text{ t/ha}$$

Given the close agreement among the methods, it may be more practical to use the soil pH measurements (Equation V.3-3) to estimate lime requirement, particularly in CAGLR given the dearth of information on Al and ECEC. Because of the generalization involved in using a wide range of soils to develop the soil pH approach, it may under- or over-predict the lime requirements for extreme conditions of soil pH buffering and crop tolerance. The pH-based equation will be further refined as more field data become available, particularly with respect to different crops.

## **VI.2. Using the Calcium Carbonate Equivalent (CCE)**

In the former paragraph, the LR was estimated for the standard lime, pure CaCO<sub>3</sub> (VI.1). Using the soil pH approach (Equation V.3-3) and the same soil as in the former paragraph, it will be illustrated how, for other liming material, the LR is derived from the LR for pure CaCO<sub>3</sub>. Three examples are presented: the use of CaO, the material with the highest CCE (179; V.1.2), and the use of a relatively high and a relatively low quality Rwandan agricultural lime. Among the eight agricultural limes that have been sampled and analyzed (V.2), the highest CCE that has been found is 113; the lowest is 73 (Appendix C).

Assuming that 100% of the particles of lime are less than 0.25 mm in diameter (equal fineness factors), all liming rates are first calculated (t/ha) based on differences of CCE only.

In Equation V.3-3, **LR = 16.0 - 2.87 pH** was used to estimate the CaCO<sub>3</sub> requirement for increasing the pH from 4.9 to 5.5:

$$\text{LR} = 16.0 - 2.87 * 4.9 = 1.9 \text{ t/ha CaCO}_3 \text{ (pure)}$$

Next, to calculate the equivalent rate of application of another liming material, Z, knowing the CCE, use:  $\text{LR}_Z = (\text{LR}_{\text{CaCO}_3} \div \text{CCE}_Z/100)$ . In the case of CaO, this leads to a  $\text{LR}_{\text{CaO}}$  of  $1.9/(179/100) = 1.1$  t/ha of CaO. For the highest and one of the lowest quality agricultural limes that were sampled in 2007/2008, with CCE values of 110 and 74, the LR are, respectively,  $1.9/(113/100) = 1.7$  t/ha, and  $1.9/(74/100) = 2.6$  t/ha.

In practice, there is even much greater difference in the amounts required for the two types of agricultural lime. The CCE values were determined based on dry weight. However, during the analyses, the highest quality lime had a water content of 6.8%, and the lowest had 13.3%. This implies that, in fact, the LR of the highest quality agricultural lime is  $1.7 \times 100/(100 - 6.8) = 1.8$  t/ha; the LR of the lowest quality is  $2.6 \times 100/(100 - 13.3) = 3.0$  t/ha. This correction is useful, knowing that one of lime samples had an average water content of almost 21%.

These calculations yield estimated rates of application of the three liming materials needed to adjust soil pH to 5.2–5.5, given that the particle size of all five liming materials is identical and less than or equal to 0.25 mm diameter. The calculated liming rates are estimated, because the effectiveness of the liming materials will vary in practice, depending upon such variables as:

- Evenness of application to the soil.
- Extent of incorporation of the lime in the soil (lime that is simply broadcast does not interact rapidly with soil in the top 30 cm and causes locally high pH values, inherent soil erosion [II.2], and lime runoff with rainfall).
- Fineness factor (dependent upon the sizes of the particles of each liming material; finer particle size = greater reactivity).

### VI.3. How to Calculate the LR, Taking Into Account the Fineness Factor

Overall, lime quality depends upon the effective CCE, moisture content, content of essential plant nutrients, and a fineness factor (FF). Finer particles are more reactive and more effective at neutralizing soil acidity than coarse particles. Lime, which is composed mainly of fine particles (<60 mesh), is most reactive; therefore, it exhausts its neutralizing capacity faster than lime with a range of particle sizes. For coarse particles to become effective, several years may be required. When screening a liming material, the particles can be grouped into different size classes.

Once the liming rate has been established (VI.1 and VI.2), the lime of different sources should be screened to determine its quality from a particle-size standpoint. Different countries and even different states within countries may have different FFs for agricultural limestone. The following is a method to determine the FF that is widely used to rate the efficiency of agricultural limestone in the United States. The FF is determined for oven-dry material and is the weighted average of the particle-size classes and their respective efficiency factors (Table 5).

**Table 5. Relationship Between Particle Size and Efficiency Factor**

Particle Size (mesh)	Opening Size (mm)	Efficiency Factor
>8	>2.36	0
8–60	2.36–0.25	0.5
<60	<0.25	1.0

Source: Havlin et al., 2005.

To compare two liming materials, based on *both* their neutralizing capacity *and* their fineness, calculate the total application rate taking into account the rate as calculated above in tons per hectare. Then calculate the FF (if it is not known), based on data obtained by screening the liming material. Then use the LR and FF to calculate the adapted liming rate,  $LR_{FF}$ , in tons per hectare, which takes into account both the neutralizing capacity and particle-size distribution of the liming material. The FF is an index that indicates the approximate time period when the lime will dissolve and neutralize soil acidity. An FF of 100 indicates that all of the liming material sampled is less than 0.25 mm in diameter and should dissolve relatively rapidly. FF values that are less than 100 indicate a mixture of particles of different size classes (as indicated

in Table 5); the lower the FF, the longer the time period will be when the particles of the liming material dissolve. Liming materials with high FF values are more reactive than liming materials with low FF values.

Two liming materials are screened to compare their relative effectiveness, taking into account their particle-size distribution. Then, the percentage passing or retained on the sieve is measured for particles >8 mesh, 8–60 mesh, and <60 mesh, using screens whose “mesh” is the number of openings per inch. A 60-mesh sieve has 60 openings per inch; thus, a particle passing a 60-mesh sieve would have a diameter of <0.0098 inch, or <0.25 mm. Data of average yield responses of six different crops over 6–8 years showed that when the percentage of lime passing a 60-mesh sieve was less than 20%, the average yield was 60% of the highest yield, which was achieved when more than 80% of the lime used passed a 60-mesh sieve (Havlin et al., 2005, citing Barber, 1984).

*Fineness factor calculation:* [ $>8$  mesh percentage  $\times$  0 efficiency] + [8–60 mesh percentage  $\times$  0.5 efficiency] + [ $<60$  mesh percentage  $\times$  1.0] = Total FF (FF, the sum of the three factors)

The effective calcium carbonate (ECC) rating of a liming material = CCE  $\times$  FF. By doing this calculation after calculating the lime requirement, one can estimate the effectiveness of ground liming material compared with other liming materials. Particle size is a crucial aspect of the reactivity of lime. Purchasers of lime are urged to take samples of lime for sale and to calculate the amount required (ECC) before purchasing it. Fine lime neutralizes soil acidity more rapidly than coarser textured lime.

To calculate the rate of application of a liming material, take into account the FF ( $LR_{FF}$ ). Once the rate based on relative effectiveness, LR, has been determined, divide LR by FF expressed as a fraction. The LR values of the two qualities of liming material (high and low quality agricultural lime) obtained at the end of VI.2 are 1.8 t/ha and 3.0 t/ha, respectively. The respective FF of both materials are 58% and 51% (Appendix C), or—expressed as fractions—0.58 and 0.51. So, the amounts of liming material required for rapidly increasing the pH from 4.9 to 5.2 are, respectively,  $1.8/0.58 = 3.1$  t/ha and  $3.0/0.51 = 5.9$  t/ha. For a similar effect, one needs

almost 2 times more from the low quality agricultural lime than from the high quality agricultural lime.

## **VI.4. Other Practical Questions**

### ***VI.4.1. How to Apply Lime***

Once the materials for lime application have been chosen and the  $LR_{FF}$  has been estimated, the lime should be applied. Studies have shown that if lime is applied to the surface and not incorporated in the soil, it can take as long as 10 years to raise the soil pH at a depth of 15 cm. The reactivity of the lime with soil acidity is greatly increased once it has been homogeneously incorporated in the soil. The deeper the lime is incorporated in the soil, the greater the volume of soil will be that has an increase in pH. Root growth will be greater in larger volumes of soil treated with lime. One must realize, however, that the proposed formula and the estimated LRs (V.3 and VI.1–3) concern the first 15 cm of topsoil only. Treating the soil to a depth of 30 cm, for example, implies that pH, Al toxicity, etc., must be measured for the first 30 cm and that the LR may become twice as high.

For resource-poor farmers, applying 2–4 t of lime/ha based on the above criteria may not be possible. The option of banding or applying lime in the planting hole/mound to a depth of at least 15 cm at the recommended rate (but in less area) should be evaluated. The time of application (VI.4.2) becomes more critical for such application.

### ***VI.4.2. Time and Depth of Lime Application***

Preferably, lime should be spread evenly at the prescribed rate on the soil and incorporated to a depth of at least 15 cm as long as possible before planting.<sup>15</sup> In particular, caustic forms of lime—CaO and Ca(OH)<sub>2</sub>—should be applied and incorporated in the soil well before planting to avoid injury to seeds. Incorporating lime can be done by using manual labor, animal traction, or machinery with an internal combustion engine. If manual labor is used, it is recommended that lime be incorporated to a depth of 15 cm. If animal traction or plowing with the aid of a tractor is done, the lime should be incorporated to a depth of 30 cm (see Footnote 14 and comment above). This will give the lime a chance to neutralize soil acidity before planting.

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<sup>15</sup>In regions with one single growing season, liming 6 months before planting is recommended.

Crop calendars for Rwanda, Tanzania, and Uganda (Appendix D) can be used to plan the timing of lime application for several crops in these three countries.

#### ***VI.4.3. Frequency of Lime Application***

Acidification of soils is a natural process that can be increased or decreased by human activities. Assuming that enough quality lime is used, it is suggested that liming should be done every 3 years in the humid tropics (Tropsoils, 1987). However, farmers will ultimately consider the economics of liming and, for example, the sensitivity of the next season's crop. Also, the frequency of application depends upon several factors, which vary across landscapes and production systems. A key factor is leaching of basic cations; soil acidification occurs where rainfall is significantly higher than the evapotranspiration, and its effect increases proportionally with the water and nutrient storage capacity of soils.<sup>16</sup> Therefore, the frequency of liming depends upon the texture and the buffer capacity of the soil. Liming frequency will have to increase going from fine-textured clays and loams to coarse, sandy soils, and from soils with high to low SOM. However, the amount of lime required is inversely proportional with the frequency. Hence, if the lime application rates are low and soil pH is increased to 5.2 or less, then lime application may be more frequent (once a year). Also, if the switch is made from a more tolerant crop to a less acid-tolerant crop (e.g., from potato to wheat), then liming may be necessary. Banding or application of lime in planting holes or mounds may require lime applications on even a seasonal or annual basis. The low lime rates thus increase the frequency of liming and labor costs, but also spread the costs and risks.

Leaching is not the only way to lose cations such as K, Ca, and Mg; exporting products and byproducts from fields concerns another loss that provokes acidification. This is particularly true when the byproducts do not return to the field in the form of manure or compost.<sup>17</sup> Still, other agricultural practices influence the rate of soil acidification (in other words, the liming frequency). The intensive use of N and S fertilizers accelerates acidification; calcium ammonium nitrate (CAN) is an alternative source of N with a slight liming effect (VII.1.3). Effective erosion

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<sup>16</sup>With increasing aridity, not only does leaching decrease, but the soils contain more carbonates, counteracting eventual acidification.

<sup>17</sup>Of produce from mixed farming enterprises in northeastern Victoria (Australia), hay required the greatest amount of lime (270–1,260 kg CaCO<sub>3</sub>/ha/year) to replace lost alkali from the soil. By comparison, removal of cereal produce required much less lime (7–20 kg CaCO<sub>3</sub>/ha/year) to replace lost alkali, as did removal of wool and lamb (0.8 and 6.0 kg CaCO<sub>3</sub>/ha/year, respectively).

control can help prevent a more acid subsoil from becoming the topsoil. However, when (radical) terracing is used to stop erosion, without paying effective attention to high water storage and water use (SOM management and crop intensification), leaching may be reinforced, causing increased acidification.

Several factors affect the frequency of liming; hence, the soil, particularly sand soils should be sampled every 2 years (as explained above) if the means are available. Determination of exchangeable Al and Al saturation or at least a simple test of the soil pH (H<sub>2</sub>O) should be performed. Then, using the criteria and calculations described above, it can be determined if and at what rate lime should be reapplied. Medium-textured soils (e.g., loams) and fine-textured soils should be sampled and the pH determined every 3 years. The rate of application will again be determined using the calculations described above. Excess liming should be avoided; the pH (H<sub>2</sub>O) should certainly not become 6 or higher (II.2).

## VII. Living With Acid Soils

“Sustainable management of an agroecosystem should aim at balancing the inputs of acid with additions of alkalinity from both internal and external sources. External sources of alkalinity include lime and organic matter additions, while the most important internal source of soil’s acid-neutralizing capacity is mineral weathering” (Wong et al., 2004).

### VII.1. Plant Nutrition

#### VII.1.1. Principles

Plants require 17 essential nutrients that are either part of an essential component of the plant or needed for the plant to complete its lifecycle. The elements are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), boron (B), chlorine (Cl), molybdenum (Mo), and nickel (Ni). Carbon is absorbed by the plant as a component of gaseous carbon dioxide through the leaves. Hydrogen and oxygen are absorbed mainly as water through the roots, as are the rest of the essential plant nutrients. The Law of the Minimum, developed by the agricultural chemist, Justus von Liebig, in the early 1800s, states that the essential element that is most limiting to plant growth will determine the rate at which the plant grows. For example, some acid soils are deficient in molybdenum, a plant nutrient needed in very small quantities. This deficiency can be just as limiting to plant growth as a deficiency in N, which is the mineral nutrient that plants need in the greatest amount after H and O.

In acid soils, deficiencies in phosphorus, calcium, magnesium, and molybdenum are common. Nitrogen deficiency may also occur if mineralization and nitrification processes are hindered due to low pH ( $\text{pH} < 4.5$ ). Toxicities of aluminum and hydrogen ions are common for plants growing in acid soils; manganese toxicity is less frequently observed in the region, and iron toxicity occurs in irrigated rice. These deficiencies and toxicities decrease the uptake of other essential plant nutrients, such as nitrogen and potassium. By using liming materials, anions such as  $\text{OH}^-$ ,  $\text{CO}_3^{2-}$ , or  $\text{SiO}_4^{4-}$  form non-dissociated or hardly dissociated combinations with  $\text{H}^+$ ; in other words, anions eliminate protons. In fact, the cation is not of interest for the pH increase (VI.1; Groupe Chaulage du COMIFER, 2000). Consequently,  $\text{Ca}^{2+}$  replaces  $\text{Al}^{3+}$  and  $\text{H}^+$  on the CEC, and the pH increases. If dolomitic limestone [ $\text{CaMg}(\text{CO}_3)$ ] is used to increase soil pH, then  $\text{Mg}^{+2}$  will also displace  $\text{Al}^{3+}$  cations and  $\text{H}^+$  on the CEC. Beernaert (1999) has noted that travertine in

Rwanda is very low in Mg content; he recommends either a mixture of travertine and dolomite or addition of volcanic soil or Mg fertilizer to meet the Mg needs of crops to be grown on soils remediated with travertine. As discussed (V.2.1), average Mg content of travertine sources varied from 0.25% to 1.74% (Appendix C). Such differences may be significant in soils with very low exchangeable Mg. It should be noted that the reclamation of strongly acid soils with lime will result in most of the CEC being saturated with  $\text{Ca}^{+2}$ . It is essential that other major cations such as  $\text{Mg}^{+2}$  and  $\text{K}^{+}$  be added to the soil to meet the nutritional needs of plants to be grown in the reclaimed soils.

### ***VII.1.2. Fertilizing Soils Corrected for Soil Acidity***

As indicated above, some plant nutrients are added to the soils through liming. However, liming should not replace soil fertilization. The risk exists, because through the increased pH, biological processes are again intensified, and through mineralization of SOM, nutrients such as N and P become available at the cost of a degrading SOM status. This is at the basis of the Dutch expression derived from soil liming without soil fertilization: “Rich parents, poor children.”<sup>18</sup>

Because P was lost from solution by adsorption with Al in acid soils, it is important to add P with fertilizer when acid soils are remediated by raising pH. Increasing the soil pH will not rapidly bring P into solution, because aluminum phosphate compounds are very insoluble. N is normally in short supply in all cultivated soils and thus should be added; because K will probably be in very short supply in the acid soil, there will likely not be adequate K for crop growth. Therefore, it is important to fertilize with N, P, and K. Additions of organic matter counteract the increased SOM turnover, provoked by the increase in pH. In the meantime, they can provide relatively small, but important, amounts of all the essential plant nutrients.

### ***VII.1.3. Choice of Inorganic Fertilizers***

Nitrogen and sulfur from fertilizers are oxidized by soil micro-organisms; hydrogen ions are produced during the oxidation. Therefore, soil pH decreases as a result of using fertilizers that provide these two essential plant nutrients, without which plants cannot grow and produce useable food, feed, and fiber. Nitrogen and sulfur fertilizers should be chosen to minimize the

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<sup>18</sup>The Dutch verb “uitmergelen” has the same background (“mergel” = liming material). It is used for persons who became extremely meager and it concerns a comparison with an entirely depleted soil.

acidification of soils. A useful index of the acidification that will result from the use of various fertilizers containing N or S is listed in Table 6, which indicates the number of kilograms of calcite,  $\text{CaCO}_3$ , needed to neutralize the acidity produced by the oxidation of a kilogram of N or S from a fertilizer compound (Havlin et al., 2005).

Without alternative fertilizer choices, one has to accept that intensification goes hand in hand with a degree of acidification, increasing the required lime frequency. However, besides the acidifying N-fertilizer urea, CAN is available; CAN is a source of N that has a (limited) liming effect. Short- and long-term benefits will determine farmers' choice.

**Table 6. Amount of  $\text{CaCO}_3$  in Kilograms Needed to Neutralize the Acidity Produced by the Oxidation of a Kilogram of N or S Supplied from Fertilizer Compounds (Havlin et al., 2005)**

Fertilizer Source	$\text{CaCO}_3$ (kg) Applied to Neutralize Acidity Per kg N or S
Anhydrous ammonia	3.6
Urea	3.6
Ammonium nitrate	3.6
Diammonium phosphate	5.4
Ammonium thiosulfate	5.4
Ammonium sulfate	7.2
Monoammonium phosphate	7.2
Elemental sulfur	7.2

In II.1, it was stressed that soluble salts, e.g., from the addition of fertilizers, can displace  $\text{Al}^{+3}$  on the exchange complex of acid soils, resulting in the further decrease of soil pH as  $\text{Al}^{+3}$  hydrolyzes, with the production of  $\text{H}^+$ . High rates of band-applied fertilizers in soils with  $<5.0$  can result in higher soluble toxic  $\text{Al}^{+3}$ , decreasing plant growth; band application of fertilizers at high rates should be avoided on acid soils. However, in many acid soils, high amounts of applied P fertilizers are fixed; under such conditions, band application of P is recommended.

## VII.2. Tolerant Crops and Cultivars

Tea and sweet potatoes are two crops observed frequently in the CAGLR, a region known for its acid soils. Crops, forage plants, and cultivars of both differ in their tolerance for soil acidity and Al toxicity. A key mechanism is the root release of citrate or malate in response to root exposure to toxic Al, forming complexes with Al in the rhizosphere (Wong et al., 2004).

While other mechanisms of tolerance exist,<sup>19</sup> all Al tolerance enables plants to develop root systems and to penetrate the subsoil. This is also the case after liming that has some effect on the subsoil acidity.

In addition to tea and sweet potato, potato is also a rather tolerant crop able to achieve optimum growth in a narrow range of pH from 5.0 to 5.4. Maize and wheat, on the other hand, require a soil pH range of 5.5–7.0. Rice grown under flooded conditions seldom responds to liming. Flooding of acid soils results in increases in soil pH. In Burundi, it was found that triticale was more tolerant of acid soils and aluminum toxicity than wheat (III.1). Compared with other Hawaiian crops, pineapple stands out as a tropical crop that can produce well within a pH range of 4.7–5.7 (Table 7).

**Table 7. The pH Growth Optima for Several Hawaiian Crops**

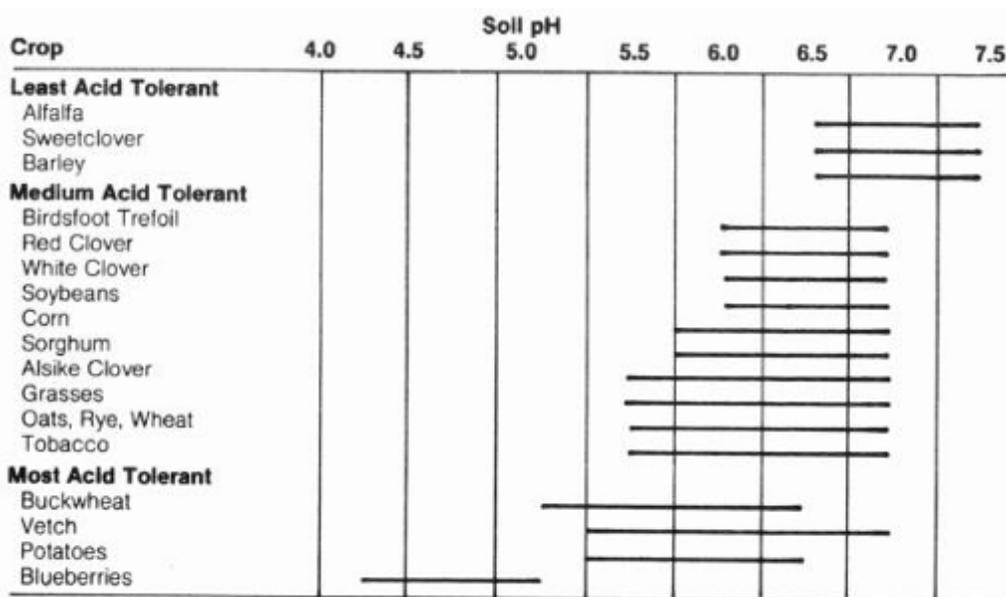
Crop	pH
Alfalfa	6.5–7.5
Sugarcane	6.0–7.0
Ginger	6.0–7.0
Avocado	6.0–6.5
Taro	5.5–6.5
Macadamia	5.0–6.5
Camelia	4.5–5.5
Pineapple	4.7–5.7
Azalea	4.5–5.0

Source: Hue and Ikawa.

Blueberry is the most tolerant of acid soils among field crops grown in temperate climates (Figure 4), some of which can be grown in the tropics (such as maize, sorghum, and potatoes). The figure also illustrates the relative tolerance of buckwheat and potato, two crops that are produced in the Rwandan region that has the most acid soils.

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<sup>19</sup>In the case of maize and sorghum, it has been found that differences in reaction on soil acidity are related to the accessibility of Mg (Tan, 1993).



**Figure 4. The pH Growth Optima for Forages and Other Crops in the United States (Purdue Forage Information)**

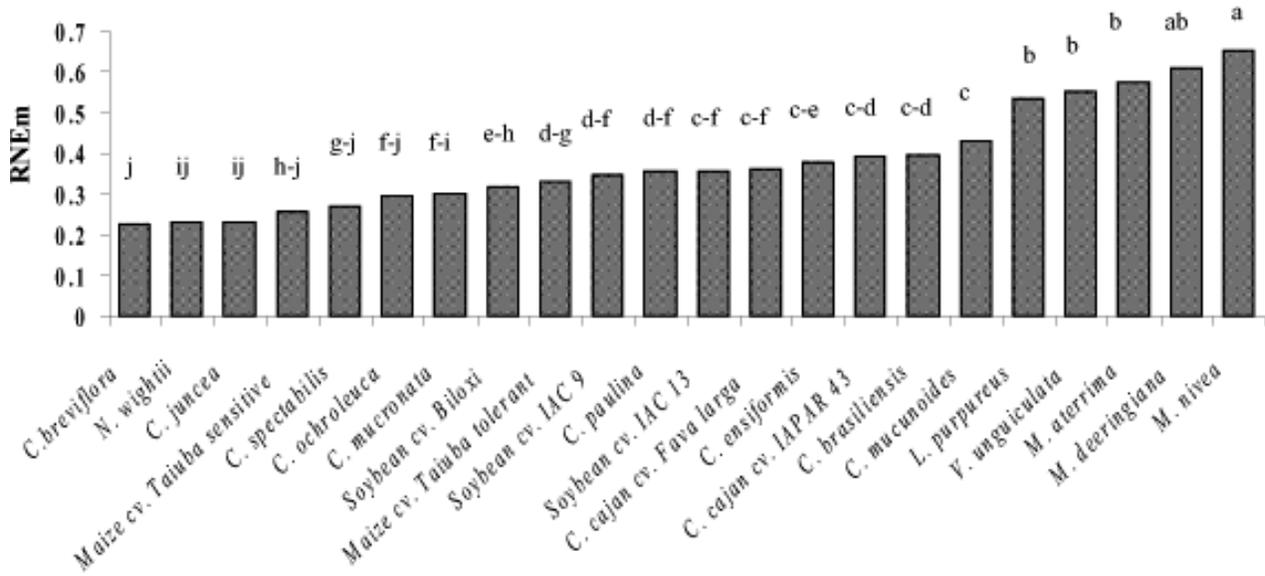
Because the genetic potential of various plant species differs regarding tolerance to soil acidity and aluminum, considerable research has been done to categorize plant species' tolerance. Crops can be classified by their pH sensitivity into three groups (Janssen, 1999):

- Crops with a preference for neutral to weak alkaline conditions: tomato, celery, peanut, barley, many vegetables and flower bulbs, cotton, beet, bean, swede, and lucerne.
- Crops with a preference for neutral to weak acidic conditions: maize, clover, Jerusalem artichoke, turnip, wheat, soybean, oats, and pea.
- Crops with a preference for weak acidic conditions: potato, rye, lupin, and tobacco.

In V.3.2, the last group is still divided in moderately tolerant and tolerant crops and cultivars. In areas where acid soils are endemic and lime and other external inputs are not profitable (enough), farmers will focus on such crops and cultivars. It is recommended that agronomists and extension specialists are able to classify crops and cultivars in the CAGLR in relation to their Al-toxicity tolerance. Intensive contact with producers will be an indispensable tool.

Meda and Furlani (2005) have studied a number of tropical leguminous plants and two maize cultivars, which differ in tolerance of aluminum toxicity. They used the relative root net elongation of plants growing in nutrient solutions with different Al levels (Figure 5 and Table 8).

The figure and table show the correlation between root development and AI tolerance. The most tolerant species of the 22 tested shows an almost three times higher mean root net elongation than the most sensitive species after only 9 days. For a 50% reduction of root net elongation, an eight times higher AI concentration is required for the most tolerant species in comparison with the most sensitive one.



**Figure 5. Mean Relative Root Net Elongation for 20 Leguminous Plants and 2 Maize Cultivars**

**Table 8. Reaction to Al Toxicity and Critical Values of Al Concentration [Al]<sub>50</sub> and Al Activity {Al}<sub>50</sub> for 50% Reduction of Root Net Length of 20 Leguminous Plants and 2 Maize Varieties**

<b>Plant material</b>	<b>[Al]<sub>50</sub></b>	<b>{Al}<sub>50</sub></b>	<b>Reaction to Aluminum</b>
<i>Crotalaria juncea</i>	39	11	sensitive
Maize cv. Taiuba sensitive	39	11	sensitive
<i>Crotalaria breviflora</i>	42	12	sensitive
<i>Neonotonia wightii</i>	43	12	sensitive
<i>Crotalaria mucronata</i>	58	15	moderately tolerant
<i>Crotalaria spectabilis</i>	65	16	moderately tolerant
Maize cv. Taiuba tolerant	68	17	moderately tolerant
<i>Canavalia ensiformis</i>	73	18	moderately tolerant
<i>Crotalaria ochroleuca</i>	75	18	moderately tolerant
Soybean cv. Biloxi	80	19	moderately tolerant
<i>Crotalaria paulina</i>	88	21	tolerant
Soybean cv. IAC 13	92	21	tolerant
<i>Cajanus cajan</i> cv. Fava larga	95	22	tolerant
<i>Calopogonium mucunoides</i>	97	22	tolerant
Soybean cv. IAC 9	100	23	tolerant
<i>Canavalia brasiliensis</i>	104	23	tolerant
<i>Cajanus cajan</i> cv. IAPAR 43	111	25	tolerant
<i>Lablab purpureus</i> cv. Rongai	189	37	highly tolerant
<i>Vigna unguiculata</i>	192	38	highly tolerant
<i>Mucuna aterrima</i>	229	44	highly tolerant
<i>Mucuna deeringiana</i>	262	49	highly tolerant
<i>Mucuna nivea</i>	334	59	highly tolerant

Table 9 shows a series of crops and fodder species (or their cultivars) that tolerate acid soil conditions and require minimal liming. Three classes are shown that (from the left to the right) have a lower level of tolerance. In other words, to maintain the acceptable pH and Al saturation, increasing levels of maintenance liming are required.

**Table 9. Crops and Pasture Species That Tolerate Acid Soil Conditions and Require Minimal Liming**

Soil pH	4.5–4.7	4.7–5.0	5.0–5.3
Exchangeable Al saturation (%)	68–75	45–58	31–45
Lime rate (t/ha)	0.25–0.5	0.5–1.0	1.0–2.0
Suitable crops (provided tolerant varieties are used)	upland rice cassava, mango cashew, citrus pineapple Stylosanthes Centrosema Paspalum Cajanus cajan Lablab purpureus Mucuna spp.	cowpea plantains maize	maize Phaseolus beans sorghum wheat

*Adapted from NuMaSS Expert System (Osmond et al., 2002).*

### **VII.3. Integrated Soil Fertility Management**

#### **VII.3.1. Soil Amendments Plus Inorganic Fertilizers**

Liming, the use of inorganic fertilizer and manure, and sources of OM should be combined (VII.1.2). The Rwandan example of past research (III.3) combines these three production inputs in an agroforestry context. In fact, similar research exists from Burundi and the Kivu (e.g., Wong et al., 1995). It can be considered part of the research that has led to integrated soil fertility management (ISFM), an approach that involves increased agricultural production and soil quality maintenance or improvement. The best use of this past research is optimizing the combination of inputs and treatments to receive a maximum response with minimum inputs and costs through synergy. Simply using the inputs and treatments all together will not be economic and will risk threatening soil quality in the long term.

In the following paragraphs, different ISFM technologies to combat Al toxicity and soil acidity will be presented. A rich source of information has been Wong et al. (2004), who promote an “integrated soil acidity management” (ISAM) strategy. They consider the strategy to be “a major support for the low-input production systems commonly practiced in the tropics.” Major problems in applying the strategy in regions such as the CAGLR are overexploitation of natural resources by extreme overpopulations, the related small sizes of land for dominant smallholder farming, the inherent disappearance of perennial species, including bushes and trees,

and low income. Consequently, farmers with low-input production systems have extremely limited access to plant residues, organic waste, manure, tree prunings, and other OM sources in comparison with their needs. Even if the required OM sources are available, smallholder farmers do not have the means to procure it; for example, buying manure as a source of N may cost more than buying inorganic fertilizer per unit of N (e.g., Gikongoro, South Province, Rwanda). In parallel, the costs of OM sources may be higher than the costs of lime when expressed per unit of equivalent basicity. Therefore, the technologies of the ISAM strategy are proposed below in the context of ISFM, which emphasizes improved access to external inputs<sup>20</sup> instead of replacing them at least partially.

### ***VII.3.2. Organic Matter Management***

The use of manure and other OM sources is tested and suggested in the struggle against acid soils. An equivalent yield of sorghum was achieved with about 20 t/ha of compost compared with sorghum in an acid soil treated with CaCO<sub>3</sub> applied at a rate of 0.6–1.7 t/ha (III.1). In a comprehensive thesis regarding treatment of soil acidity with OM in Rwanda, Mbonigaba (2007) offers abundant evidence that OM can be used to improve several characteristics of acid soils. In an experiment conducted in Rwanda, 30 t/ha of compost composed of vegetative OM, household waste, and bovine manure was added to acid soil. After 5 months, compared with the control treatment, the amount of exchangeable Al<sup>+3</sup> decreased from 3.77 to 2.44 cmol+/kg, and the Al<sup>+3</sup> + H<sup>+</sup> decreased from 4.0 to 2.7 cmol+/kg. During the same period, the massive amount of OM added as compost only raised the pH of the soil from 4.4 to 4.6. In an experiment cited by Mbonigaba (2007), application of 150 t/ha of municipal organic waste to an acid soil raised its pH from 3.3 to 6.7 after 18 months.

It is improbable that farmers in the CAGLR will have access to such large amounts of OM and be willing and able to spread it on their land. Also, examples exist of OM causing decreased soil pH. For optimal use of manure and other OM sources, the complexity of both the negative and positive effects should be understood. Wong et al. (2004) present an effective document for better understanding.

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<sup>20</sup>Production factors such as inorganic fertilizers and amendments such as lime.

### *OM and Soil Acidification*

Two forms of soil acidification in which OM plays a role are discussed in II.1. Acidification when producing OM is one of them; *nutrient transformation and uptake by plants are sources of soil acidity*. Because most plants take up more cations than anions,  $H^+$  is extruded by plants, resulting in an ionic balance, but a decrease in pH, of the soil solution. Removing crop products (grains, fruits, etc.) and byproducts from fields causes a “permanent” net gain of  $H^+$  (gradual buildup of soil acidity); export of plant material causes acidification.

### *Acidification Also Occurs When (S)OM is Degraded*

SOM is a source of  $CO_2$ ; as micro-organisms in the soil decompose OM,  $CO_2$  gas released from the decomposition combines with water in the soil to produce  $H^+$  and bicarbonate ( $HCO$ ). Acidity produced from soil  $CO_2$  is greater than acidity produced from  $CO_2$  in the atmosphere. SOM also contains organic acids and reactive carboxylic and phenolic groups that are sources of acidity ( $H^+$ ). Finally, further mineralization of ammonium to nitrate degrades organic N and causes acidity.

### *OM and Buffering Capacity*

Clay minerals, Al and Fe oxides, and (S)OM are sources of  $H^+$  in the soil solution resulting from the dissociation of the  $H^+$  from these materials (see II.1 and above: “OM and Soil Acidification”). However, buffering is also provided by (S)OM and these other materials, which have functional groups that can accept and lose  $H^+$ . Soils with high SOM, clay, or oxides of Al or Fe have greater capacity to buffer soil pH than sandy soils or soils low in OM. With an increasing buffer capacity due to SOM, the CEC also increases, and consequently, the ECEC could improve. The SOM contribution is typically a short- and medium-term effect; over a long period of time, weathering of soil minerals buffers the soil pH and, in doing so, releases nutrients such as K, Mg, and Ca (Wong et al., 2004; see VII.3.3).

The higher the soil's buffer capacity, the more lime is required to change the soil pH. More lime is required to increase the pH of a soil with a high, rather than a low, SOM status; more lime is needed to change the pH of a clayey soil than a sandy soil.<sup>21</sup>

### *OM as Liming Material*

Organic acids are mentioned above as a source of soil acidity. However, the same acids contribute effectively to the correction of Al toxicity, *forming complexes with H<sup>+</sup> and Al<sup>+</sup>*; soil acidity and Al toxicity are not simply proportional.<sup>22</sup> Wade et al. (1986) cultivated soybean (a sensitive crop) on soils from a rainforest that had just been cleared. Liming had no significant extra yield effect; Al toxicity was suppressed because of all the organic acids that were produced in the process of SOM degradation. Wong et al. (2004) stress that this effect of OM has two advantages in comparison with lime: (a) because lime causes higher Al solubility, higher pH values are required to decrease Al toxicity; and (b) lime has a limited effect on subsoil acidity, while fulvate-type components of humified OM are expected to increase subsoil pH in view of their mobility.

OM can also have a liming effect when it contains considerable concentrations of alkalinity and related cations. Because of this, manure frequently has a rather high pH (7–9). Recycling OM to the soil can add cations back to the soil and reverse the acidification process. A laboratory incubation experiment was conducted to investigate the effect of adding a range of organic amendments to an acid soil on pH and exchangeable and soluble Al (Narabuye and Haynes, 2006). The wastes included plant materials (maize, sorghum, kikuyu grass, soybean, red clover residues, and acacia prunings), animal manures (kraal, pasture and feedlot cattle, pig, and layer and broiler poultry), household compost, sewage sludge, and an industrial waste filter cake. Amendments were analyzed for a number of different tests, which have been proposed as predictors of the liming effect of specific organic residues. Ash alkalinity and basic cation content were the tests most closely correlated with increases in soil pH. Ash alkalinity was proposed as a suitable laboratory test for predicting the liming potential of organic materials.<sup>23</sup>

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<sup>21</sup>For a loamy soil, the LR may be twice as high as for a sandy soil if the pH increase is the same. For a clayey loam, the LR may even be four times higher than for sand. But because of the high buffer capacity, it also takes much more time before the pH is back to its original level before liming.

<sup>22</sup>Wong et al. (2004) show the complexity regarding the liming effect of OM, mentioning complexation of protons by organic anions, microbial decarboxylation of organic anions, and ammonification of plant materials high in N.

<sup>23</sup>Ash alkalinity is proposed because it is relatively simple to measure, and the values reflect the initial content of organic acid anions, humic materials, and CaCO<sub>3</sub> in wastes (Narabuye and Haynes, 2006).

One must realize that manure or other OM sources cannot be regarded as extra liming material if they were produced on the field to be treated.<sup>24</sup> In that case, cations that were taken away by harvesting are brought back, a process that will always be accompanied by losses (e.g., grain and fruits are not composted). Manure, compost, and other sources of OM with adequate alkalinity and cation content can be regarded as real liming material if produced outside of the fields to be limed (roadsides, bush, livestock-grazing pastures, poultry fed with concentrates, etc.). For example, Nabahungu and Ruganzu (2001) have used *Tithonia diversifolia* to amend acid soils used to cultivate climbing beans and maize in Rwanda. The yield of beans and biomass of maize increased significantly with 4 t/ha of *Tithonia diversifolia*, combined with 0, 0.5, or 1.0 t/ha of travertine, compared with the control to which neither soil amendment was applied.

### *Balance*

OM appears to be at the basis of processes that on one hand contribute to acidification and on the other hand slow down or correct acidification. Some processes have short-term effects and others medium- or long-term. Different plant materials also contribute to the observed differences. It is therefore difficult to determine the effect of an individual OM treatment. However, a form of generalization is possible. Anthropogenic activities increase and accelerate soil acidification, despite the fact that the opposite occurs temporarily,<sup>25</sup> such as in the case of the forest clearing discussed above (Wade et al., 1986). One process has already been treated: the use of acidifying inorganic fertilizers containing N and/or S (VII.1.3). Worse are, however, the export of OM in the form of plant or plant-derived animal material (see above: “OM and Soil Acidification”) and the related decrease in the SOM status of the soil. The latter occurs under unsustainable agriculture, with negative plant nutrients and OM balances of soils. A negative SOM balance causes a progressive decrease in the water and nutrient retention capacity of the soil and an inherent increase in leaching. Nitrate<sup>26</sup> leaching appeared to have, by far, the highest contribution to soil acidification in high rainfall (>2,000 mm/year) in tropical regions. Acidification related to the production of nitrate cannot be neutralized any longer when the

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<sup>24</sup>Agroforestry is an exception (VII.3.3).

<sup>25</sup>Decreasing acidity due to SOM losses is only temporary, because the soil is losing its buffering and acidity-neutralizing capacity.

<sup>26</sup>The main sources of nitrate are mineralizing SOM, urea, and ammonium fertilizers.

nitrate leaches in the form of a neutral salt. Its effects are the highest under unsustainable intensive systems (Wong et al., 2004).

Wong et al. (2004) also present an example of the opposite: the Al detoxification using a form of agroforestry leading to an increase in SOM. Nine years after the start of a hedgerow intercropping experiment in the tropics, soil samples using five different tree species and their prunings<sup>27</sup> were taken and analyzed (0–15 cm topsoil). The annual contribution of about 8.5 t/ha of OM had increased the SOM content of the plots in different degrees (2.00%–6.25%). A positive correlation existed with the pH and the ECEC, and a negative correlation with the Al saturation and the concentration of exchangeable Al.

This positive effect of OM on soil acidity is related to the above-mentioned higher uptake of cations compared with anions. Alive or dead plant material contains anionic functional groups—the so-called alkalinity—that are bound to basic cations. The degree of alkalinity determines the liming effect of OM (see V.1). Its linkage with the basic cations ( $\text{Ca}^+$ ,  $\text{Mg}^+$ ,  $\text{K}^+$ , and  $\text{Na}^+$ ) implies however that the total concentration of these base cations is closely related to the ability of the plant material to neutralize soil acidity. This is used for quantifying the alkalinity of OM through ashing. The “ash alkalinity” can be measured or estimated from published tables (Drechsel and Zech, 1991; Palm et al., 2001).

Plant material contains different concentrations of alkalinity in relation to the place of production and to plant species properties. Even under the same climate, soils may differ in pH. Plants produced on soils with a pH above 7 have on average a much higher alkalinity content than plants produced on soils with a pH below 7. In other words, OM derived from the first plants has a much higher liming capacity than OM derived from the latter. The first type of OM can be used to transfer alkalinity to acid soils, progressively acidifying the basic soils where it is produced. Also, weathering of soil minerals allows for alkalinity accumulation in plant biomass. Certain plant species play an active role in soil weathering and will therefore be (relatively) good producers of OM high in alkalinity. A similar effect occurs when deep-rooting plant species bring leached cations back to the soil surface. This process, sometimes called “nutrient pumping,” is exploited in agroforestry (VII.3.3).

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<sup>27</sup>Hedgerow trees were pruned during the growing season and all pruned biomass was returned to the plots as mulch.

There is a distinction between this so-called pumping of nutrients and the alkalinity transfer from elsewhere. Nutrient pumping causes the speed of soil depletion and the related acidification to decrease; the alkalinity that is brought back to the soil surface is an element of the field or the farm that otherwise would be lost. Transfer of alkalinity from outside the farm can lead to a real positive correction of soil acidity; it concerns an external input comparable to lime. In this context, one must distinguish between sources of OM, and inherently alkalinity, that are produced on the farm or that are brought from elsewhere (organic wastes, manure, compost, straw, other agricultural byproducts, etc.). Using one's own products as effectively as possible decreases the acidification rate related to farming (production and export of OM and the alkalinity it contains from fields and farms). The use of the same products obtained from elsewhere adds alkalinity and leads to a certain degree of neutralizing acidity.

Key differences between OM and lime are the limited alkalinity content and the limited availability of OM (VII.3.1). In the first example in VII.3.2, an equivalent yield of sorghum was achieved with about 20 t/ha of compost, compared with sorghum in acid soil treated with  $\text{CaCO}_3$  applied at a rate of 0.6–1.7 t/ha. In other words, 1 t of compost had a liming efficiency varying between 0.03 and 0.08 t/ha of  $\text{CaCO}_3$  equivalency. In the second example, 30 t/ha of compost led to a decrease of Al toxicity from 3.77 to 2.44 cmol/kg. Using Equation V.3-2, for neutralizing 1.33 cmol/kg of Al toxicity to estimate the liming efficiency of the compost:

$$\text{LR} = \text{factor} \times 1.33$$

a value of 1.3 t/ha lime is required for moderately tolerant crops (factor =1) and 2 t/ha for Al-sensitive crops (factor = 1.5). Thus, 1 t/ha of compost has a CCE of 0.04–0.07 t/ha.

A rough estimation of the average availability of OM is easily made in the CAGLR, where most of the land is cultivated and/or overexploited. The average cereal yield is 1 t/ha/season and the harvest index is about 25% or 3 t/ha of byproduct straw. In other words, 1 ha produces yearly in two seasons: 6 t/ha of OM besides the 2 t/ha of grain. One hundred percent recycling byproducts in the fields where it is produced helps to decrease the acidification rate, particularly for the acidity that is caused by the export of grain (or other products) and by erosion and leaching losses. However, the alkalinity of freshly produced OM such as straw will

be a factor lower than the alkalinity of compost or manure. This is even the case when the same OM is used to produce manure or compost; during the production process, the alkalinity will be concentrated. Well-managed manure will have two to three times the concentration, and compost may even have five times the concentration.<sup>28</sup> During this concentration, the amount of OM decreases more or less proportionally. Losses of OM and/or nutrients during the transformation processes will lead to losses of alkalinity. From the viewpoint of acidity control, the optimum use of crop byproducts is recycling on the spot; economically, transformation into manure or other uses may be more interesting. It increases, however, the risk of acidification, in view of the labor required to return the byproduct in the form of manure or compost to the field where it was produced.

The practical consequence of what has been described is that OM is seldom a solution for the acid soils of poor smallholder farmers. With the exception of roadsides, they do not have wastelands, pastures, or forests where they can collect, by hand or with the use of livestock, OM for alkalinity transfer to improve their fields. They can only try, using their own crop byproducts, to keep the acidification rate as low as possible. Like lime and fertilizers, the use of OM for its liming potential is mainly a solution for the rich, who have land, livestock, and/or capital.

### ***VII.3.3. Agroforestry***

The positive role that agroforestry can play in improving acid soils was illustrated in III.1, III.3, and VII.3.2, but the processes through which this role is realized have not yet been treated. However, in the case of agriculture in the humid tropics (VII.3.2), it became clear that increased agricultural exports and elimination of woody components from the production system lead to decreased SOM, increased nitrate leaching, and acidification. More than 8.8 kmol/ha of  $H^+$  are lost annually from the first 1 m of the soil profile in Yurimaguas, Peru (Wong et al., 2004), at 2,200 mm/year of rainfall, under high-input intensive agriculture. The opposite takes place under peach palm agroforestry, with rice and legumes as undergrowth; the acidification rate is negative:  $< -4.0$  kmol/ha of  $H^+$ . Shifting cultivation, low-input agriculture, and multistrata agroforestry without external inputs all show acidification, but much lower than in the case of intensive agriculture. In the meantime, the productivity and therefore the export of agricultural

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<sup>28</sup>The weight of straw is expressed in dry matter, while the amounts of manure or compost used are often expressed as “fresh matter” without correction for the amounts of water it contains.

products have been much lower. Processes causing these differences will be discussed below, as well as the fact that high-input intensive agriculture becomes less acidifying and therefore more sustainable if executed in an agroforestry context.

### *Agroforestry, One of the ISFM Technologies*

Agroforestry is one of the ISFM technologies and a form of OM management in agriculture (VII.3.2). It is a very effective form, making, on average, more and better quality OM available than other technologies. Woody species, shrubs, and trees are the sources of this OM. Their OM production is high due to their perennial life, leading to a progressive accumulation of plant nutrients in the plants and in the soil around them. Their OM is relatively good (level of alkalinity) due to (relatively) deep rooting and the related “pumping” of cations that are lost by leaching or produced by soil weathering. Agroforestry is more difficult to manage than other technologies because the competition of shrubs and trees with crops makes benefits too low in view of the crop production decrease.

### *Different Forms of Agroforestry*

Farmers can benefit in different ways from trees for agricultural goals; optimizing such goals requires different management systems for the tree component<sup>29</sup> of the production system (Breman and Kessler, 1995). In the context of the struggle against soil intensification, two main forms must be distinguished, based on the presence of woody species within the field or outside the field. In the first case, the acidification rate decreases due to the presence of woody species; in the second, transfer of OM from woody species can contribute to correction of the field soil acidity (see “OM as Liming Material” in VII.3.2). For a certain farm, the most interesting case from the viewpoint of soil acidity correction is getting the OM from woody species from outside the field. The acidification accompanying OM transfer takes place elsewhere, and there is neither competition for space (on-farm woodlots), nor for light, water, or nutrients (trees in fields).

In III.1, a Burundian example of lateral transfer of OM from woody species is mentioned: 3–6 t/ha of prunings from pure stands of agroforestry trees were applied on fields with well-fertilized maize or beans. Presumably due to lower soil acidity and Al toxicity, the maize and bean yields of fields with prunings were significantly higher than without prunings; prunings

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<sup>29</sup>The distinction between shrubs and trees is often useful. This distinction is only made when useful. When not, the terms “trees” or “woody species” will be used.

made the fertilizer more effective (Wong et al., 1995). Woody species with high productivity and high ash alkalinity will be the most effective for such treatments. However, because of the low liming effect, few farmers will have the energy and time to transport the OM to their fields, even for species producing a lot of OM with very high ash alkalinity (see Balance in VII.3.2). Even less is the chance that they will use space for woodlots that produce the concerned OM. A chance exists, however, that farmers with livestock will plant forage shrubs or let livestock graze on roadsides, wastelands, or bush. In these cases, the alkalinity from woody species can be brought to the field in the form of manure, which biomass will be one-half to one-third of the original biomass.

The other form of agroforestry concerns the presence of woody species in the field. Three subforms can still be distinguished: the “agroforestry parkland,” “alley farming” or “hedgerow intercropping” (see an example in “Balance” in VII.3.2), and “rotating woodlots.” In the case of agroforestry parkland, the right types of trees are distributed homogeneously in the field and managed in such a way to limit the competition with crops as much as possible (Breman and Kessler, 1995).<sup>30</sup> In the case of alley farming or hedgerow intercropping, rows of woody species are alternated with strips of crops. To avoid extreme competition, the woody species are cut two to three times through the growing season, and the cuttings are used as mulch in the strips of crops. Rotating woodlots is part of the production system and one out of four or five rotating crops. Its rotation is, however, only once every 4–5 years; the young trees are uprooted, wood is harvested, and twigs and leaves are left in the field.

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<sup>30</sup>Key elements of management are: trees are homogeneously distributed; the total cover of crowns of trees is not more than 20%–25%; tree stems are at least twice the diameter of the crown; as much produced biomass as possible is recycled; and superficial roots are cut.

**Table 10. Comparison of Different Agroforestry Systems Contributing to the Struggle Against Acidification**

	Deep Rooting <sup>a</sup>	Biomass Production <sup>b</sup>	Competition With Crop	Alkalinity Content <sup>c</sup>	Acidification Rate Field
<i>Woody species outside the field</i>					
On-farm	+++	+++	++ <sup>d</sup>	+++	-
Elsewhere	? <sup>e</sup>	? <sup>e</sup>	-	? <sup>e</sup>	-
<i>Woody species inside the field</i>					
Parkland	+++	+++	+	+++	+
Rotating woodlot	++	++	++ <sup>d</sup>	++	++
Alley cropping	+	++	++	+	+++

-, +, ++, +++ = absent or negative, relatively low, medium, and high.

a. Rooting as influenced by management; in other words, property of species not taken into account.

b. Per unit of area over many years.

c. Of the produced OM.

d. Limited direct competition, but serious competition for space.

e. Depending on a source of woody OM obtained outside the farm.

Table 10 compares the two forms of agroforestry and their subforms that can play a role in the struggle against acidification. The first two subforms, which are at the basis of alkalinity transport to the field, can decrease the soil acidity; the last three can decrease the rate of acidification. The last three concern subforms that are based on the presence of woody species in the fields. Among the three, agroforestry parkland will decrease the acidification rate the most, and alley cropping presumably the least. The difference is caused by the difference in rooting, in biomass production, and in their influence on the environment. Only the parkland trees have the time to develop deep taproots and an extended root system. In the case of alley cropping, no taproots develop and the entire root development is relatively limited because of regular above-ground cutting.

In well-managed parkland, the competition between trees and crops will be lower than for rotating woodlot or alley cropping. In spite of competition and limited contribution in the struggle against soil acidification, farmers may prefer alley cropping or rotating woodlots, because some other values of the tree products could more than compensate for the crop production losses. Rotating woodlots is practiced close to cities, with markets for charcoal and poles (Toose et al., in press). Alley cropping may be appreciated, e.g., for their fodder production.

### *Agroforestry Definition*

In this report, trees and/or shrubs must contribute to crops and to the intensification of agricultural production. In other words, here, agroforestry concerns agricultural production systems in which trees are present and beneficial enough to compensate for their negative effects on crops that result from their competition for light, nutrients, and water. Agroforestry is, in this context, a “double-cutting sword”: it supports the struggle against acidification through the “delivery” of alkalinity as described above, and it makes the use of inorganic fertilizer more effective and profitable as described in Breman and Kessler (1995). It is an ISFM technology that includes ISAM (Wong et al., 2004) as one of its effective components. When well managed, it makes crops more productive due to improved crop rooting, improved nutrient and water storage capacity of the soil, and improved accessibility of nutrients and water. The inherent improved efficiency of fertilizers and other inputs makes their use more profitable.

### *Role of Trees in Agroforestry Systems*

Wong et al. (2004) stress that two properties make woody species particularly effective for ISAM: high productivity and a high base cations content (almost equivalent with high alkalinity content). They indicate that natural tropical forests, the dominant vegetation for regions sensitive to soil acidification, show themselves limited acidification. They owe this to limited export of OM, large species diversity, and limited leaching due to rapid immobilization of nutrients (large permanent root system) and large storage of nutrients in biomass (alive and dead). They call tree-based agroecosystems “economic mimics of natural ecosystems.”

The amounts of basic cations ( $\text{Ca}^+$ ,  $\text{Mg}^+$ ,  $\text{K}^+$ , and  $\text{Na}^+$ ) that are released by trees in the topsoil of forests and help avoid significant acidification are relatively small. In a forest in Scotland, it varies between 0.2 and 3.2 keq/ha/year in the first 50 cm, depending on the parent material of the soils (Guicharnaud and Paton, 2006). Kolka et al. (1996) measured 0.2–0.5 keq/ha/year, depending on the soil texture, for a forest in the United States. Values for agroforestry systems will be a fraction of those observed in forests, because the total cover of the tree component of the systems should not be more than 20%–25%.

Breman and Kessler (1995) describe in detail the difference between woody species and annual crops, and the way in which crops in agroforestry can share part of the “surplus value” of woody species with the latter as components from production systems. Perennity, large genetically determined dimensions, a long life, and an efficient internal and external recirculation of nutrients decrease nutrient losses and cause nutrient accumulation. Consequently, in well-managed systems, the SOM content is much higher than for annual crops. The main benefit for crops is higher nutrient and water use efficiency due to decreased nutrient and water losses (through runoff and leaching). Getting leached nutrients back to the surface (“nutrient pumping”) is only a small fraction of the positive contributions of trees, but a relatively important one in the case of ISAM (see above).

Because a main contribution of trees in agroforestry systems is the decrease in nutrient losses, the positive role of trees increases when the availability of nutrients is high. In the Acacia Faidherbia parkland in semiarid West Africa, the availability of N for millet or sorghum is about 25 kg/ha due to the presence of acacia trees, compared with  $\leq 20$  kg/ha for fields without trees. If inorganic fertilizer is used for offering the crop 100 kg/ha more N, the N from fertilizer is also used with at least 25% higher efficiency (Breman and Kessler, 1995). Instead of about 5 kg/ha extra N, the crop receives  $5 + 25 = 30$  kg/ha extra N. Agroforestry for making external nutrients more efficient is more beneficial for farmers than agroforestry that views decreased use of external nutrients. Agroforestry that views increased accessibility of inorganic fertilizers for smallholder farmers leads to much higher crop production and to higher overall biomass, alive and dead (crop plus trees, mulch, and SOM).

Similarly, agroforestry that views making liming more efficient will be a more profitable alternative for liming than agroforestry. The absolute amounts of alkalinity that are required to correct Al toxicity in the region are extremely high in comparison to the alkalinity that can be offered by the OM from shrubs and trees (compare the indications of lime requirements in V and VI with the potential offer of lime equivalency by OM in “Balance” in VII.3.2). For full and more sustainable benefits of agroforestry plus liming, inorganic fertilizers have to be a key component of the package (e.g., VII.1.2 and VII.3.2); without them, the lime will lead to soil depletion over time (Footnote 18). The use of inorganic fertilizers will also be beneficial for trees, which will grow larger than under natural conditions, produce more biomass, and lead to

more mulch and SOM. In other words, while their cover in agroforestry systems should not be more than 25%, their effect can be greater than that of a quarter of a natural forest (see above).

Besides cover and the use of inorganic fertilizers, the properties of agroforestry tree species play a key role in their ultimate contribution to the control of soil acidification. Positive properties indicated by Breman and Kessler (1995) are the form (trees, not bushes), the rooting pattern and density (extensive rooting but not too superficial), and the mineralization rate of the OM (not too fast, to enable building up of SOM). They should have added “a high basic cations content” in case the agroforestry system also has to serve soil acidity management. Little seems to be known about these properties in relation to tree species in the region. Even for the species that are used in agroforestry, information regarding these tree properties has not been found. An interesting exception is the banana. It is not a woody species, but it is a high biomass-producing perennial that gives stability to many production systems in the region. The banana is known for its high K content and presumably plays an important role in keeping K in circulation, instead of losing it from the system by leaching. The International Institute of Tropical Agriculture (IITA) illustrated its importance by studying coffee and banana production in isolation and in combination; together, both plants have a higher total production than the sum of separate production (Van Asten et al., 2008).

### *Problems Regarding Agroforestry*

In spite of the positive role that woody species can play, in many cases, farmers prefer the elimination of shrubs and trees from their field. Competition with crops for light, nutrients, and water is an important reason. Table 10 shows that for woody species in the field, the parkland system has the lowest degree of competition with crops. Footnote 30 summarizes the key management tools for diminishment of tree-crop competition in parkland.

Another problem in using agroforestry to control soil acidification is the sensitivity of tree and bush species to soil acidity. Again, limited knowledge exists about the properties of potential agroforestry species. Yamoah et al. (1989) studied the performance of alley shrubs in the highland region of Rwanda. They determined that *Sesbania sp.* grew faster than *Leucaena sp.* in the Central Plateau and in the Buberuka Highland. Soil pH was 4.3 in the Central Plateau location and 4.8 in the Buberuka Highland location. Lime application as low as 0.75 t/ha

increased the growth of all the shrubs. *Calliandra sp.* and *Leucaena sp.* were most responsive to lime application, and *Sesbania sp.* was the shrub least responsive. In other words, *Sesbania sp.* seems to be the most tolerant for soil acidity.

Finally, land tenure can be a serious bottleneck, particularly in the DRC. Planting of woody species is often not appreciated by the landlords. If it is accepted, special contracts have to be established, and the costs of land use increase considerably.

#### ***VII.3.4. Crop-Livestock Integration and the Role of Legumes***

Strong parallels exist between crop-livestock integration and agroforestry in support of soil acidity control for crop production:

- OM that is brought from outside the farm in the form of manure contributes to a decrease in soil acidity; manure that is produced from on-farm OM (e.g., crop byproducts) decreases the rate of acidification. Only manure produced at the basis of fodder from outside concerns external alkalinity (and nutrients; see below). The amount of alkalinity that is obtained in this way depends not only on the number of tropical livestock units (TLU) involved in transport, but also on the available and accessible fodder and the livestock species. Presumably, the alkalinity content of manure increases with fodder going from annual plants, over perennial herbaceous species to woody species. Presumably, the manure of browsers such as goats has higher alkalinity content than of grazers such as cattle.
- Much more OM is available when crop-livestock integration is used for making the use of inorganic fertilizers economically feasible rather than for limiting the use of inorganic fertilizers. It has been shown for Rwanda that the livestock density increases with the fraction of land used for crop production. This is typical for agriculture that is limited by lack of nutrients: livestock primarily serves the transport from nutrients to the farm. With increasing occupation of the land for crops and the more than proportional increase of livestock, the latter progressively lose their production and savings function, while the land is depleted and degraded (Breman et al., 2007). Only the use of inorganic fertilizers can stop the process, increasing the amount and the quality of fodder and allowing for higher stocking rates and/or higher animal production.

It is impossible to sustainably maintain a single cow on an average farm of 0.7 ha if grazing is not possible outside the 0.7 ha; but several cows can be held and can produce well on the 0.7 ha when inorganic fertilizers are used. In other words, crop-livestock integration can play a role in soil acidity control if grazing outside the farm is possible and/or if inorganic fertilizers are used. Per TLU, somewhat more than 1 t of manure (dry matter) becomes available, of which the alkalinity content will be 2–3 times higher than from crop byproducts.

In Rwanda, it was found that because of phosphorus deficiency and strong soil acidity, lime and P fertilizer were needed to raise sorghum yields. On acid and very poor ferralitic soils (Ultisols), yields were suppressed by the lack of phosphorus and acidity, despite soil and water conservation and application of 10 t/ha of cattle manure and 6 t/ha of leguminous mulch. Roose and Ndayizigiye (1997) concluded that the acid soil deficient in N, P, and Ca could not be adequately supplied with P by the use of manure. P fertilizer and lime were also required.

A study on crop rotation and soil amendments in the Zaire-Nile Watershed Divide of Rwanda (Rutunga and Neel, 2006) found that over a 9-year period, there was no or very low harvest without fertilizers. Application of fertilizers slightly increased yields, with potatoes and finger millet responding the best. Liming was absolutely necessary to get acceptable yield responses using NPK fertilizers (i.e., urea, triple superphosphate, and various NPK formulas), and a high rate of rich farmyard manure showed positive effects on yields up to 4 years after it was applied. One, 4.5, and 8 t/ha of burnt lime (39.2% CaO, 4.0% MgO) applied three times in 8 years increased soil pH to 6.5. Under the conditions of the Mata experiment, the effects of 2 t/ha of burnt lime remained significant up to three or four seasons. The effects of NPK fertilizers lasted for a year, and 35 t/ha of barnyard manure had discernible, positive effects on yield for up to four consecutive seasons. After a basal dose of burnt lime, with subsequent applications of 8 t/ha of manure in years 2, 4, and 7, the pH (water) of the acid soil increased from 4.7 to 5.2.

Using the formula from V.3.3, a dose of 2.31 t of  $\text{CaCO}_3$  is obtained for such an increase in pH. Or, the 24 t of manure had a liming value equivalent to 2.31 t of  $\text{CaCO}_3$ . In other words, 1 t of manure has a liming efficiency of almost 0.1 CCE/t. This is slightly more than the values that have been estimated for compost under “Balance” in VI.3.2.

As indicated in the former paragraph, a link between crop-livestock integration and agroforestry can be created through the introduction of anti-erosion bands of perennial fodder grasses and/or fodder bushes. Leguminous bush species are suggested by Wong et al. (2004), in view of their high protein value. This suggestion should be considered with care. One has to verify first if protein is more limiting than energy for the concerned livestock system and the amount and quality of fodder it offers. When leguminous fodder is fed to ruminants while energy is limiting, the extra protein is lost. Besides, Wong et al. (2004) themselves indicate: “depending on the legume species, between 0.2 and 0.7 of a mole of H<sup>+</sup> is excreted per mole of N fixed.” In other words, biological nitrogen fixation contributes slightly to soil acidification.

### ***VII.3.5. Intensification in an ISFM x ISAM Context***

The preceding paragraphs have shown that no effective organic alternative for liming exists; it certainly does not exist as a cheap alternative for poor smallholder farmers:

- The liming equivalency of OM is 0.1–0.05 in comparison with CaCO<sub>3</sub> for manure and compost; for crop byproducts, mulch, etc., the equivalency will generally be lower.
- OM that is produced on the farm will not contribute to a decrease in acidification, because its production causes acidification. It will, however, decrease the acidification rate.
- Getting OM from outside the farm requires too much labor and/or money. OM with high alkalinity content will often be more expensive than lime.

Nevertheless, optimum OM management is highly recommended; it does not only serve control of soil acidity, it also helps prevent rapid soil depletion and degradation. If means are available, OM management, ISAM, liming, and fertilizer use should all be components of ISFM. Such an ISFM approach leads to high crop and livestock productivity, high input use efficiency, high soil buffering capacity, increased availability of wood, and decreased erosion. If lime and inorganic fertilizers are not available or accessible, a combination of optimum OM management and the choice of acid-tolerant crops is the best way to maintain farm production as long as possible, in spite of acidification and soil depletion. Optimum OM management in this case is, if possible, a combination of maximum on-farm use of crop byproducts, agroforestry, and crop-livestock integration.

## **VIII. Preliminary Impressions of the Economic Feasibility of the Correction of Al Toxicity**

### **VIII.1. Estimating Benefits of the Correction of Al Toxicity**

Systematic data have not been identified that show the effects of liming on yield. Even using Internet search engines, very limited data sets have been found. In temperate regions, the profitability of liming could be too obvious; in developing tropical countries, even fertilizer use is limited, not to mention liming. Nevertheless, enough is known about liming for a first estimate of its profitability in Rwanda. The way this is done and the results are shown below.

#### ***VIII.1.1. The Acidity to be Corrected***

Table 11 presents an image of the Rwandan soil acidity problem. The table uses the former administrative structure in view of the statistics that have been used and the soil acidity map (Appendix B). The position of each district regarding agricultural productivity has been derived from MINECOFIN (2003) statistics regarding eight crops, using (a) the frequency that the average yields of the eight crops in a district are among the highest and the average of the lowest of the country and (b) the relative yield levels of these three groups. Gisenyi appears to have the highest crop productivity, and Butare the lowest.

The soil acidity figures are derived from the Rwandan soil acidity map in Appendix B, estimating the relative area for each of the four pH classes and calculating the weighted average (last column). The next-to-last column (% < pH 5) presents the area occupied by the class with the lowest pH. Guided by CATALIST sampling and analysis, the average pH value of this class has been estimated to be 4.7.

**Table 11. A Comparison of the Agricultural Productivity in Rwanda Per (Former) District With the Average Rainfall and Soil Acidity**

District	Productivity relative (%)	Rainfall mm/year	Soil Acidity	
			% < pH 5	pH average
Gisenyi	100	1,000	50	5.8
Ruhengeri	92	1,300	40	5.4
Kibungo	90	900	5	5.7
Kigali	90	1,000	20	5.2
Cyangugu	87	1,300	60	5.1
Umutara	85	900	10	5.3
Byumba	82	1,200	30	5.4
Kibuye	77	1,000	70	4.9
Gitarama	72	1,100	60	5.0
Gikongoro	67	1,300	70	4.9
Butare	64	1,100	20	5.2

No correlation appears to exist between productivity and rainfall; soil factors (fertility and acidity) strongly dominate over rainfall. Nevertheless, in view of soil acidity and the inherent limited root development, crops will be sensitive for periods of drought, in relatively dry, and in more humid regions. Control of soil acidity will have positive effects through lower drought sensitivity and improved nutrient availability and efficiency. A clear correlation exists between relative productivity and soil acidity. A graph representing the relation shows, as expected,<sup>31</sup> a more than proportional decrease in productivity with decreasing pH: respectively, 100%, 90%, 80%, 70%, 60%, and 50% productivity is related to average pH values of 5.8, 5.4, 5.15, 4.95, 4.8, and 4.7. The presented correlation is not entirely due to soil acidity; regions with relatively high pH values are also regions with a considerable fraction of fertile volcanic soils. Consequently, the correlation that has been found between pH and productivity could lead to an overestimation of the liming potential.

### ***VIII.1.2. Relative Yield Increase Through Liming***

Limited data availability and lack of a soil analysis system are at the basis of the choice to use the simple formula in V.3.3 as a basis for the estimation of the profitability of liming. In other words, only the soil pH is used for the estimate, and the amount of lime to reach pH (H<sub>2</sub>O) 5.2 is at the basis of the indicated profitability. It is the pH level that is accompanied by a critical

<sup>31</sup>The pH is presented as a logarithmic scale.

Al saturation (CAS) of  $\leq 30\%$ , an acceptable level for many crops. Increasing the pH from 4.7 to 5.2 requires 2.31 t/ha  $\text{CaCO}_3$ . In view of Table 11, it will lead to an average production increase from 50% to 82% in Rwanda, a 64% increase in comparison with the starting situation. It is true that higher yields are obtained using pH 5.5 or even 6.0 as levels to be reached by liming. However, the effect per unit of lime decreases rapidly above pH 5.2, and the risk of negative liming effects (erosion) increases.

The yield increases due to liming will be estimated for intensive agriculture that also uses fertilizer. VII.1.2 stresses the danger of using lime without fertilizer. Nevertheless, farmers may do so because they lack the means to buy both or because of the short-term benefits they experience at the cost of sustainability of production. To obtain an idea of this risk, yield increases through liming will also be estimated for extensive agriculture without significant fertilizer use. This is easy extra information in view of the fact that the yield effect of liming is often presented through the relative yield at different levels of pH or Al toxicity.

According to reports of individual trials, rather large variations in yield increases are observed. This is not astonishing, particularly when observations concern one or a limited number of years; for example, weather alone can cause huge variations. In Mauritius, liming of two potato varieties led to a yield increase of 22% and 8%. CATALIST obtained up to 27% in Burundi (Kyanza), an average of 16% increase in South Rwanda ( $n = 5$ ), and of 19% in the North ( $n = 5$ ). For wheat, CATALIST obtained an average yield increase of 25% in North Rwanda ( $n = 5$ ). Particularly in North Rwanda (Gicumbi district), the variation was strong: for potatoes, the yield increase varied between -10% and +66%, and for wheat, between -10% and +93%.

Liming of tolerant and sensitive maize varieties in Cameroon increased the pH from 4.7 to 5.1 and led to yield increases of 82% and 209%, respectively (The et al., 2001). With lime, the yields were almost equal (about 4 t/ha); without it, the tolerant variety produced 2.1 t/ha, and the sensitive variety, only 1.3 t/ha. The absolute yield increases from liming were 1.7 and 2.7 t/ha, respectively. Fertilizer-P decreases the difference between the control yield of the tolerant and the sensitive cultivar; they become 2.2 and 1.8 t/ha, respectively. Combining P and lime leads to an almost equal effect of liming, a yield increase of 93% and 95%, respectively.

Syntheses of data from several years and fields form a better basis for obtaining a quantitative impression about the effect of liming. Janssen (1999) presents results from Germany about relative yields and soil pH (KCl). Only in the case of sandy soils, pH (H<sub>2</sub>O) levels below 5.2 were presented (pH H<sub>2</sub>O = pH KCl + 1)<sup>32</sup>. For potatoes, the 100% yield level was found at pH  $\geq$  5.5; the yields were 96% and 82% at pH 5.0 and 4.5, respectively. Wheat and maize proved to be more pH sensitive; their 100% yield was found at pH 6.0. For wheat, the relative yields were 97%, 83%, and 35% at pH 5.5, 5.0, and 4.5, respectively; for maize, yields were 97%, 85%, and 51%. Or, increasing the pH from 4.7 to 5.2 led to an average production increase from 88% to 98% for potatoes, an 11% increase in comparison with the starting situation. For maize, a 34% increase was obtained, increasing the pH from 4.7 to 5.2; for wheat, a 50% increase was obtained.

Wade et al. (1999) present similar data for the tropics (Table 12). They used levels of Al saturation instead of pH. A graph such as Figure 1 makes it possible to obtain a rough idea of the related pH values: for the Burundi case in Figure 1, 25%, 50%, and 75% Al saturation were the average values related to pH 5.0, 4.7, and 4.6, respectively.

**Table 12. Relative Yields in Relation To Levels of Al Saturation and the Critical Al Saturation CAS of Acid-Tolerant (Cassava) and More Sensitive Crops**

Crop	No. <sup>a</sup>	CAS <sup>b</sup> (%)	Relative Yield <sup>c</sup> (%)		
			25%	50%	75%
Cassava	3	59 (38–69)	95	93	83
Groundnut	6	32 (1–47)	93	84	57
Maize	13	22 (0–55)	87	63	36
Soybean	13	13 (0–32)	89	59	30

a. Number of observations.

b. Critical Al saturation.

c. At three levels of Al saturation.

The graph presented in Figure 1 varies with soil, climate, weather (rainfall distribution), etc., because the effect of soil acidity on crops varies with these variables. This is illustrated by the column in Table 12 that presents the critical Al-saturation (CAS) values for the different

<sup>32</sup>The relationship depends on soil texture, mineralogy, and organic matter content.

crops; behind the average value per crop, the extreme values are presented. Nevertheless, Dierolf et al. (1999) present critical Al-saturation values that indicate similar differences in acid sensitivity. For soybean, maize, and groundnut, they found CAS values of 17%, 30%, and 40%, respectively.

Using the data from Wade et al. (1999), the relative yield increase is estimated when the pH increases from 4.7 to 5.2 due to liming. For the tolerant cassava, the yield increases from 93% to 98%, a 5% increase in comparison with the starting situation. For the less tolerant groundnut, the yield increases from 84% to 94%, a 12% increase; for the sensitive maize and soybean, the increase is from 60% to 92%, or an increase of 53%.

The data from Janssen (1999) and Wade et al. (1999) will be used to estimate the effect of liming. Three cases will be considered: tolerant crops, using potato and cassava as examples; sensitive crops, based on the data above considering soybean, maize, and wheat; and a relatively tolerant group. In the first case, the pH increase with half a unit, from 4.7 to 5.2, has been chosen because it leads to a yield increase in comparison with the starting situation of 15%. This is closer to the value for potatoes than for cassava because of the economic value of potatoes and the tendency of intensification of its production. For sensitive crops, a 50% increase will be used, which is derived from the rough average of two values from Germany and two from the tropics. For relatively tolerant crops, 35% is chosen; it is an average value for leguminous species with the exception of the sensitive soybean (groundnut, cowpea, and pigeon pea), derived from Wade et al. (1999).

These increases are lower than those expected on the basis of the correlation between the average pH and productivity values in Table 11 (64% in comparison with the productivity at pH 4.7, rising to pH 5.2; see above). However, in relation to this table, it has already been stressed that high productivity values are not only due to relatively high pH levels but also to the presence of highly fertile volcanic soils.

### ***VIII.1.3. Absolute Yield Increases by Liming***

The absolute yield increases due to liming can be estimated by combining Table 11 and average crop yields in Rwanda: 1.0 t/ha for cereals, 0.7 t/ha for beans, and 7.3 t/ha for tubers.

Average yields are those related to a productivity of 82% ( $= (Gisenyi + Butare)/2$ ). At a pH of 4.7, the productivity is 50% (see above), or the yields of cereals are  $1.0 \times 50/82 = 0.6$  t/ha; for beans,  $0.7 \times 50/82 = 0.4$  t/ha; and for tubers,  $7.3 \times 50/82 = 4.5$  t/ha. For extensive agriculture, without the use of fertilizer, average yield increases from doses of 2.31 t/ha of lime (standard  $\text{CaCO}_3$ ; pH increases from 4.7 to 5.2) are: for tolerant tubers, 15% of 4.5 t/ha = 0.67 t/ha; for intermediate tolerant beans, 35% of 0.4 t/ha = 0.14 t/ha; and for sensitive cereals, 50% of 0.6 t/ha = 0.3 t/ha.

For intensive agriculture, the estimation is more difficult, because the fertilizer effects on acid soils without liming are unknown. Figure 2 is not of direct use. It presents the accessibility for crops of soil nutrients; it presents, at most, the minimum level of accessibility of fertilizer nutrients. Soluble fertilizers are more accessible than soil nutrients; their average accessibility will depend on soil and weather conditions and the time, method, and frequency of fertilizer application. The efficiency of certain nutrients such as fertilizer-P will, however, be reduced at low pH; applied P will be fixed (bound with Al and Fe). This will particularly influence the fertilizer use efficiency of beans. Using Figure 2 and comparing the accessibility of P at pH 4.7 in comparison with pH 6.0, it has been estimated that only a quarter of the fertilizer-P can be used at pH 4.7. For the yield estimation of fertilized tubers, beans, and cereals at pH 4.7, the approach presented in Table 13 (Nzohabonayo et al., in prep.) will be used. They use the average profitable fertilizer formula for potatoes, beans, and maize in Rwanda,<sup>33</sup> derived from Kelly and Murekezi (2000), and the average low and high agronomic efficiency of the key nutrient (N for tubers and cereals and P for leguminous species such as beans). For the present objective, the low agronomic efficiency has been chosen.<sup>34</sup> 1 kg of N adds 150 kg of potatoes or 12.5 kg of cereal grain; 1 kg of P adds 22 kg of beans. However, in the last case, only one-quarter of fertilizer-P will be accessible. This approach leads to average yields at pH 4.7 with the use of fertilizers: for tubers of 12.0 t/ha; for beans of 0.7 t/ha; and for cereals of 1.3 t/ha. Average yield increases due to doses of 2.31 t/ha of lime (standard  $\text{CaCO}_3$ ; pH increases from 4.7 to 5.2) are: for tolerant tubers, 15% of 12.0 t/ha = 1.8 t/ha; for intermediate tolerant beans, 35% of 0.7 t/ha = 0.24 t/ha; and for sensitive cereals, 50% of 1.3 t/ha = 0.65 t/ha. The obtained

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<sup>33</sup>N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O = 50:50:20 for potatoes, 18:46:0 for beans, and 60:40:15 for cereals.

<sup>34</sup>It might be that the low agronomic efficiency is still too high. It is based on work in semiarid and subhumid regions of West Africa, where soil acidity is much rarer than in the CAGLR. If indeed the low efficiency is too high, the effect of liming will be more profitable than estimated in the present chapter.

estimations of yield increases for extensive and intensive agriculture are summarized in Table 14.

**Table 13. Doses of Fertilizers and Agronomic Effectiveness (AE) Considered for Two Levels of Fertilizer Application.**

Crop	N :P <sub>2</sub> O <sub>5</sub> :K <sub>2</sub> O (kg/ha)	AE <sup>a</sup>	
		Low <sup>b</sup>	High <sup>c</sup>
Potatoes	50 :50 :20	150	225
Beans	18 : 46 : 0	22	44
Maize	60 :40 :15	12.5	25
Paddy	55 :35 :15	12.5	25

a. Kg of the main product per kg of the key element (N in the case of potatoes and cereals, P<sub>2</sub>O<sub>5</sub> in the case of beans).

b. Cases of inexperienced producers in the beginning stage of using fertilizers.

c. Case of experienced producers in favorable conditions of production.

**Table 14. Yield Increase for Three Classes of Crops, With and Without the Use of Fertilizers, Due to the Application of 2.31 t/ha of CaCO<sub>3</sub>, Increasing the Soil pH From 4.7 to 5.2**

Crops	Yield Increase	
	Without Fertilizer	With Fertilizer
	(kg/ha)	
Tolerant tubers	670	1,800
Intermediate beans	140	240
Sensitive cereals	300	650

## VIII.2. Preliminary Cost:Benefit Estimates

### VIII.2.1. Costs of Liming

Price, quality, and transport of available agricultural lime must be taken into account to determine the costs of 2.31 t/ha of CaCO<sub>3</sub> in Rwanda. Three cases will be discussed, in view of the large differences in quality (V.2) and costs. Table 15 summarizes the information. The three cases have been given letters instead of names because of the lack of insight regarding quality variation. The table shows the extreme consequences: the lime requirement expressed in \$/ha differs more than a factor of 10 when comparing the cheapest and the most expensive lime. The degree of grinding (fineness factor [FF]) creates much more difference in quality than the CaCO<sub>3</sub> equivalency (degree of heating besides Ca content original material). However, transport costs

still have to be added. Producers close to the source of lime “A” have a real advantage. Using \$15/t per 100 km transport and using 100 km as the average distance between lime mines and producers, the average liming costs, depending on the source, are \$141 (A), \$352 (B), and \$997/ha (C). One has to conclude that application of lime with the qualities of “C” is not economical, while “B” is only more economical than “A” for farmers who are extremely close to the mine. Consequently, the costs of liming, depending on the distance between mines and farmers, vary between \$100 (close to mine of “A”) and \$320/ha ( $\leq 50$  km from mine of “B”). None of the available agricultural limes including “A” and “B” have enough quality to be used for a long time (V.2); the Mg content is too low. Rwanda should start exploiting its dolomite instead of using (exclusively) lime derived from travertine.

**Table 15. Comparison of Three Sources of Rwandan Agricultural Lime**

	Price <sup>a</sup>	CCE	FF	Required <sup>b</sup>	Costs <sup>c</sup>
	(\$/t)			(t/ha)	(\$/ha)
A	18	87	62	4.28	77
B	73	105	55	4.00	292
C	100	74	36	8.67	867

- a. 2006–2007 seasons; the prices in Burundi are still about 50% higher than the most expensive lime in Rwanda (amounts exploited extremely small).  
 b. The equivalent for 2.31 t of CaCO<sub>3</sub>, for changing soil pH from 4.7 to 5.2.  
 c. Only procurement costs, transport not included.

### ***VIII.2.2. Benefits of Liming***

Potatoes, beans, and maize will be used as examples for tolerant, moderately tolerant, and sensitive crops, respectively. The prices in 2006 were \$0.21, \$0.42, and \$0.29/kg, respectively. Combining the information in Table 14 with these prices leads to the brute benefits of liming for one season. The results are presented in Table 16. Liming appears to be more profitable in intensive rather than in extensive production systems if fertilizer use is profitable. The costs and benefits of using the latter are not covered here; they are discussed for the region by Nzohabonayo et al. (in prep.; see VIII.2.3 and Table 18).

Liming affects yields for more than one season. The period depends on factors such as soil type (light or heavy; badly or well buffered), the intensity of agriculture (intensity of fertilizer use; amounts of products exported from the field), its frequency (number of growing seasons per year), and agricultural practices (ISFM adoption). Data about these factors and the

required frequency of liming are badly needed (VI.4.3). Reports such as Beernaert's (1999) speak about a correction dose and a maintenance dose; others speak about liming every 2–3 years. The correction dose that is used here is a minimum dose, attempting to reach pH 5.2 and  $\leq 30\%$  Al saturation (VIII.1.2). The effect of correction will probably not be maintained for the average “inter-liming time”; benefits and value:cost ratio (VCR) values will be estimated on a correction dose every 2.5 years. The benefits and the VCR value to be derived will be presented for the entire average correction dose, which is the investment required to create chances for intensification in regions with acid soils. One may expect that the benefits will only be reached during the five production seasons when farmers respect the maintenance doses of lime. The economics of maintenance liming (per season based on about one-fifth of the correction doses) is another question that should be answered by making liming an additional production cost.

**Table 16. Brute Benefits of Liming for Three Types of Crops in Extensive (Without Fertilizer) and Intensive Agriculture (With Fertilizer) Per Season and for the Supposed Average Inter-Liming Time of 2.5 Years or of Five Seasons**

	Brute Benefits Per Season		Brute Benefits During 5 Seasons	
	Without Fertilizer	With Fertilizer	Without Fertilizer	With Fertilizer
	(\$/ha)		(\$/ha)	
Potatoes	141	378	705	1,890
Beans	59	101	295	505
Maize	87	188	435	940

### **VIII.2.3. VCR of Correction Liming**

Combining the results from the two preceding paragraphs makes it possible to calculate the VCR of liming. It is done for two extreme situations of costs: close to the source of lime “A” (liming costs \$100/ha) and far enough away from it that it is more beneficial to use source “B” (liming costs \$320/ha). The benefits that are used are for five seasons (Table 16). The results presented in Table 17 should be considered maximum values that will be reached when farmers respect maintenance liming, become experienced fertilizer users, and adopt ISFM.

**Table 17. The Value:Costs Ratio of Liming for Extensive and Intensive Forms of Agriculture on Two Extreme Distances From the Source of the Best Agricultural Lime**

	VCR Without Fertilizer Use		VCR With Fertilizer Use	
	Close to “A”	Too Far From “A” <sup>a</sup>	Close to “A”	Too Far From “A” <sup>a</sup>
Potatoes	7.0	2.0	19.0	6.0
Beans	3.0	1.0	5.0	1.5
Maize	4.5	1.5	9.5	3.0

a. Distance in which it becomes more beneficial to use lime “B.”

Using a VCR of  $\geq 2$  as under limit for farmers’ adoption, it appears that with the 2006 prices, liming is generally profitable when part of an entire package of intensification, including inorganic fertilizers. For extensive farming, it is only profitable close to the mine for lime “A,” but liming is not recommended under such conditions because increased soil depletion and degradation is the final effect. This conclusion is reflected by the present use of lime in Rwanda, which is almost exclusively linked to externally supported projects for intensification; only rarely, farmers buy lime themselves. What farmer can afford to invest \$100–\$320/ha for raising the soil pH to 5.2, while his/her benefits will be below those in Table 16 for several years because of lack of experience with fertilizers and ISFM? Therefore, the question to be answered is: what reasons would prompt governments and donors to make the use of lime more profitable by subsidizing it? The answer involves the profitability of the required<sup>35</sup> and planned agricultural intensification. Without liming, the VCR of fertilizer use is and will stay relatively low in two-thirds of the country, the regions with serious or moderate soil acidity (III.3). Without liming, the situation will be aggravated through intensification; several fertilizers (as well as the increased export of crops from fields) cause decreases in pH (VII.1.2).

Nzohabonayo et al. (in prep.) present an indication of the profitability of fertilizer use and distinguish between efficient and inefficient fertilizer use. They link the inefficient use to low quality soils and/or inexperienced farmers. The transfer to efficient fertilizer use can be made by investments in soils through ISFM and by obtaining experience. Inefficient fertilizer use was at the basis of the estimation of the liming effect in intensive agriculture in VIII.1.3.

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<sup>35</sup>Rwanda has an extreme negative soil nutrient balance, caused by overexploitation linked to overpopulation and to an extremely limited use of inorganic fertilizers until recently (Breman et al., 2008).

**Table 18. The Profitability of Fertilizer Use in Rwanda at Two Levels of Fertilizer Use Efficiency**

	VCR Fertilizer Use <sup>a</sup>	
	Low Efficiency <sup>b</sup>	High Efficiency <sup>c</sup>
Potatoes	9.2	13.8
Maize	1.4	2.8
Paddy	2.5	5.0
Beans	6.1	12.2

a. Based on Nzohabonayo et al. (in prep.), who used prices of the 2007 “A” season.

b. Observed on low quality soils and/or with inexperienced farmers.

c. Observed on good quality soils and with experienced farmers, using ISFM.

Table 18 shows the extreme need for farmers and governments in the CAGLR to invest in soil improvement, using inorganic fertilizers and liming in an ISFM context (VII.3). Without it, agricultural intensification is much less profitable; the VCR of using inorganic fertilizers will be equal (or even lower—see above and Footnote 34) to those of low fertilizer use efficiency in Table 18. Farmers are not able to make the investments themselves; the VCR of liming is too low for inexperienced farmers on poor soils (Table 17). Governments and/or donors should make lime cheap enough to interest farmers in its use. Once the farmers are experienced and have adopted ISFM, they will be able to take care of maintenance liming. “Making lime cheap enough” should not be considered a subsidy but an investment, enabling farmers to raise agricultural productivity to another level. It concerns an investment that is more profitable and that can reach many more farmers than investments in irrigation; the investment is even more profitable when grafted on the promotion and introduction of ISFM (Breman et al., 2003). The large-scale use of lime that will be triggered will also decrease the lime costs (Beernaert, 1999).

### VIII.3. Conclusion

Controlling soil acidity by liming is profitable as a component of agricultural intensification that also includes inorganic fertilizer use and ISFM. In spite of the fact that acid soils dominate in CAGLR, general recommendations of lime use by farmers at present prices should be avoided:<sup>36</sup>

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<sup>36</sup>This is even the case for Rwanda, which is presently the country with the most favorable agricultural policy environment and the most profitable inorganic fertilizer use.

- Most agricultural lime is low quality and expensive
- Present sources of lime used in Rwanda are low in Mg. Dolomite is not being exploited in Rwanda. In Burundi lime (including dolomite) use is limited to project-funded use.
- The required investment is high in comparison with the average farmers' income.
- Liming without inorganic fertilizer will further deplete and degrade soils.
- Liming combined with the use of inorganic fertilizers in an ISFM context is not easily profitable from the start; farmers must become acquainted with the use of fertilizers and lime and adopt ISFM.

Governments and donors can improve the situation considerably by ensuring that high quality lime is available at low prices during a transition period of agricultural intensification. As long as this is not yet a reality, recommendations of using lime should be limited to the surroundings of sources of good, reasonably priced lime. Such recommendations have to be as specific as possible, taking soils, crops, and climate as well as the financial position of farmers into account.

## **IX. Practical Recommendations for Governments and Donors, Farmers, and Their Advisers**

### **IX.1. Recommendations for Governments and Donors**

1. Governments of the CAGLR and donors should consider investments in soils, enabling farmers to intensify agriculture.
2. Investments concerned should focus on the improved availability and accessibility of organic matter (OM), lime, and phosphate rock.
3. Investments should be accompanied by a national and regional policy supporting agriculture and by the promotion of integrated soil fertility management.
4. Governments and donors should compare the economics of investments in irrigation with those in OM management and liming. The latter makes crops more drought resistant, while the investment costs per hectare are low and the profitability is high.
5. Governments have to develop a lime quality control system, taking three factors into account:
  - The  $\text{CaCO}_3$  equivalency (e.g.,  $\geq 80\%$ ), depending on the Ca content of the starting material and the intensity and duration of heating.

- The fineness factor (e.g.,  $\geq 70\%$ ), depending on the intensity and duration of grinding.
  - The Mg content (dolomite instead of travertine should be used as starting material).
  - The moisture content (e.g.,  $< 5\%$ ).
6. Governments should promote and support a) research regarding liming and b) the development of a system to determine soil acidity and Al toxicity (as cheap as possible). Key subjects for research should concern:
- The development of recommendations in relation to soil, climate, crop, and cultivar.
  - Other opportunities to optimize the economics of liming.
  - The frequency of liming in relation to soil, crop, and climate.
7. Governments should promote and support credit facilities for soil improvement through liming; the investment costs are high in view of farmers' income, while the benefits become available over a series of seasons.

## **IX.2. Recommendations for Farmers and Their Advisers**

1. Under the present conditions, the use of lime on acid soils is only recommended for certain crops (those with highly profitable intensification, such as potatoes) in the neighborhood of mines from which high quality lime is produced (high CCE and high FF) and sold for a reasonable price ( $< \$0.20/\text{kg}$ ).
2. Through liming, farmers should not only view decreased Al toxicity for their crops, but also increased drought resistance.
3. Farmers should insist that sellers of lime mention and guarantee the key quality characteristics: CCE, FF, Mg concentration, and moisture content.
4. When travertine or other sources with a low Mg content are at the basis of agricultural lime, liming should be limited to one or two serious investments. In time, farmers should look for agricultural lime with a dolomite basis for maintenance liming.
5. The technology of liming:
  - Liming should be combined with inorganic fertilizer use; both should be components of the ISFM approach.
  - Liming should be done well before planting, ensuring that the lime is homogeneously distributed in the topsoil (first 20–30 cm). Local concentrations of lime should be avoided to avoid higher erodibility of soils.
6. For other farmers on acid soils, who do not live close to a mine, the production of tolerant crops in an ISFM context is recommended. Products to be used are wood ash, prunings of

shrubs and trees, and manure and compost; whenever possible, they should be based on products from outside the farm.

Farmers, extension workers, agronomists, and scientists should make a combined effort to recognize the typical characteristics of regions with acid soils in relation to soil x climate combinations, enabling them to transfer and generalize results obtained on certain fields with a (limited) number of farmers. Farmers' behavior and practices regarding crop choices and their use have to be understood, and weeds should be recognized in a soil acidity context. Crops and cultivars in the CAGLR should be classified in relation to their Al-toxicity tolerance. Lime requirement should be based on exchangeable Al and not pH *per se*. The effects of lime are dissipated more rapidly in tropical regions, rather than in temperate regions. Thus, it is logical to make more frequent and lighter applications in the tropics.

**Appendix A. Scope of Work and Scopes of Work for Economic Analysis**

**CATALIST PROJECT**  
A Regional Project to Intensify Agricultural Productivity  
and Improve Product Marketing

*Terms of Reference*

**Soil Scientist**

**Background**

The CATALIST Project (*Catalyze Accelerated Agricultural Intensification for Social and Environmental Stability*) is a 5-year regional activity funded by the Dutch Government and implemented by IFDC, an International Center for Soil Fertility and Agricultural Development, headquartered in the United States. The project began in October 2006 and will run through September 2011. Field headquarters are located in Kigali, Rwanda. In addition to Rwanda, the project will work in Burundi, eastern Democratic Republic of Congo (DRC), southern Uganda, and western Tanzania, where country offices are or will be established.

CATALIST's overarching goal is to contribute to regional peace and security through intensified, sustainable agricultural production and improved product marketing. The linkage between peace and productivity highlights a core belief that a *sine qua non* for regional stability is increased productivity to improve food security and rural incomes.

CATALIST will achieve its goals of sustainable agricultural productivity and improved product marketing by focusing resources on the following objectives:

- Supporting agricultural product chain development.
- Promoting an optimum and integrated use of external inputs, while insuring environmental and economic sustainability.
- Improving the efficiency and effectiveness of agricultural input markets; creating expanded marketing opportunities for agricultural products.
- Improving rural infrastructure that can directly contribute to increased productivity and marketing; this objective is implemented through a subcontract with Helpage, a regional NGO specializing in rural public works in support of responsible environmental stewardship.
- Contributing to the creation and deepening of enabling national and regional policy environments that promote intensified agricultural production and improved marketing.

CATALIST works with a wide spectrum of partners that include producer organizations, private sector operators involved in all stages of the farm-to-market continuum, industry associations, government policymakers, research and extension services, and regional organizations.

CATALIST's subsectoral approach focuses on staple crops rather than high-value commodities as intensification of staple production holds the greatest potential impact on poverty reduction and increased producer revenue.

The objective of this proposed task is to develop a CATALIST approach to address acid soils and possible acidification of soils resulting from agricultural intensification in the project focus areas in Burundi, DRC, Rwanda, western Tanzania, and southern Uganda.

## **General Activities**

The consultant will prepare a report defining the CATALIST approach to addressing amelioration of acid soils and preventing increased acidification of soils as agricultural production is intensified. Recommendations are to be centered on the promotion and use of lime. Identification of key information should be collected for the entire CATALIST region: Burundi, eastern DRC (North and South Kivu Province), Rwanda, western Tanzania (Kagera and Kigoma), and southern Uganda (Bushenyi, Kabale, Kisoro, Mbarara, Ntungamo, and Rukengeri). However, efforts regarding specific recommendations should focus on Rwanda. These recommendations should, to the extent possible, take into account soil, climate, crops, production systems, and the socioeconomic context. Special attention should be given to acidity as a bottleneck for economic agricultural intensification of the priority crops (potato, maize, and wheat) and the transversal livestock value chain in Rwanda. The report will also identify major organizations that could be involved in promotion and implementation of the recommendations.

## **Specific Tasks**

1. Conduct literature searches for the identification of regions within the CATALIST intervention zone for which acidity is or can easily become a problem hindering agricultural intensification. Information gathered in the literature review and during the consultancy will be used by IFDC scientists and geographic information specialists to develop a soil/climate/agricultural zone map for the entire CATALIST project region.
2. Collect and interpret data in Rwanda to answer when, where, and for which crops liming materials or other soil amendments are required to enable external nutrient inputs to increase yields.
3. Make general recommendations concerning the use of fertilizers and identify fertilizer formulas that decrease the risk of soil acidification on the majority of Rwandan soils.
4. Make general recommendations concerning application of lime and other soil amendments at rates necessary to significantly improve the feasibility of using fertilizers to increase yields. Deliverables from this consultancy will be available to IFDC economists for assessing the economic feasibility of using lime or other soil amendments.
5. Estimate the cost-benefit analysis of investment in liming as a soil amendment. Required information will include :
  - a. Quantity of lime needed per hectare by crops and area:
    1. One-time capital investment.
    2. Annual application, if needed.
    3. How often capital investment should be repeated, with or without annual application.
  - b. Benefits of liming by crop and area:
    1. Incremental yield over time (for how many years) from one-time capital investment.
    2. Incremental yield from annual application.
  - c. Other secondary benefits (quantifiable) of lime, if any.
  - d. Synergistic benefits of lime: Incremental crop yields from fertilizer use with and without lime application by crop and area.

Note: If different types of lime are recommended, these parameters should be estimated for each.

6. Prepare a report presenting results that can be used for training events to promote liming and other appropriate soil amendments to increase the pH of acid soils.

### **Estimated Level of Effort**

The estimated level of effort for this assignment is 12 working days (6-day work week), plus 3 travel days. A maximum total of 18 days has been reserved. The consultant should plan to arrive in Rwanda on or about August 1. Prior to departure, the consultant will debrief the CATALIST staff. The consultant will submit the final report by August 30.

### **Reporting**

The consultant will report to the Chief of Party or his designated representative.

### **Economic Analysis of Liming/Other Soil Amendments**

The consultant will estimate the cost-benefit analysis of investment in liming as a soil amendment.

#### **Soil Scientist**

The soil fertility specialist will provide the following background information for this analysis.

1. Quantity of lime needed per hectare by crops and area:
  - a. One-time capital investment.
  - b. Annual application, if needed.
  - c. How often capital investment should be repeated, with or without annual application.
2. Benefits of liming by crop and area:
  - a. Incremental yield over time (for how many years) from one-time capital investment.
  - b. Incremental yield from annual application.
3. Other secondary benefits (quantifiable) of lime, if any.
4. Synergistic benefits of lime: Incremental crop yields from fertilizer use with and without lime application by crop and area.

Note: If different types of lime are recommended, these parameters should be estimated for each.

#### **Economist**

1. The consultant will collect the following information for economic analysis.
2. Farm-level cost of lime per ton (delivered cost).
3. Value of stream of incremental benefits: incremental yield x price for different crops.
4. Value of stream of incremental benefits: incremental crop residue x price for different crops.
5. Estimate present discounted value of costs and benefits to estimate benefit-cost ratio.
6. Estimate internal rate of return of investment in liming and soil amendments.
7. Prepare a brief report on the cost-benefit analysis of liming.

## **Appendix B. Maps**

The Entire CATALIST Project

Areal Extent

Soil pH

Major Soil Types

Burundi

Soil pH

Crops

Democratic Republic of Congo – North Kivu and South Kivu Provinces

Soil pH

Rwanda

Soil pH

Agroclimatic Regions

Agroecological Zones

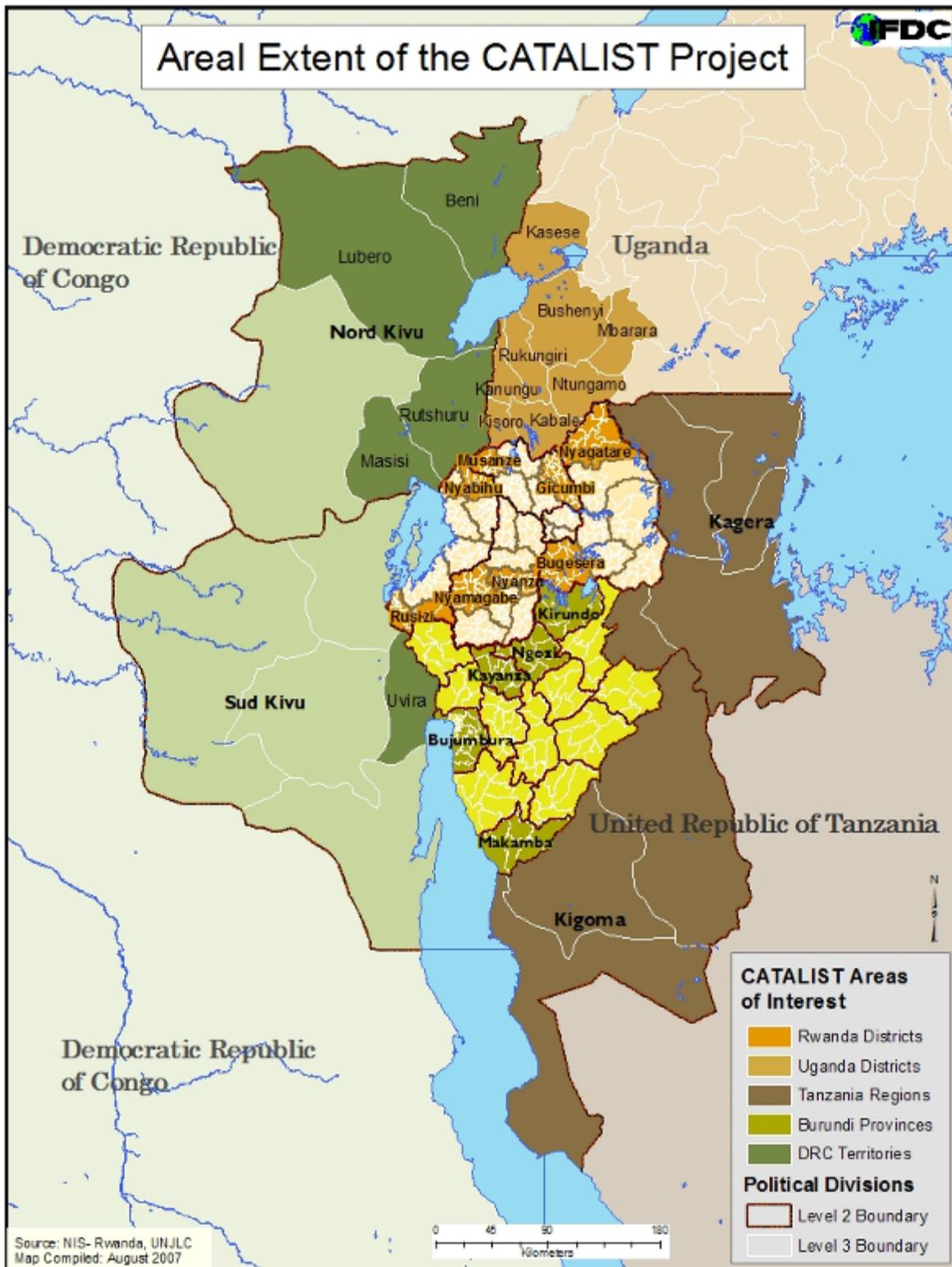
Classification of Agrobioclimatic Regions

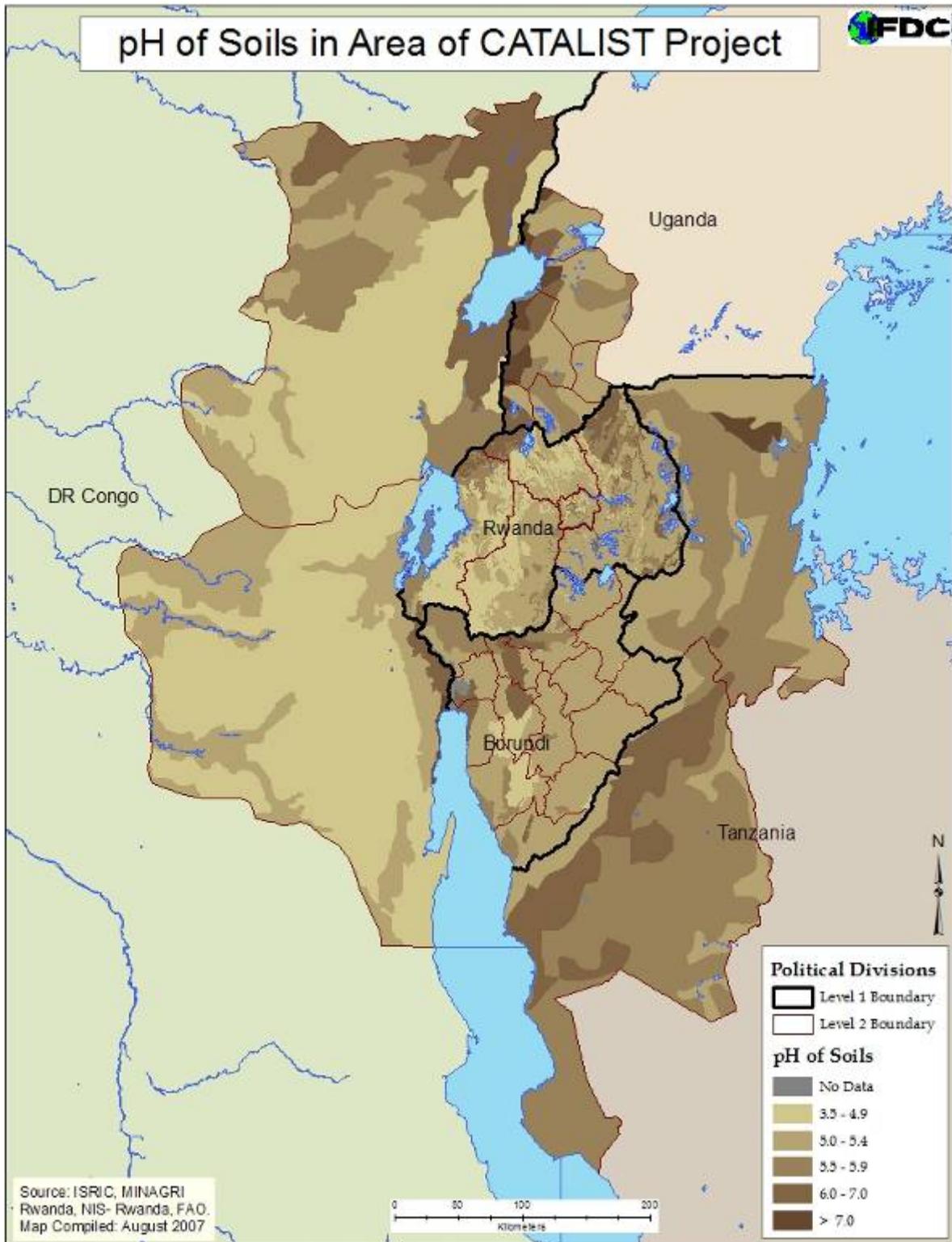
Tanzania – Akagera and Kigoma Provinces

Soil pH

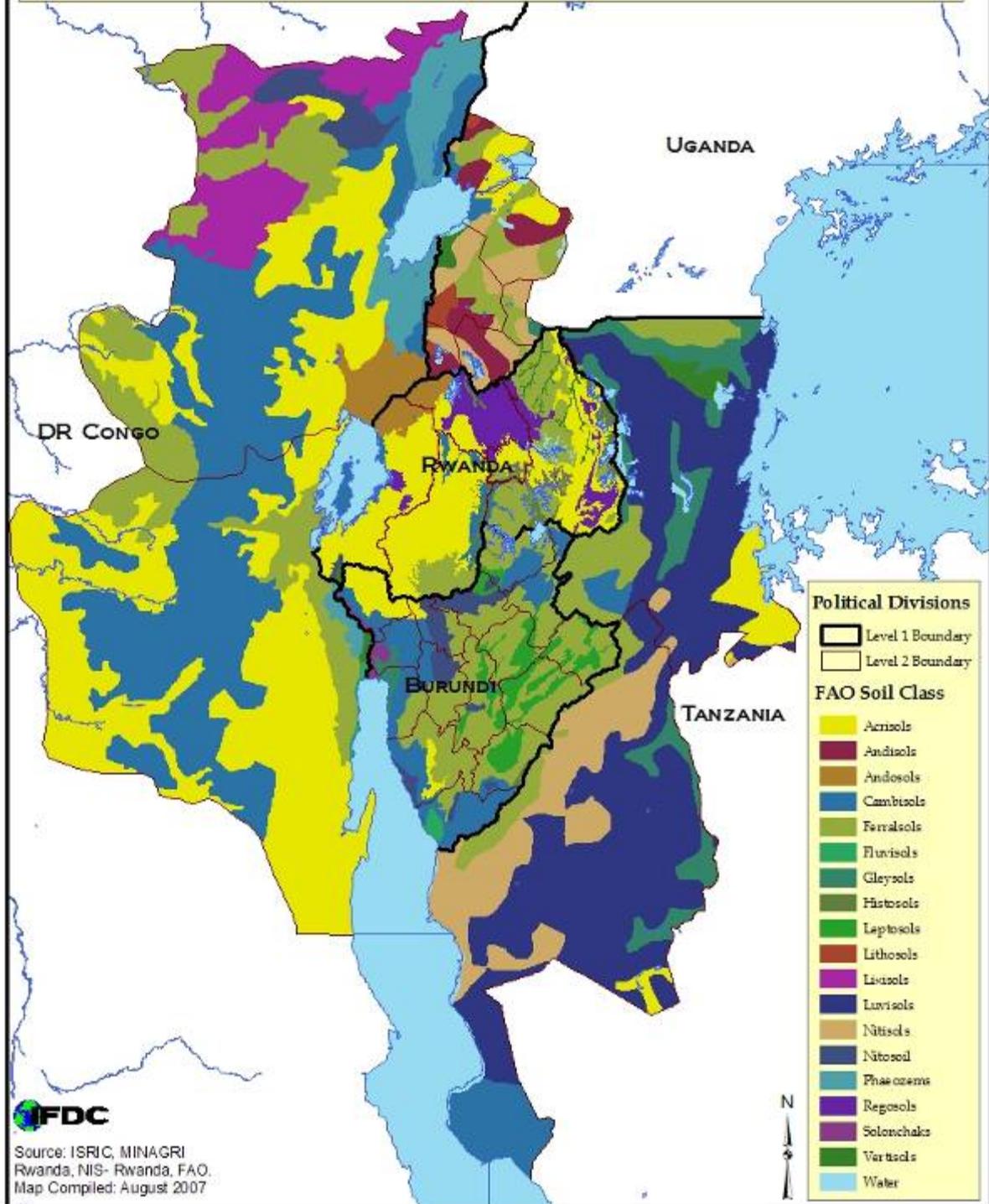
Uganda – Bushenyi, Kabale, Kasese, Kisoro, Ntungamo, and Rukungiri Districts

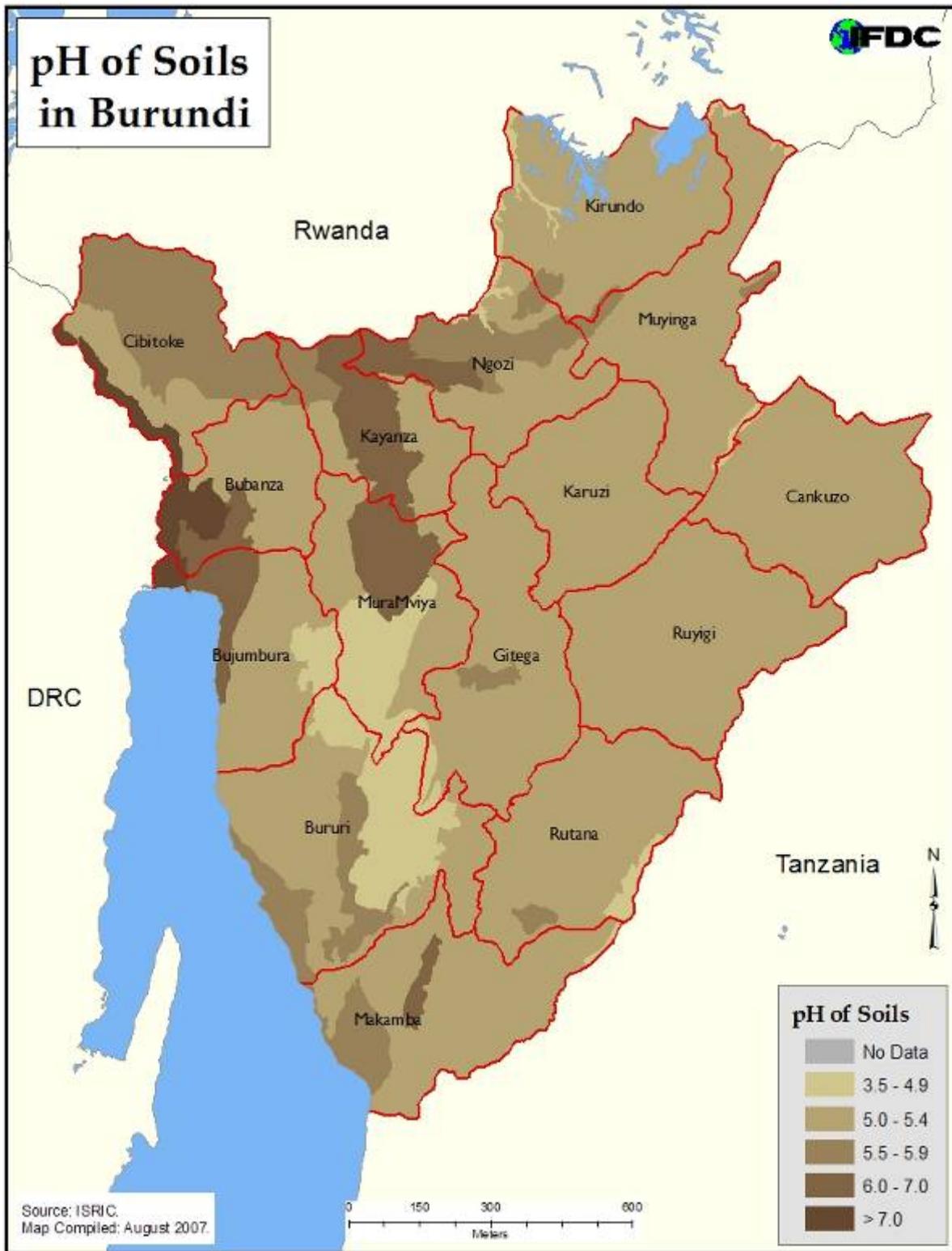
Soil pH

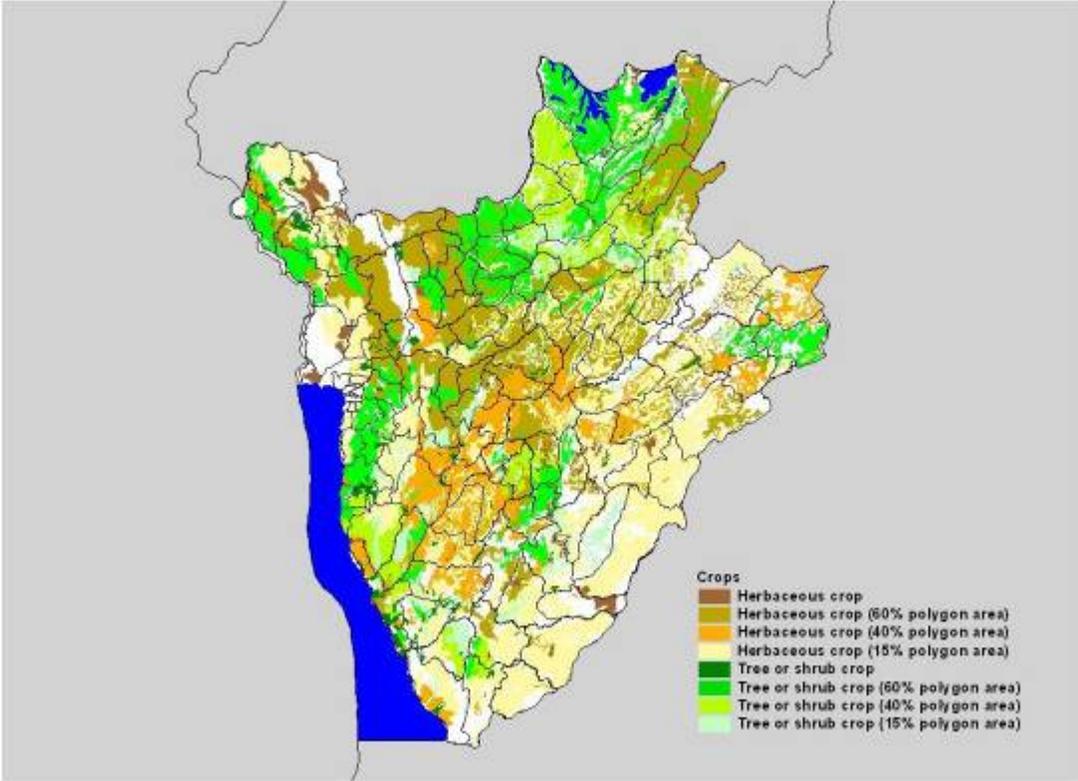




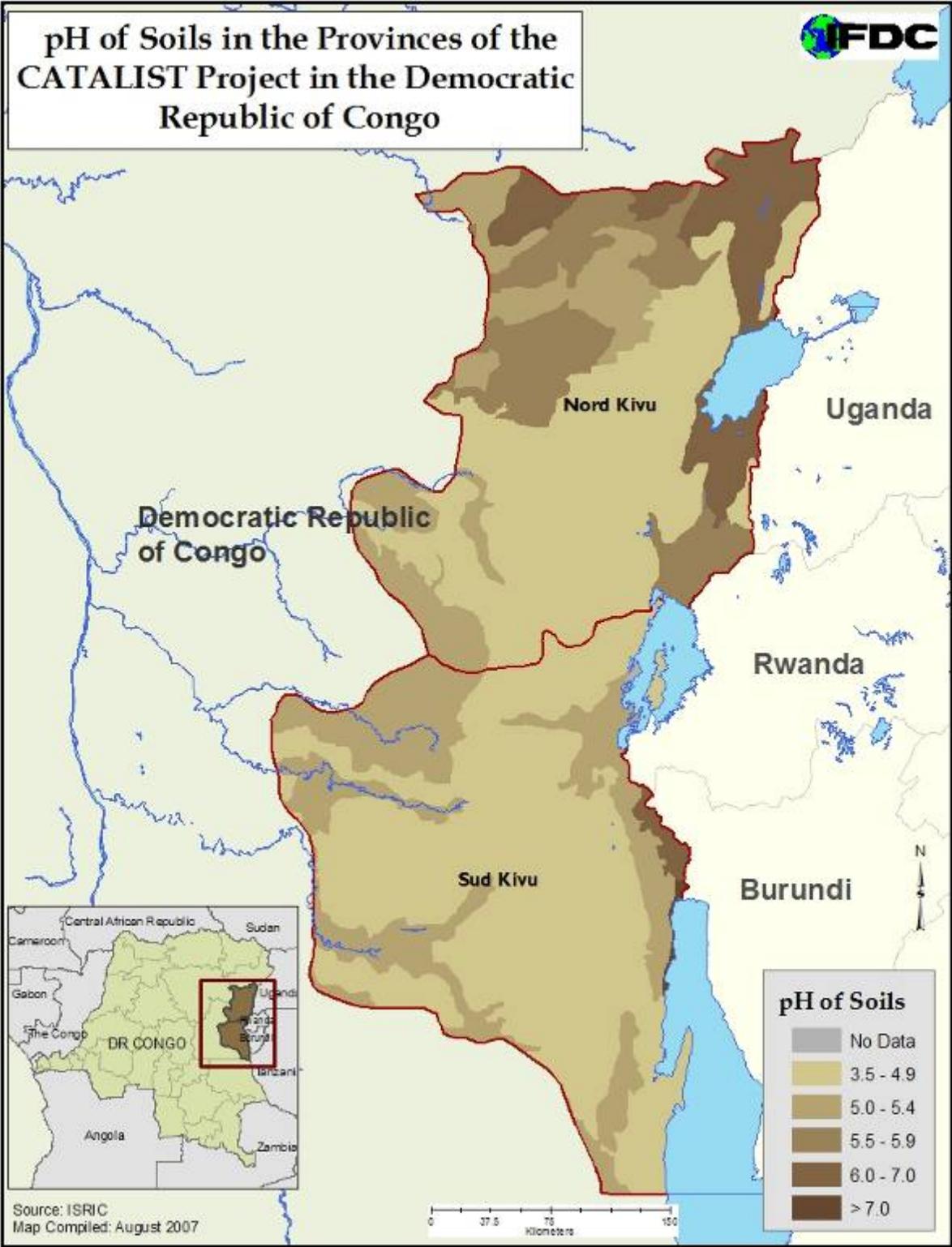
## Major Soil Types in the Area of the CATALIST Project

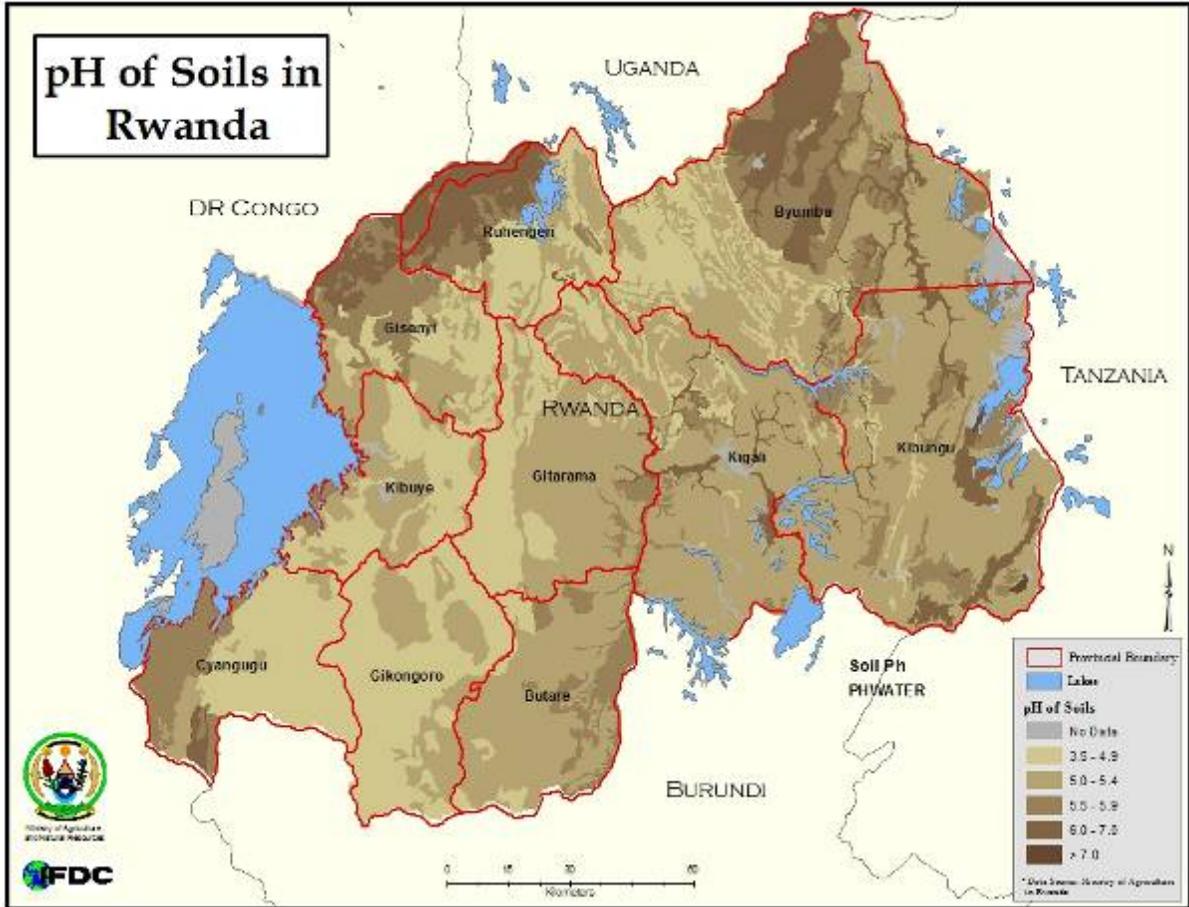


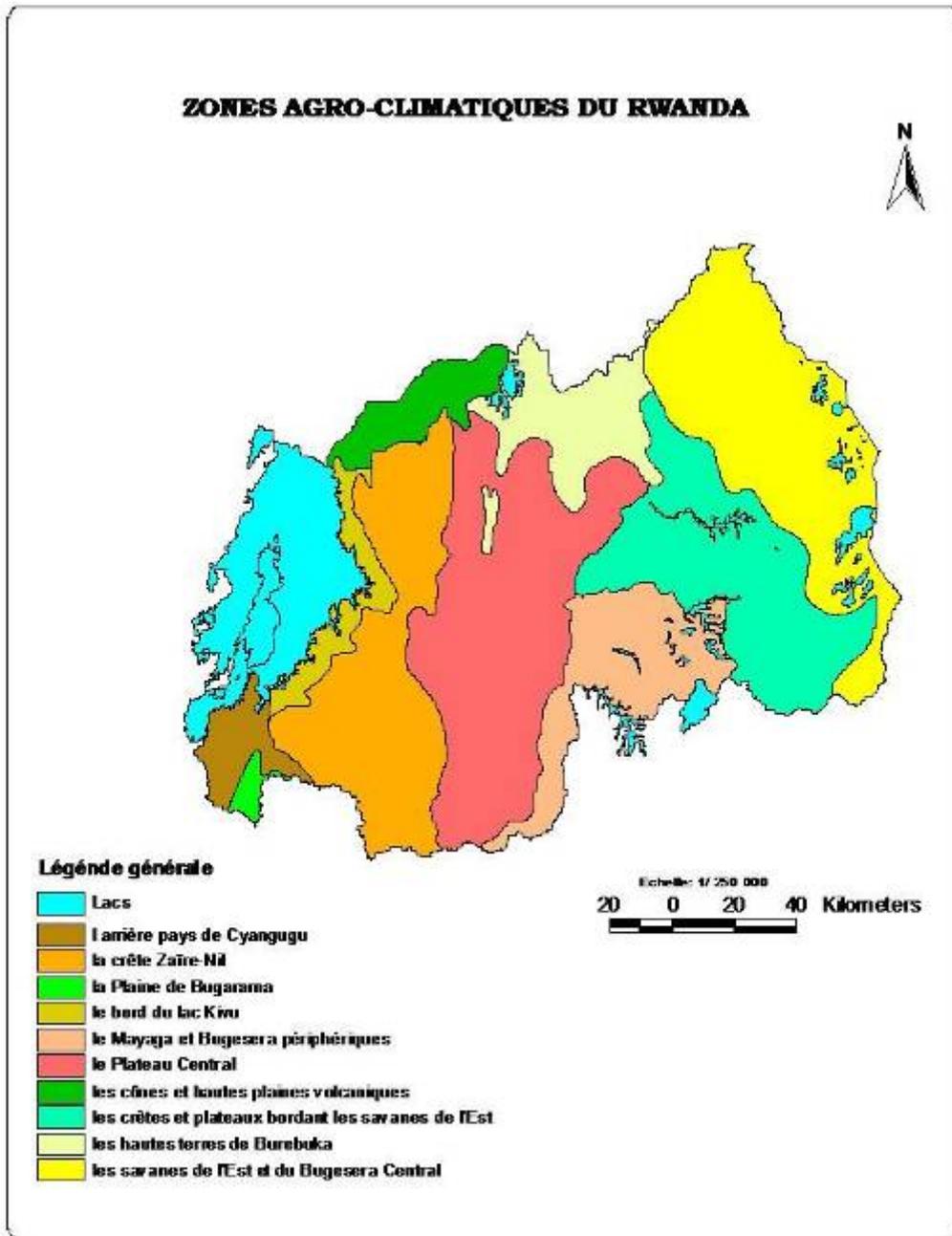




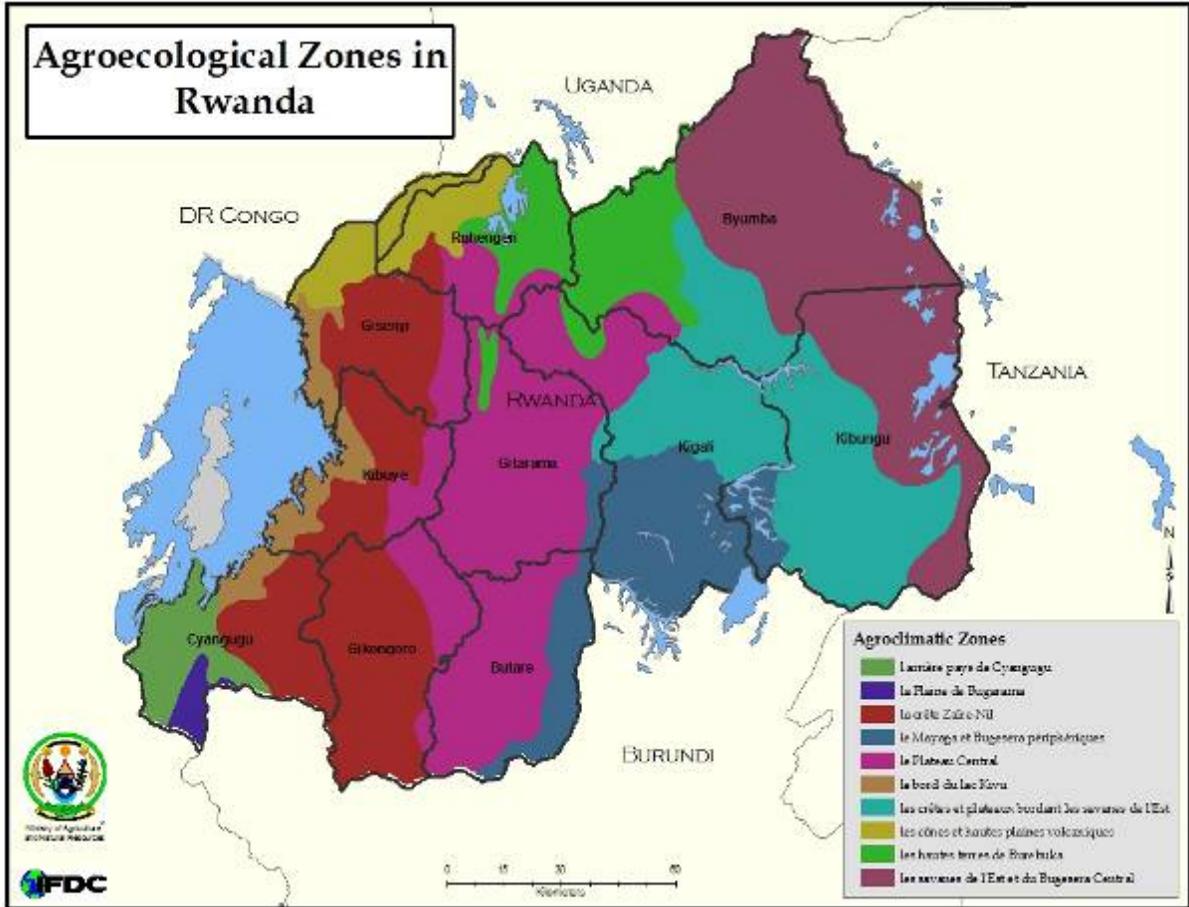
**Burundi – Crops**



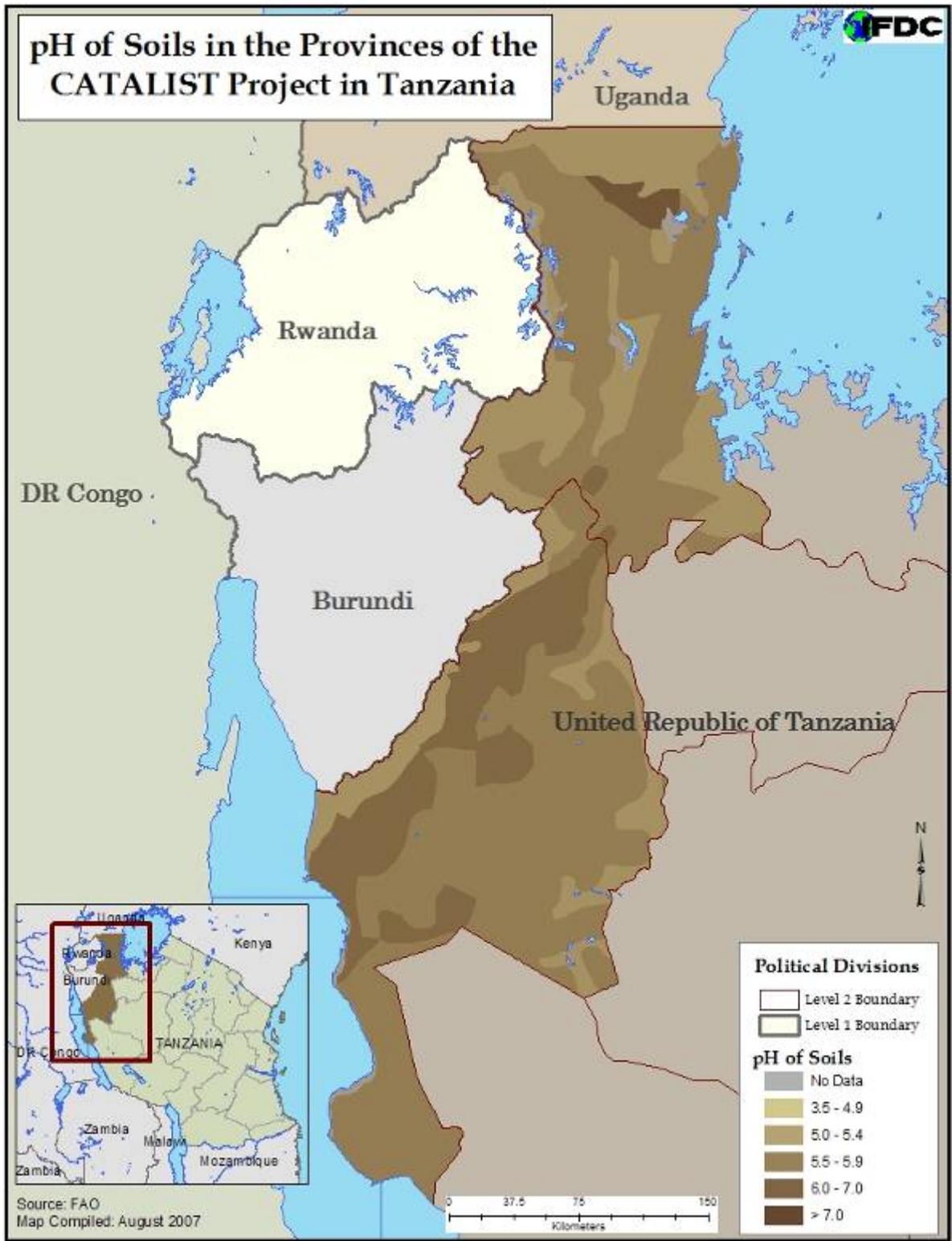




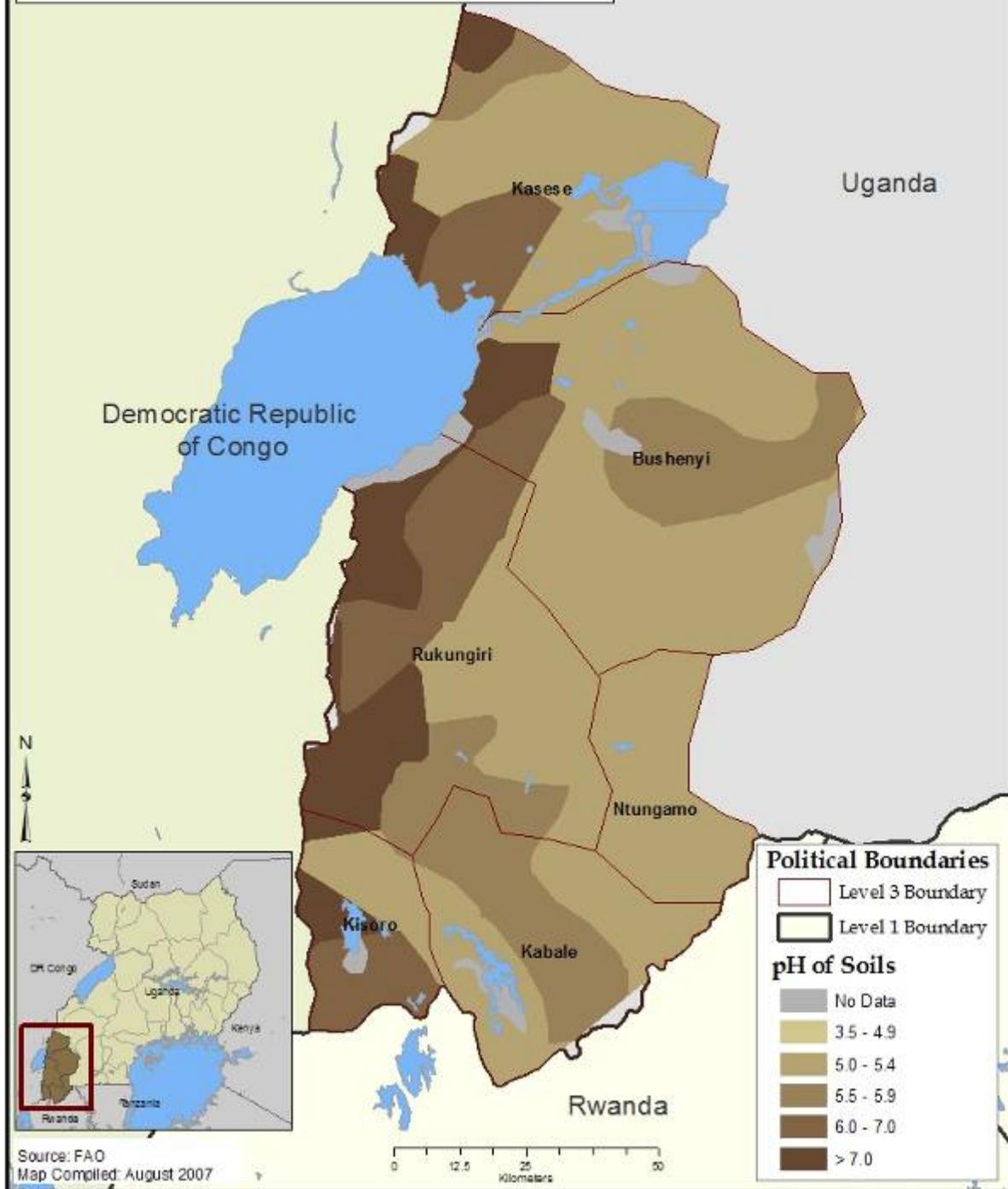
**Agroclimatic Regions of Rwanda**







# pH of Soils in the Districts of the CATALIST Project in Uganda



**Appendix C. Tables Comparing Physical and Chemical Characteristics  
of Rwandan Lime and Travertine Samples and Dolomite Samples  
Obtained in 2007 and 2008**

**Table C-1. Analysis of Rwandan Lime and Travertine Samples and Dolomite Samples Obtained in 2007 and 2008—Sorted by Sample No.**

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(% )		(% )				(% )		(% )		(%)	(ppm)	(ppm)	(ppm)
1	Lime—No. 1 Quality	116		0.5		96.6		46.3		0.50		0.036	9	0	12
2	Lime—No. 2 Quality	120		0.5		81.5		47.6		0.46		0.044	51	1	23
3	Lime—No. 3 Quality	73.5		1.0		35.7		28.4		1.00		0.070	26	0	38
4	Travertine—for agricultural use	80.0		1.1		58.1		31.8		0.30		0.087	694	1	10
5	Lime	97.6		3.4		66.5		37.4		0.76		0.046	367	3	6
6	Lime	100		1.4		49.1		37.6		1.70		0.021	447	0	9
7	Lime—for agricultural use	82.8	74.8	18.6	18.8	61.9	52.7	31.9	29.1	0.62	1.32	0.095	11	0	12
8	Lime—used for construction	96.3	103	5.6	3.2	66.2	71.2	37.4	40.4	0.93	0.64	0.080	6	0	14
9	Travertine—for agricultural use	84.0	80.8	32.5	20.4	43.5	45.8	31.4	32.2	0.91	1.16	0.095	678	0	14
10a	Lime—for agricultural use	90.6	85.2	12.0	4.6	61.7	58.2	36.1	34.0	0.89	1.08	0.111	33	0	17
10b	Lime—used for construction		83.1		7.8		55.8		34.1		1.02				
11a	Travertine—for agricultural use	74.1	73.8	15.1	11.6	57.1	44.9	29.3	28.7	0.52	1.22	0.070	523	0	20
11b	Travertine—for agricultural use		79.8		7.2		45.2		30.7		1.13				
12	Lime—for water purification and industrial uses	126	120	0.5	0.8	97.7	97.0	50.9	47.6	0.48	0.43	0.035	554	5	19
13	Lime—used for construction	115	122	1.7	0.7	88.8	93.0	46.2	49.2	0.44	0.39	0.053	54	2	20
14	Lime—for agricultural use	91.3	104	1.9	0.6	66.5	65.4	36.4	40.6	0.31	0.34	0.092	582	8	25
15	Travertine—for agricultural use	87.6	87.1	8.6	5.5	57.2	54.6	34.8	34.4	0.33	0.25	0.048	1,070	0	8
16	Travertine—for agricultural use	59.7	81.0	6.9	15.5	62.6	45	24.3	31.6	0.19	0.22	0.080	677	0	8
17	Travertine—for agricultural use	79.0	73.8	3.2	1.8	67.0	52	31.5	34.7	0.21	0.23	0.067	1,800	0	10
18	Lime—for water purification and industrial uses	120	127	1.7	1.8	86.7	96.7	42.2	41.6	2.85	2.57	0.017	27	0	12
19	Lime—used for construction	121	121	0.7	3.9	88.1	81.2	42.7	41.7	2.50	2.90	0.011	280	6	10
20	Lime—for agricultural use	110	116	7.5	6.2	60.9	54.6	40.0	41.1	2.50	2.85	0.019	275	3	16
21a	Travertine—for agricultural use	91.5	96.6	6.6	0.2	63.7	35.4	33.6	36.7	1.58	1.22	0.006	543	0	11
21b	Travertine—for agricultural use		92.8		0.7		39.6		34.1		1.74				
21c	Travertine—for agricultural use		94.6		0.5		28.4		35.5		2.27				
22	Lime—for water purification and industrial uses	125	120	10.5	9.1	67.7	80.6	45.5	43.2	2.32	2.45	0.003	16	0	6
23	Lime—used for construction	117	118	0.6	12.9	81.3	72.9	42.6	42.8	2.31	2.45	0.022	192	1	15
24	Lime—for agricultural use	97.5	102	0.3	2.7	28.4	55.1	35.3	37.4	1.80	2.05	0.021	342	0	8
25	Travertine—for agricultural use	96.2	91.9	1.1	6.7	44.5	51.3	35.5	34.8	1.84	1.79	0.023	553	0	10
26	Travertine—for agricultural use		93.7		1.0		35.4		35.1		1.74				
Bur-1	Ground Dolomite—for agricultural use		102		0.5		64		31.0		11.6				

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(%)		(%)				(%)		(%)					
Bur-2	Unground Dolomite Rock A—for agricultural use (after grinding)		102		0.6		NA		19.9		12.0				
Bur-3	Unground Dolomite Rock B—for agricultural use (after grinding)		102		0.3		NA		21.7		12.2				
QAQC	Standard for determination of Calcium Carbonate Equivalent (CCE)	100.3		0.0		99.4			39.8		0.00				

Note: The samples were gently boiled in 50 mL of 0.5 N HCl, cooled, and titrated with 0.25 N NaOH to determine CCE. The samples were acidified with 1 mL of 0.5 N HCl, filtered, and diluted to 250 mL.

The Ca, Mg, Fe, Mn, Cu, and Zn were determined by ICP-OES (results are on a dry weight basis).

**Table C-2. Analysis of Rwandan Lime and Travertine Samples and Dolomite Samples Obtained in 2007 and 2008—  
Sorted by Average Calcium Carbonate Equivalent (CCE)**

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(% )		(% )				(% )		(% )		(%)	(ppm)	(ppm)	(ppm)
18	Lime	120	127	1.7	1.8	86.7	96.7	42.2	41.6	2.85	2.57	0.017	27	0	12
12	Lime	126	120	0.5	0.8	97.7	97.0	50.9	47.6	0.48	0.43	0.035	554	5	19
22	Lime	125	120	10.5	9.1	67.7	80.6	45.5	43.2	2.32	2.45	0.003	16	0	6
19	Lime	121	121	0.7	3.9	88.1	81.2	42.7	41.7	2.50	2.90	0.011	280	6	10
2	Lime	120		0.5		81.5		47.6		0.46		0.044	51	1	23
13	Lime	115	122	1.7	0.7	88.8	93.0	46.2	49.2	0.44	0.39	0.053	54	2	20
23	Lime	117	118	0.6	12.9	81.3	72.9	42.6	42.8	2.31	2.45	0.022	192	1	15
1	Lime	116		0.5		96.6		46.3		0.50		0.036	9	0	12
20	Lime	110	116	7.5	6.2	60.9	54.6	40.0	41.1	2.50	2.85	0.019	275	3	16
Bur-1	Ground Dolomite		102		0.5		64		31.0		11.6				
Bur-2	Unground Dolomite Rock A		102		0.6		NA		19.9		12.0				
Bur-3	Unground Dolomite Rock B		102		0.3		NA		21.7		12.2				
6	Lime	100		1.4		49.1		37.6		1.70		0.021	447	0	9
24	Lime	97.5	102	0.3	2.7	28.4	55.1	35.3	37.4	1.80	2.05	0.021	342	0	8
8	Lime	96.3	103	5.6	3.2	66.2	71.2	37.4	40.4	0.93	0.64	0.080	6	0	14
14	Lime	91.3	104	1.9	0.6	66.5	65.4	36.4	40.6	0.31	0.34	0.092	582	8	25
5	Lime	97.6		3.4		66.5		37.4		0.76		0.046	367	3	6
21c	Travertine		94.6		0.5		28.4		35.5		2.27				
21a	Travertine	91.5	96.6	6.6	0.2	63.7	35.4	33.6	36.7	1.58	1.22	0.006	543	0	11
25	Travertine	96.2	91.9	1.1	6.7	44.5	51.3	35.5	34.8	1.84	1.79	0.023	553	0	10
26	Travertine		93.7		1.0		35.4		35.1		1.74				
21b	Travertine		92.8		0.7		39.6		34.1		1.74				
10	Lime	90.6	85.2	12.0	4.6	61.7	58.2	36.1	34.0	0.89	1.08	0.111	33	0	17
15	Travertine	87.6	87.1	8.6	5.5	57.2	54.6	34.8	34.4	0.33	0.25	0.048	1,070	0	8
10b	Lime		83.1		7.8		55.8		34.1		1.02				
9	Travertine	84.0	80.8	32.5	20.4	43.5	45.8	31.4	32.2	0.91	1.16	0.095	678	0	14
4	Travertine	80.0		1.1		58.1		31.8		0.30		0.087	694	1	10
11b	Travertine		79.8		7.2		45.2		30.7		1.13				
7	Lime	82.8	74.8	18.6	18.8	61.9	52.7	31.9	29.1	0.62	1.32	0.095	11	0	12
17	Travertine	79.0	73.8	3.2	1.8	67.0	52	31.5	34.7	0.21	0.23	0.067	1,800	0	10
11a	Travertine	74.1	73.8	15.1	11.6	57.1	44.9	29.3	28.7	0.52	1.22	0.070	523	0	20

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(%)		(%)				(%)		(%)					
3	Lime	73.5		1.0		35.7		28.4		1.00		0.070	26	0	38
16	Travertine	59.7	81.0	6.9	15.5	62.6	45	24.3	31.6	0.19	0.22	0.080	677	0	8
QAQC	Standard for determination of Calcium Carbonate Equivalent (CCE)	100.3		0.0		99.4			39.8		0.00				

Note: The samples were gently boiled in 50 mL of 0.5 N HCl, cooled, and titrated with 0.25 N NaOH to determine CCE. The samples were acidified with 1 mL of 0.5 N HCl, filtered, and diluted to 250 mL.

The Ca, Mg, Fe, Mn, Cu, and Zn were determined by ICP-OES (results are on a dry weight basis).

**Table C-3. Analysis of Rwandan Lime and Travertine Samples and Dolomite Samples Obtained in 2007 and 2008—Sorted by Average Moisture Content**

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(%)		(%)				(%)		(%)		(%)	(ppm)	(ppm)	(ppm)
9	Travertine	84.0	80.8	32.5	20.4	43.5	45.8	31.4	32.2	0.91	1.16	0.095	678	0	14
7	Lime	82.8	74.8	18.6	18.8	61.9	52.7	31.9	29.1	0.62	1.32	0.095	11	0	12
11a	Travertine	74.1	73.8	15.1	11.6	57.1	44.9	29.3	28.7	0.52	1.22	0.070	523	0	20
16	Travertine	59.7	81.0	6.9	15.5	62.6	45	24.3	31.6	0.19	0.22	0.080	677	0	8
22	Lime	125	120	10.5	9.1	67.7	80.6	45.5	43.2	2.32	2.45	0.003	16	0	6
10a	Lime	90.6	85.2	12.0	4.6	61.7	58.2	36.1	34.0	0.89	1.08	0.111	33	0	17
10b	Lime		83.1		7.8		55.8		34.1		1.02				
11b	Travertine		79.8		7.2		45.2		30.7		1.13				
15	Travertine	87.6	87.1	8.6	5.5	57.2	54.6	34.8	34.4	0.33	0.25	0.048	1,070	0	8
20	Lime	110	116	7.5	6.2	60.9	54.6	40.0	41.1	2.50	2.85	0.019	275	3	16
23	Lime	117	118	0.6	12.9	81.3	72.9	42.6	42.8	2.31	2.45	0.022	192	1	15
8	Lime	96.3	103	5.6	3.2	66.2	71.2	37.4	40.4	0.93	0.64	0.080	6	0	14
25	Travertine	96.2	91.9	1.1	6.7	44.5	51.3	35.5	34.8	1.84	1.79	0.023	553	0	10
5	Lime	97.6		3.4		66.5		37.4		0.76		0.046	367	3	6
21a	Travertine	91.5	96.6	6.6	0.2	63.7	35.4	33.6	36.7	1.58	1.22	0.006	543	0	11
17	Travertine	79.0	73.8	3.2	1.8	67.0	52	31.5	34.7	0.21	0.23	0.067	1,800	0	10
19	Lime	121	121	0.7	3.9	88.1	81.2	42.7	41.7	2.50	2.90	0.011	280	6	10
18	Lime	120	127	1.7	1.8	86.7	96.7	42.2	41.6	2.85	2.57	0.017	27	0	12
24	Lime	97.5	102	0.3	2.7	28.4	55.1	35.3	37.4	1.80	2.05	0.021	342	0	8
6	Lime	100		1.4		49.1		37.6		1.70		0.021	447	0	9
14	Lime	91.3	104	1.9	0.6	66.5	65.4	36.4	40.6	0.31	0.34	0.092	582	8	25
13	Lime	115	122	1.7	0.7	88.8	93.0	46.2	49.2	0.44	0.39	0.053	54	2	20
4	Travertine	80.0		1.1		58.1		31.8		0.30		0.087	694	1	10
3	Lime	73.5		1.0		35.7		28.4		1.00		0.070	26	0	38
26	Travertine		93.7		1.0		35.4		35.1		1.74				
21b	Travertine		92.8		0.7		39.6		34.1		1.74				
12	Lime	126	120	0.5	0.8	97.7	97.0	50.9	47.6	0.48	0.43	0.035	554	5	19
Bur-2	Unground Dolomite Rock A		102		0.6		NA		19.9		12.0				
Bur-1	Ground Dolomite		102		0.5		64		31.0		11.6				
1	Lime	116		0.5		96.6		46.3		0.50		0.036	9	0	12
2	Lime	120		0.5		81.5		47.6		0.46		0.044	51	1	23

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(%)		(%)				(%)		(%)					
21c	Travertine		94.6		0.5		28.4		35.5		2.27				
Bur-3	Unground Dolomite Rock B		102		0.3		NA		21.7		12.2				
QAQC	Standard for determination of Calcium Carbonate Equivalent (CCE)	100.3		0.0		99.4			39.8		0.00				

Note: The samples were gently boiled in 50 mL of 0.5 N HCl, cooled, and titrated with 0.25 N NaOH to determine CCE. The samples were acidified with 1 mL of 0.5 N HCl, filtered, and diluted to 250 mL.

The Ca, Mg, Fe, Mn, Cu, and Zn were determined by ICP-OES (results are on a dry weight basis).

**Table C-4. Analysis of Rwandan Lime and Travertine Samples and Dolomite Samples Obtained in 2007 and 2008—Sorted by Average Fineness Factor (FF)**

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(% )		(% )				(% )		(% )		(%)	(ppm)	(ppm)	(ppm)
QAQC	Standard for determination of Calcium Carbonate Equivalent (CCE)	100.3		0.0		99.4			39.8		0.00				
12	Lime	126	120	0.5	0.8	97.7	97.0	50.9	47.6	0.48	0.43	0.035	554	5	19
1	Lime	116		0.5		96.6		46.3		0.50		0.036	9	0	12
18	Lime	120	127	1.7	1.8	86.7	96.7	42.2	41.6	2.85	2.57	0.017	27	0	12
13	Lime	115	122	1.7	0.7	88.8	93.0	46.2	49.2	0.44	0.39	0.053	54	2	20
19	Lime	121	121	0.7	3.9	88.1	81.2	42.7	41.7	2.50	2.90	0.011	280	6	10
2	Lime	120		0.5		81.5		47.6		0.46		0.044	51	1	23
23	Lime	117	118	0.6	12.9	81.3	72.9	42.6	42.8	2.31	2.45	0.022	192	1	15
22	Lime	125	120	10.5	9.1	67.7	80.6	45.5	43.2	2.32	2.45	0.003	16	0	6
8	Lime	96.3	103	5.6	3.2	66.2	71.2	37.4	40.4	0.93	0.64	0.080	6	0	14
5	Lime	97.6		3.4		66.5		37.4		0.76		0.046	367	3	6
14	Lime	91.3	104	1.9	0.6	66.5	65.4	36.4	40.6	0.31	0.34	0.092	582	8	25
Bur-1	Ground Dolomite		102		0.5		64		31.0		11.6				
10a	Lime	90.6	85.2	12.0	4.6	61.7	58.2	36.1	34.0	0.89	1.08	0.111	33	0	17
17	Travertine	79.0	73.8	3.2	1.8	67.0	52	31.5	34.7	0.21	0.23	0.067	1,800	0	10
4	Travertine	80.0		1.1		58.1		31.8		0.30		0.087	694	1	10
20	Lime	110	116	7.5	6.2	60.9	54.6	40.0	41.1	2.50	2.85	0.019	275	3	16
7	Lime	82.8	74.8	18.6	18.8	61.9	52.7	31.9	29.1	0.62	1.32	0.095	11	0	12
15	Travertine	87.6	87.1	8.6	5.5	57.2	54.6	34.8	34.4	0.33	0.25	0.048	1,070	0	8
10b	Lime		83.1		7.8		55.8		34.1		1.02				
16	Travertine	59.7	81.0	6.9	15.5	62.6	45	24.3	31.6	0.19	0.22	0.080	677	0	8
11a	Travertine	74.1	73.8	15.1	11.6	57.1	44.9	29.3	28.7	0.52	1.22	0.070	523	0	20
21a	Travertine	91.5	96.6	6.6	0.2	63.7	35.4	33.6	36.7	1.58	1.22	0.006	543	0	11
6	Lime	100		1.4		49.1		37.6		1.70		0.021	447	0	9
25	Travertine	96.2	91.9	1.1	6.7	44.5	51.3	35.5	34.8	1.84	1.79	0.023	553	0	10
11b	Travertine		79.8		7.2		45.2		30.7		1.13				
9	Travertine	84.0	80.8	32.5	20.4	43.5	45.8	31.4	32.2	0.91	1.16	0.095	678	0	14
24	Lime	97.5	102	0.3	2.7	28.4	55.1	35.3	37.4	1.80	2.05	0.021	342	0	8
21b	Travertine		92.8		0.7		39.6		34.1		1.74				
3	Lime	73.5		1.0		35.7		28.4		1.00		0.070	26	0	38

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(%)		(%)		(%)		(%)		(%)	(ppm)				
26	Travertine		93.7		1.0		35.4		35.1		1.74				
21c	Travertine		94.6		0.5		28.4		35.5		2.27				
Bur-2	Unground Dolomite Rock A		102		0.6		NA		19.9		12.0				
Bur-3	Unground Dolomite Rock B		102		0.3		NA		21.7		12.2				

Note: The samples were gently boiled in 50 mL of 0.5 N HCl, cooled, and titrated with 0.25 N NaOH to determine CCE. The samples were acidified with 1 mL of 0.5 N HCl, filtered, and diluted to 250 mL.

The Ca, Mg, Fe, Mn, Cu, and Zn were determined by ICP-OES (results are on a dry weight basis).

**Table C-5. Analysis of Rwandan Lime and Travertine Samples and Dolomite Samples Obtained in 2007 and 2008—Sorted by Average Calcium (Ca) Content**

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(%)		(%)				(%)		(%)		(%)	(ppm)	(ppm)	(ppm)
12	Lime	126	120	0.5	0.8	97.7	97.0	50.9	47.6	0.48	0.43	0.035	554	5	19
13	Lime	115	122	1.7	0.7	88.8	93.0	46.2	49.2	0.44	0.39	0.053	54	2	20
2	Lime	120		0.5		81.5		47.6		0.46		0.044	51	1	23
1	Lime	116		0.5		96.6		46.3		0.50		0.036	9	0	12
22	Lime	125	120	10.5	9.1	67.7	80.6	45.5	43.2	2.32	2.45	0.003	16	0	6
23	Lime	117	118	0.6	12.9	81.3	72.9	42.6	42.8	2.31	2.45	0.022	192	1	15
19	Lime	121	121	0.7	3.9	88.1	81.2	42.7	41.7	2.50	2.90	0.011	280	6	10
18	Lime	120	127	1.7	1.8	86.7	96.7	42.2	41.6	2.85	2.57	0.017	27	0	12
20	Lime	110	116	7.5	6.2	60.9	54.6	40.0	41.1	2.50	2.85	0.019	275	3	16
QAQC	Standard for determination of Calcium Carbonate Equivalent (CCE)	100.3		0.0		99.4			39.8		0.00				
8	Lime	96.3	103	5.6	3.2	66.2	71.2	37.4	40.4	0.93	0.64	0.080	6	0	14
14	Lime	91.3	104	1.9	0.6	66.5	65.4	36.4	40.6	0.31	0.34	0.092	582	8	25
6	Lime	100		1.4		49.1		37.6		1.70		0.021	447	0	9
5	Lime	97.6		3.4		66.5		37.4		0.76		0.046	367	3	6
24	Lime	97.5	102	0.3	2.7	28.4	55.1	35.3	37.4	1.80	2.05	0.021	342	0	8
21c	Travertine		94.6		0.5		28.4		35.5		2.27				
21a	Travertine	91.5	96.6	6.6	0.2	63.7	35.4	33.6	36.7	1.58	1.22	0.006	543	0	11
25	Travertine	96.2	91.9	1.1	6.7	44.5	51.3	35.5	34.8	1.84	1.79	0.023	553	0	10
26	Travertine		93.7		1.0		35.4		35.1		1.74				
10a	Lime	90.6	85.2	12.0	4.6	61.7	58.2	36.1	34.0	0.89	1.08	0.111	33	0	17
15	Travertine	87.6	87.1	8.6	5.5	57.2	54.6	34.8	34.4	0.33	0.25	0.048	1,070	0	8
21b	Travertine		92.8		0.7		39.6		34.1		1.74				
10b	Lime		83.1		7.8		55.8		34.1		1.02				
17	Travertine	79.0	73.8	3.2	1.8	67.0	52	31.5	34.7	0.21	0.23	0.067	1,800	0	10
4	Travertine	80.0		1.1		58.1		31.8		0.30		0.087	694	1	10
9	Travertine	84.0	80.8	32.5	20.4	43.5	45.8	31.4	32.2	0.91	1.16	0.095	678	0	14
Bur-1	Ground Dolomite		102		0.5		64		31.0		11.6				
11b	Travertine		79.8		7.2		45.2		30.7		1.13				
7	Lime	82.8	74.8	18.6	18.8	61.9	52.7	31.9	29.1	0.62	1.32	0.095	11	0	12
11a	Travertine	74.1	73.8	15.1	11.6	57.1	44.9	29.3	28.7	0.52	1.22	0.070	523	0	20

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(%)		(%)				(%)		(%)					
3	Lime	73.5		1.0		35.7		28.4		1.00		0.070	26	0	38
16	Travertine	59.7	81.0	6.9	15.5	62.6	45	24.3	31.6	0.19	0.22	0.080	677	0	8
Bur-3	Unground Dolomite Rock B		102		0.3		NA		21.7		12.2				
Bur-2	Unground Dolomite Rock A		102		0.6		NA		19.9		12.0				

Note: The samples were gently boiled in 50 mL of 0.5 N HCl, cooled, and titrated with 0.25 N NaOH to determine CCE. The samples were acidified with 1 mL of 0.5 N HCl, filtered, and diluted to 250 mL.

The Ca, Mg, Fe, Mn, Cu, and Zn were determined by ICP-OES (results are on a dry weight basis).

**Table C-6. Analysis of Rwandan Lime and Travertine Samples and Dolomite Samples Obtained in 2007 and 2008—Sorted by Average Magnesium (Mg) Content**

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(%)		(%)				(%)		(%)		(%)	(ppm)	(ppm)	(ppm)
Bur-3	Unground Dolomite Rock B		102		0.3		NA		21.7		12.2				
Bur-2	Unground Dolomite Rock A		102		0.6		NA		19.9		12.0				
Bur-1	Ground Dolomite		102		0.5		64		31.0		11.6				
18	Lime	120	127	1.7	1.8	86.7	96.7	42.2	41.6	2.85	2.57	0.017	27	0	12
19	Lime	121	121	0.7	3.9	88.1	81.2	42.7	41.7	2.50	2.90	0.011	280	6	10
20	Lime	110	116	7.5	6.2	60.9	54.6	40.0	41.1	2.50	2.85	0.019	275	3	16
22	Lime	125	120	10.5	9.1	67.7	80.6	45.5	43.2	2.32	2.45	0.003	16	0	6
23	Lime	117	118	0.6	12.9	81.3	72.9	42.6	42.8	2.31	2.45	0.022	192	1	15
21c	Travertine		94.6		0.5		28.4		35.5		2.27				
24	Lime	97.5	102	0.3	2.7	28.4	55.1	35.3	37.4	1.80	2.05	0.021	342	0	8
25	Travertine	96.2	91.9	1.1	6.7	44.5	51.3	35.5	34.8	1.84	1.79	0.023	553	0	10
26	Travertine		93.7		1.0		35.4		35.1		1.74				
21b	Travertine		92.8		0.7		39.6		34.1		1.74				
6	Lime	100		1.4		49.1		37.6		1.70		0.021	447	0	9
21a	Travertine	91.5	96.6	6.6	0.2	63.7	35.4	33.6	36.7	1.58	1.22	0.006	543	0	11
11b	Travertine		79.8		7.2		45.2		30.7		1.13				
9	Travertine	84.0	80.8	32.5	20.4	43.5	45.8	31.4	32.2	0.91	1.16	0.095	678	0	14
10b	Lime		83.1		7.8		55.8		34.1		1.02				
3	Lime	73.5		1.0		35.7		28.4		1.00		0.070	26	0	38
10a	Lime	90.6	85.2	12.0	4.6	61.7	58.2	36.1	34.0	0.89	1.08	0.111	33	0	17
7	Lime	82.8	74.8	18.6	18.8	61.9	52.7	31.9	29.1	0.62	1.32	0.095	11	0	12
11a	Travertine	74.1	73.8	15.1	11.6	57.1	44.9	29.3	28.7	0.52	1.22	0.070	523	0	20
8	Lime	96.3	103	5.6	3.2	66.2	71.2	37.4	40.4	0.93	0.64	0.080	6	0	14
5	Lime	97.6		3.4		66.5		37.4		0.76		0.046	367	3	6
1	Lime	116		0.5		96.6		46.3		0.50		0.036	9	0	12
2	Lime	120		0.5		81.5		47.6		0.46		0.044	51	1	23
12	Lime	126	120	0.5	0.8	97.7	97.0	50.9	47.6	0.48	0.43	0.035	554	5	19
13	Lime	115	122	1.7	0.7	88.8	93.0	46.2	49.2	0.44	0.39	0.053	54	2	20
14	Lime	91.3	104	1.9	0.6	66.5	65.4	36.4	40.6	0.31	0.34	0.092	582	8	25
4	Travertine	80.0		1.1		58.1		31.8		0.30		0.087	694	1	10
15	Travertine	87.6	87.1	8.6	5.5	57.2	54.6	34.8	34.4	0.33	0.25	0.048	1,070	0	8

Sample No.	Type of Product	CaCO <sub>3</sub> (CCE)- Dry Weight Basis		Moisture-Dry Weight Basis		FF		Ca		Mg		Mn	Fe	Cu	Zn
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008				
		(%)		(%)				(%)		(%)					
17	Travertine	79.0	73.8	3.2	1.8	67.0	52	31.5	34.7	0.21	0.23	0.067	1,800	0	10
16	Travertine	59.7	81.0	6.9	15.5	62.6	45	24.3	31.6	0.19	0.22	0.080	677	0	8
QAQC	Standard for determination of Calcium Carbonate Equivalent (CCE)	100.3		0.0		99.4			39.8		0.00				

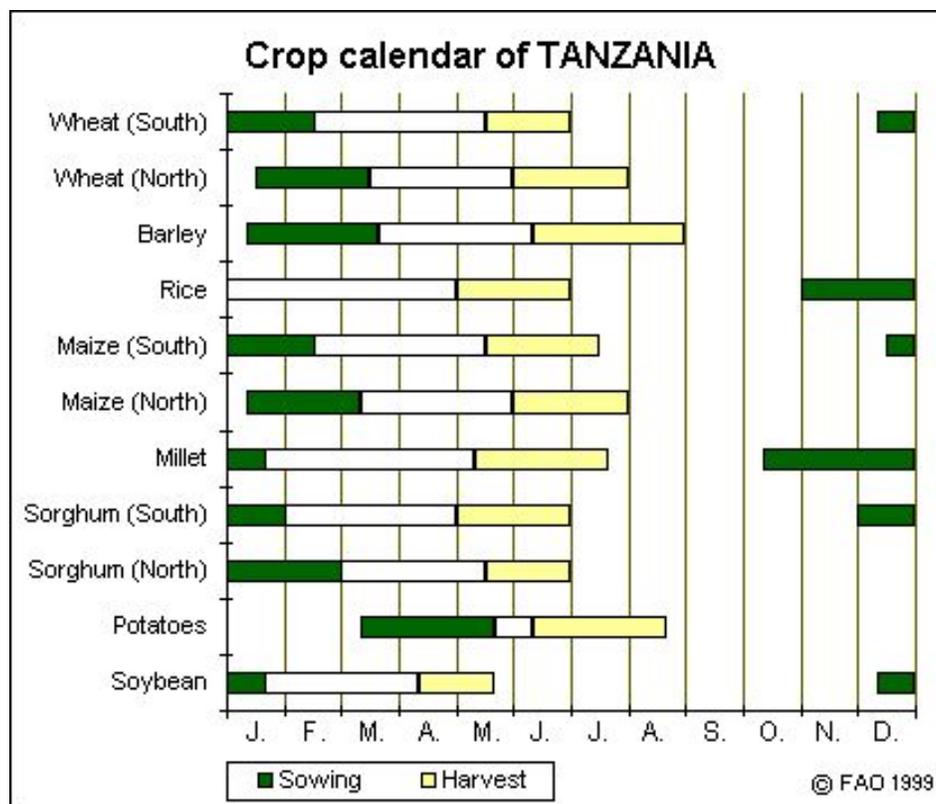
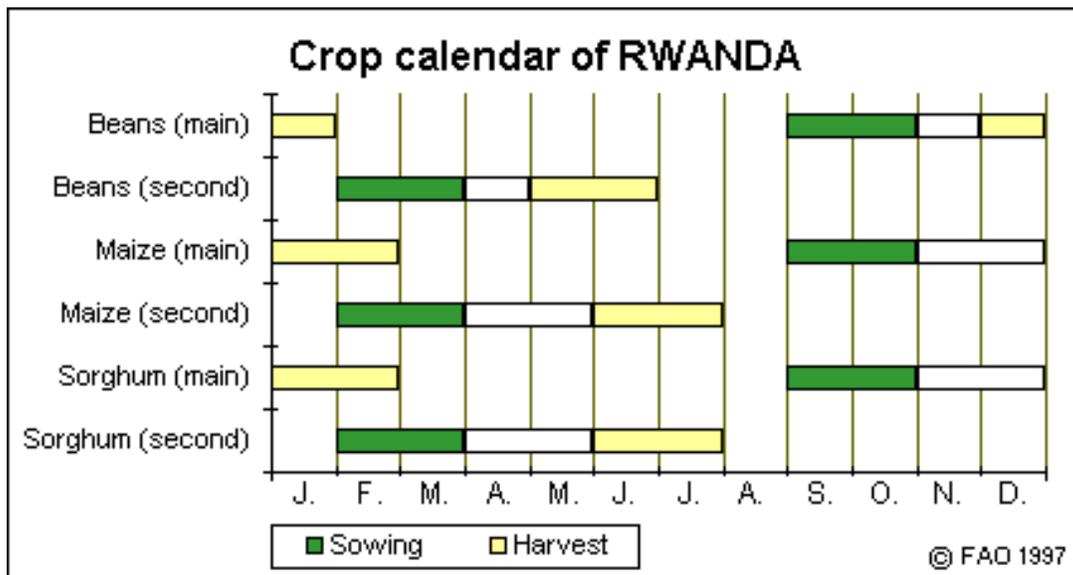
Note: The samples were gently boiled in 50 mL of 0.5 N HCl, cooled, and titrated with 0.25 N NaOH to determine CCE. The samples were acidified with 1 mL of 0.5 N HCl, filtered, and diluted to 250 mL.

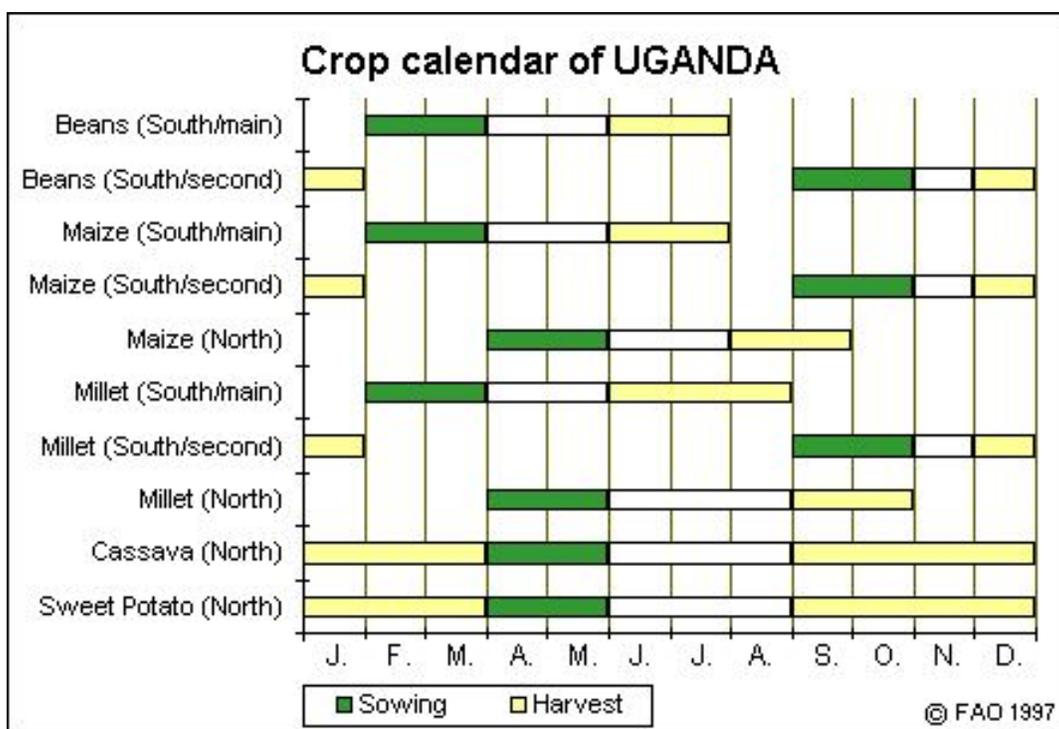
The Ca, Mg, Fe, Mn, Cu, and Zn were determined by ICP-OES (results are on a dry weight basis).

**Table C-7. Statistical Analysis and Categorization of Lime Samples from Rwanda (Also Butare Mines in Burundi), 2007–2008, Based on Calcium Carbonate Equivalent (CCE), Moisture Content, and Fineness Factor (FF)**

Sample No.	Type of Product	CCE	Moisture	FF
22	Lime	122.5	9.8	74.1
23	Lime	117.5	6.75	77.1
2	Lime	120	0.5	81.5
19	Lime	121	2.3	84.6
13	Lime	118.5	1.2	90.9
18	Lime	123.5	1.75	91.7
1	Lime	116	0.5	96.6
12	Lime	123	0.65	97.4
QAQC	Standard for determination of Calcium Carbonate Equivalent (CCE)	100.3	0	99.4
20	Lime	113	6.85	57.8
Bur 1–3	Dolomitic lime	102	0.5	64
14	Lime	97.65	1.25	66.0
5	Lime	97.6	3.4	66.5
8	Lime	99.65	4.4	68.7
21c	Travertine	94.6	0.5	28.4
26	Travertine	93.7	1	35.4
3	Lime	73.5	1	35.7
21b	Travertine	92.8	0.7	39.6
24	Lime	99.75	1.5	41.8
11b	Travertine	79.8	7.2	45.2
21a	Travertine	94.05	3.4	49.5
6	Lime	100	1.4	49.1
25	Travertine	94.05	3.9	47.9
10b	Lime	83.1	7.8	55.8
15	Travertine	87.35	7.05	55.9
4	Travertine	80	1.1	58.1
17	Travertine	76.4	2.5	59.5
10a	Lime	87.9	8.3	60.0
9	Travertine	82.4	26.45	44.6
11a	Travertine	73.95	13.35	51
16	Travertine	70.35	11.2	53.8
7	Lime	78.8	18.7	57.3

**Appendix D. Crop Calendars of Rwanda, Tanzania, and Uganda**





**Appendix E. Literature Review on Soil Acidity and Acid Soils**

## Literature Review

Identification of regions within the CATALIST intervention zone for which acidity is or can easily become a problem hindering agricultural intensification.

### All Regions

#### *Soil Chemistry*

Soil pH is an important factor in bean production in the Great Lakes Region of Africa where there is a particularly high concentration of bean production. Soil pH relates to both the soil's capacity to supply nutrients and to its aluminum and manganese toxicity problems.<sup>37</sup> Beans are grown extensively throughout the Great Lakes Region of Africa, and acid soils in which they are grown are indicated in a map of the Bean Atlas, based on FAO soils data at a 1:5 million scale. *Areas within the CATALIST project implementation region are: Subhumid highlands on acid soils at low latitudes in parts of North Kivu and South Kivu in Democratic Republic of Congo, West Province in Rwanda, and in areas around Bujumbura in Burundi. Because of the low resolution of the map provided in the Bean Atlas, it is of little use to identify specific areas of acid soils for the CATALIST project.*

A standard Adams-Evans Lime Requirement Test and modified test were compared at Clemson University.<sup>38</sup> Key assumptions in lime rate calculations are:

1. Reactivity of limestone with the soil. Specific surface area of limestone and the amount of time to completely react with soil acidity are important factors.
2. Target pH. The target pH that is best for crop productivity is not well defined (e.g., pH 6.0 and pH 6.5 have been used).
3. The amount of soil to be treated. Depth of incorporation is an important factor affecting reactivity of lime.
4. Natural variation of soil properties such as depth, cation exchange capacity which affects soil pH, and exchangeable acidity.
5. Whether the soil samples on which the recommendation for lime application is made are representative of the area to be treated.
6. The method of laboratory analysis on which the recommendation is based.

The authors of the study conclude that “laboratory error is assumed to be the major reason why soil pH does not reach the target pH, or why soil pH in a field does not change as anticipated with time following lime application. Actually, the several sources of uncertainty cited above introduce much more error than the laboratory analysis.” *Liming recommendations made in the CATALIST project will be most useful if they take into account the factors cited above, which can affect the extent and time necessary for lime applied per a recommendation to achieve a particular pH to take effect.*

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<sup>37</sup>Wortmann, C. S., R. A. Kirkby, C. A. Eledu, and D. J. Allen. 1998. *Atlas of Common Bean (Phaseolus vulgaris L.) Production in Africa*, CIAT Publication No. 297.

<sup>38</sup>Franklin, R. E., K. Moore, H. Deaton, and R. S. Mylavarapu. 1998. “Comparison of the Standard and a Modified Adams-Evans Lime Requirement Test,” SB 674, Clemson University, South Carolina, p. 11. <<http://www.clemson.edu/agcomm/pubs/Pages/AGRO/SB674.pdf>>.

Field research in the tropical uplands of Indonesia<sup>39</sup> was conducted to develop techniques for extension workers to assess soil fertility in tropical uplands when no soil test was available. Because such a technique is less accurate than chemical analysis to identify acid soils, plant indicator species were used to identify acid soils with low P. Foliar nutrient deficiency symptoms can also be used as initial indicators of possible nutrient deficiencies. *In the CATALIST project, foliar nutrient deficiency symptoms can be initial indicators of nutrient deficiencies; however, it is recommended that chemical analysis of plant and soil samples be used within project implementation areas to accurately diagnose plant nutrient deficiencies.*

Buffer pH is used to estimate lime requirement, and it is a measure of a soil's active and reserve acidity. Gavlak et al. (2003) describe four laboratory procedures and calculations that can be used to recommend lime application rates. These methods are:

1. SMP Single Buffer pH Lime Requirement. Standard calibration curves are established for liming based on a SMP value to a desired pH for soil groups in a geographic area. Local calibration of the method is desirable if the SMP method is to be used in the CATALIST project.
2. Woodruff Buffer pH Lime Requirement. The Woodruff method is better suited to soils low in exchangeable aluminum with acidity associated with ammoniacal nitrogen applications.
3. Adams and Evans Buffer pH Lime Requirement. The Adams and Evans method can detect small differences in lime requirement that may elicit large changes in pH. The procedure is generally reproducible within 0.10 pH units.
4. Mehlich Buffer pH Lime Requirement.<sup>40</sup> The Mehlich Buffer method is particularly well suited to determine the lime requirement for neutralizing very acid soils that may be harmful to crop productivity.

A method to determine lime requirement by buffer pH in CATALIST project implementation areas should be chosen and calibrated so that the data can be compared to other scientific data in order to take advantage of scientific research on soil acidity and liming.

### ***Soil Management Materials***

Sepiolite is a hydrated magnesium silicate with the formula,  $Mg_8Si_{12}O_{28}(OH)_2(OH)_6(OH_2)_4 \cdot 6H_2O$  or  $Mg_8Si_{12}O_{30}(OH)_4(OH_2)_4 \cdot 8H_2O$ ; the formulas differ only in the proportion of total "free" water content.<sup>41</sup> A large sepiolite deposit occurs at Sinya (Arusha) near the Tanzania-Kenya border, approximately 50 km southeast of Namanga. An experiment was conducted to determine whether sepiolite could be used to correct soil acidity of a moderately acid soil (pH 5.5) using maize (*Zea mays* L.) as a test crop.<sup>42</sup> The following were tested: Sepiolite topsoil – primary crushed (<10 mesh), raw sepiolite – primary milled (10 mesh), raw sepiolite – primary crushed (<10 mesh), agricultural lime – fine ground (30 mesh), and dolomite – fine ground (60 mesh). The materials varied in Ca and Mg contents, neutralizing

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<sup>39</sup>Dierolf, T. S., E. Kramer, and T. Fairhurst. 1997. "When There Is No Soil Test... Helping Extension Workers Assess Soil Fertility in the Tropical Uplands," *Better Crops International*, 11(2):14–17.

<sup>40</sup>Gavlak, R., D. Horneck, R. O. Miller, and J. Kotuby-Amacher. 2003. "Soil, Plant and Water Reference Methods for the Western Region," WREP 125, 2nd edition, Oregon State University.

<sup>41</sup>Dandy, A. J. 1971. "Zeolitic Water Content and Adsorptive Capacity for Ammonia of Microporus Sepiolite," *J. Chem. Soc. Section A—Inorg. Phys. Theor.*, No. 14:2383–2387.

<sup>42</sup>Singh, B. R., and A. P. Uriyo. 1976. "Use of Sepiolite as a Liming Material," *E. Afr. Agric For. J.*, 41(4):323–327.

value, and tons/ha required to change soil pH from 5.5 to 6.5. Of the three sepiolite materials tested, the sepiolite topsoil was the most effective to increase maize yield. While statistically equal to agricultural lime and dolomite in neutralizing soil acidity and increasing maize yield, the sepiolite topsoil may be more economical than lime, because it occurs as a surface deposit and does not need to be mined. The sepiolite topsoil may be used without any processing; however, Singh and Uriyo (1976) note that primary crushing before adding sepiolite topsoil as an amendment to soil may increase its effectiveness. *Sepiolite soil may be an economically viable source of liming material to increase the soil pH in CATALIST implementation areas in the Kagera and Kigoma Provinces of Tanzania, but further agronomic and economic investigation would need to be done before a decision is made to employ this material to increase soil pH in these two provinces.*

In a comprehensive study, M.T.F. Wong et al. (1998) developed a method to determine the acid-ameliorating capacity of plant residue, compost, urban waste compost, farmyard manure, and peat applied to tropical soils.<sup>43</sup> An Oxisol from Burundi, Spodosol from Sumatra, and Ultisol from Cameroon were incubated with 1.5% of four composts, a farmyard manure, and a sedge peat for 14 days. The increase in soil pH was directly related to the proton consumptive capacity of the OM. The laboratory procedure for estimating the final pH of a treated soil used the intersection of buffer curves determined for the soil and for the OM. *This laboratory technique can be used in the CATALIST project to determine the potential effectiveness of available OM to increase the pH of acid soils. In organic soils, the pH (H<sub>2</sub>O) ranged from 5.0 to 5.5, and in the mineral soils, a range from 6.0 to 7.0 is optimum.*

Further research was conducted by Wong et al. (2000)<sup>44</sup> using an Oxisol from Burundi and an Ultisol from Cameroon to determine the acid-neutralizing capacity of agroforestry tree prunings. They showed that when soils were amended by 3.1%, by weight, of prunings of young shoots of any of seven tree species, the soil pH was increased, and the exchangeable aluminum content decreased. The greatest increase in pH and corresponding decrease in exchangeable aluminum occurred during the first 14 days of incubation, and the decrease continued at a slower rate until 42 days of incubation. The acid-neutralizing effect decreased after 42 days but was still important at the last sampling time at 98 days. The proposed mechanism to explain the rise in soil pH is that complexation of protons and aluminum species neutralized soil acidity. *Amendment of soils with OM clearly benefits acid soils by 1) raising soil pH and 2) decreasing the concentration of soluble aluminum species. CATALIST staff developing ISFM for acid soils should view soil amendment with both lime and OM as methods that farmers can use to ameliorate the chemical properties of acid soils.*

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<sup>43</sup>Wong, M.T.F., S. Nortcliff, and R. S. Swift. 1998. "Method of Determining the Acid Ameliorating Capacity of Plant Residue Compost, Urban Waste Compost, Farmyard Manure, and Peat Applied to Tropical Soils," *Commun. Soil Sci. Plant Anal.*, 29(19&20):2927–2937.

<sup>44</sup>Wong, M.T.F., P. Gibbs, S. Nortcliff, and R. S. Swift. 2000. "Measurement of the Acid Neutralizing Capacity of Agroforestry Tree Prunings Added to Tropical Soils," *J. Agric. Sci., Cambridge*, 134:269–276.

## *Soil Management*

Spatial variability of pH in acid soils should be considered before making recommendations to diminish soil acidity.<sup>45</sup> Justification of variable-rate liming is complicated by factors such as the following: liming is a long-term investment; lime requirements in a field may not be highly variable; the time and expense involved in sampling a grid within a field and analyzing the samples may not justify the economic benefits of liming. *Except in situations where large tracts of land are to be limed, CATALIST project agronomists should take several samples per field and combine them to reduce the cost of laboratory analysis required to recommend the lime requirement.*

A recent report on fertilizer usage in Africa<sup>46</sup> makes only one passing reference to acid soils. The report has a clear focus through the viewpoint of the economist and provides insights regarding marketing and economic aspects of fertilizers in Africa. A major failure of the report, however, is its lack of inclusion of other aspects of soils besides their nutrient content (such as reaction [pH], water-holding capacity, micronutrient content, and cation exchange capacity), which can significantly affect the effectiveness of fertilizers providing N, P, and K. A case in point is that one can waste money by purchasing NPK fertilizers to apply to a strongly acid soil if the soil acidity is not reduced before the fertilizer is applied. Aluminum toxicity, manganese toxicity, or other nutrient deficiencies, which are common in untreated acid soils, can severely depress crop yields when NPK fertilizer is applied. *In order to successfully bring appropriate technologies to farmers in the Great Lakes Region, the CATALIST project must include close collaboration between biophysical scientists and socioeconomic scientists. In this way, CATALIST staff will be more likely to avoid the significant omissions regarding relevant biophysical issues with economic implications such as those exhibited by the economists who authored the recent report at The World Bank.*

A group led by K. Giller and H. van Keulen of the Plant Production Systems, Department of Plant Sciences, Wageningen University, has proposed to address the soil factors that affect nutrient use efficiency of plant nutrients introduced to soils in fertilizer.<sup>47</sup> In the project Nutrient Use in Animal and Cropping Systems – Efficiency and Scales (NUANCES), researchers are developing a modeling framework that combines spatial and temporal dimensions of African smallholder farming systems. Heterogeneity within and between farming systems will be addressed, as well as biophysical issues such as aluminum toxicity, manganese toxicity, or other nutrient deficiencies, which are common in untreated acid soils and can severely depress crop yield when NPK fertilizer is applied. The modeling framework is to include efficiency of nutrient capture, a key factor in managing acid soils. *The proposal speculates that: “A potential application would be to use the model for a retrospective analysis of farmers’ interest, adoption, and lack of adoption of various technologies (ex-post). This could then lead to better focusing of future activities through ex-ante assessments.” Because of this, it is doubtful that the CATALIST project will derive benefit from the NUANCES research project.*

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<sup>45</sup>Adamchuk, V. I., and J. Mulliken. 2005. “Site-Specific Management of Soil pH (FAQ).” Extension Circular Series No. EC 05-705, UNL/Cooperative Extension Service, U2250H001.0705-2005.

<sup>46</sup>Morris, M., V. A. Kelly, R. J. Kopicki, and D. Byerlee. 2007. “Fertilizer Use in African Agriculture – Lessons Learned and Good Practice Guidelines,” The World Bank, Washington, D.C.

<sup>47</sup>[http://ppathw3.cals.cornell.edu/mba\\_project/soilforce/NUANCES.pdf](http://ppathw3.cals.cornell.edu/mba_project/soilforce/NUANCES.pdf)

Recent research at the Africa Rice Center (WARDA) to overcome yield limitations of upland rice cultivated in acid soils combines approaches to modify both the organism and the environment.<sup>48</sup> Because P is strongly fixed by precipitation with Al species in acidic soils, P deficiency is common in acid soils in Africa. Rice varieties that are intolerant of soil acidity give no yield at all, so WARDA is selecting rice varieties with tolerance to acid soils. Landraces of rice grown in areas of acid soils have been selected for tolerance to the harsh chemical environment of soil acidity, and improved varieties tolerant of acid soils build upon the generations of selections by farmers in areas of acid soils. Ca and Mg are often deficient in acid soils. WARDA research with various fertilizers has shown that addition of N, P, Ca, and Mg gave better rice yields than application of just N, Ca, and Mg, and that the addition of Ca and Mg to the suite of fertilizers had no greater effect on yields than the application of P alone. Other research by WARDA with phosphate rock (PR) and triple superphosphate (TSP) applied to acid soils for rice production showed higher yields with TSP, but a PR from Mali showed potential to serve as an inexpensive source of P. Subsequent research in Côte d'Ivoire showed that after an initial treatment with PR, PR treatments gave significantly higher rice yields in the second year of the experiment than in the first year, demonstrating a residual effect of PR. *CATALIST staff may be able to find, from WARDA, sources of rice for the humid tropics, which are tolerant of acid soils and do well in low-P soils. Phosphorus fertilization of acid soils and soils treated to reduce soil acidity will be a crucial component of plant nutrient management in the CATALIST project.*

## Burundi

In Burundi, wheat yields were increased using lime, fertilizer, and green manure.<sup>49</sup> In the mid-altitude area of Kirimoro and the high-altitude area of North Mugamba, new lines of wheat and triticale were tested with different soil management practices. Some economic analyses were conducted to determine the economic return of soil management treatments. Recommendations for release of specific varieties are included in the paper. In high-altitude North Mugamba, a mean yield increase of 34% was obtained using 40-40 N-P/ha. In the mid-altitude Kirimoro area, 2.5 t/ha of green manure applied with 250 kg/ha of lime gave the best economical return. High rates of diammonium phosphate (DAP) alone gave good yields and good economic return, but the returns for these treatments were lower than those including lime. Data presented for soil management trials with wheat in the mid-altitude Kirimoro area show the highest wheat grain yield (1,144 kg/ha) and straw weight (4,271 kg/ha) when the following soil management was applied: 250 kg/ha of lime, 100 kg/ha of DAP, 10,000 kg/ha of green manure, and 1,000 kg/ha of coffee ash. Lesser yields were obtained when any of the four components were omitted or applied at rates less than those used for the maximum yield. *ISFM, which is to be recommended by CATALIST agronomists, can make use of both mineral inputs such as lime, DAP, and coffee ash and organic inputs such as green manure.*

In addition to the classical criteria of plant breeding, such as resistance to climatic stresses and pests, 33 varieties of wheat and triticale bred for cultivation in the Mugamba region of Burundi

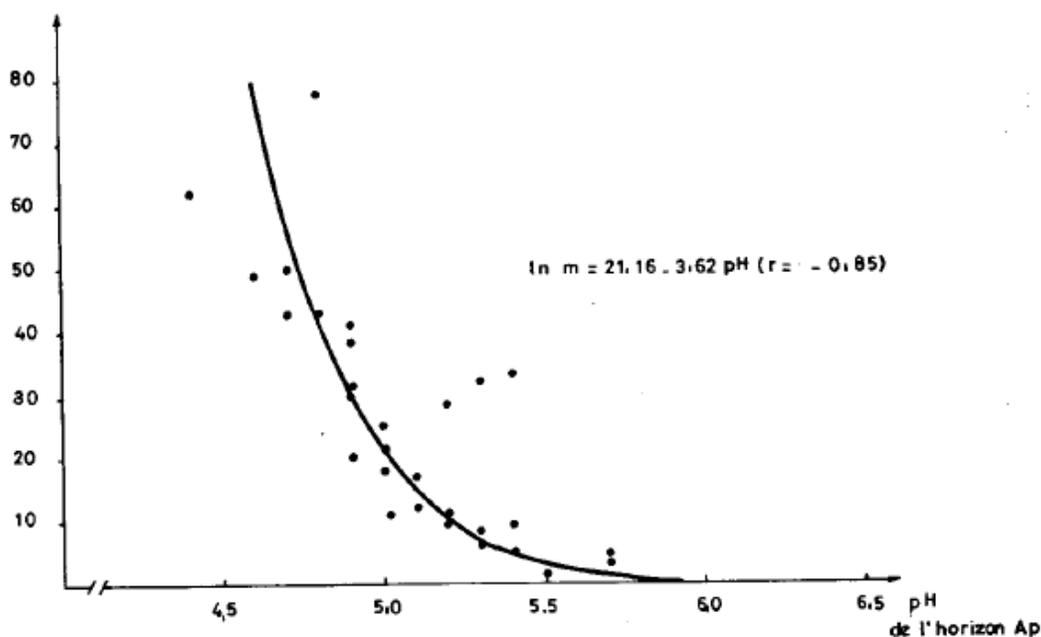
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<sup>48</sup>WARDA. "On the Road to Overcoming Soil Acidity in Upland Rice," IN *WARDA Annual Report 1999*, pp. 23–29.

<sup>49</sup>Baragengana, R. 1990. "Wheat Nutrition in High Altitude," IN *The Sixth Regional Wheat Workshop: for Eastern, Central and Southern Africa: Addis Ababa, Ethiopia, October 2–6, 1989*. pp. 198–203.

are also selected for their tolerance of acid soils and aluminum. While wheat is under widespread cultivation in the zone above 1,900 m in the Crête-Zaire-Nil, triticale was introduced to the area in 1975. In zones of the Mugamba region in which acidic, infertile kaolisols predominate, triticale was found to be more tolerant of soil acidity and aluminum than wheat.<sup>50</sup> In soils with pH <5, triticale yielded between 30% and 80% more than wheat, depending upon the degree of acidity. Figure 1 shows the relationship between aluminum saturation and pH in the kaolisols of the Mugamba region. It clearly shows that as pH increases, Al saturation decreases (see below). Tabular data show, for example, that in humid kaolisols at pH 4.7, two tested triticale varieties (Triticale BVR-Arm and Triticale Mizar) produced more grain: 183% and 155% of the grain yield of the Romany variety of wheat. Both triticale varieties also produced significantly higher grain yields than the Romany variety of wheat when yields were averaged over the range of soil pHs tested (pH 4.7 and 5.7). In hydrokaolisols and in brown, kaolinitic soils, triticale did not prove superior to the wheat varieties tested. *This research indicates the importance of recommending crop varieties tolerant of acid soils in the zones of some acid soils in the CATALIST implementation areas. It may be more cost effective to bring acid-tolerant varieties to zones of acid soils in areas where it is not economically feasible to apply lime and OM as soil amendments. However, it is worth noting that a plant variety (in this case, some triticale varieties) with superior performance in some acid soils may not provide superior performance in another acid soil.*

Saturation en Al(m)



**Figure 1. Relationship Between Al Saturation and pH in the Kaolisols of the Mugamba Region**

Wheat and maize are grown in the relatively cool and rainy zone of Burundi between 1,400 and 2,200 m in altitude; here, the most important factor limiting agricultural intensification is soil

<sup>50</sup>Schalbroeck, J. J., and L. Opedecamp. 1985. "Sensibilités Différentielles du Blé (*Triticum Aestivum*) et du Triticale (*X. Triticosecale*) à l'Acidité des Terres Dans la Mugamba (Burundi)," Actes du Dixième Forum International sur la Soil Taxonomy et les Transfers d'Agrotechnologie : Burundi et Rwanda, 1-12 Avril 1985.

acidity.<sup>51</sup> At Mahwah in the Bututsi (Kajondi) region, experiments were conducted with different combinations of soil amendments and fertilizer with wheat. The lime used for the experiments was from a tuff from the plain of Imbo, very finely ground, and not heated. The amount applied was calculated by Kamprath's method, based on the CaO equivalent and degree of aluminum toxicity in the soil. To neutralize between 85% and 90% of the exchangeable aluminum in the surface horizon of the soil, 4.3 t/ha of Gihungwe tuff (29.2% CaO and 7% MgO) were estimated to be necessary. In the manure treatment, 7 t/ha of manure (2.01% N, 1.83% P, 0.30% Ca, 0.18% Mg, 39.1% organic C) was applied, because it was the estimated amount that a Burundian farmer who has one cow and cultivates 0.4 ha of land would have. Because of the human pressure on the land, pastures are being changed to cultivated land, and manure is becoming less available; therefore, a treatment of 4 t/ha of manure and 2 t/ha of lime was included. In the manure-and-lime treatment, to approximate situations in which less manure is available, the 2 t/ha of lime is to partially correct aluminum toxicity. Fertilization with phosphorus had no economic benefit unless the soil was amended with both manure and lime to correct the aluminum toxicity. Sixty kg/ha of N as urea and 60 kg/ha of K<sub>2</sub>O as KCl were added to all treatments. **Conclusions:** As indicated by grain yield, the effect of triple superphosphate fertilizer was increased four or five times when lime and manure were added to the soil. The use of lime and OM with NPK fertilizer had immediate effects on this ferralitic, acid prairie soil with toxic levels of aluminum. Economic analysis based on the agronomic experiment showed that the only treatment that would be economically beneficial to the farmer is: 2 t/ha of lime + 4 t/ha manure + 60 kg/ha of N as urea, 120 kg/ha P<sub>2</sub>O<sub>5</sub> + 60 kg/ha of K<sub>2</sub>O as KCl. The economic calculations were based on the premise that all crop inputs would need to be bought with the income from selling that crop, with the exception of lime. The cost of the one-time application of lime was to be recovered from income from eight crops over four seasons. Lime was considered a "medium-term" investment, whereas other inputs such as fertilizer, crop protection products, seed, and manual labor were considered "short-term" investments. *The profitability of various treatments to manage acid soils (lime, OM, and fertilizers) depends upon the price that the crop will bring and the prices of the various inputs. For the CATALIST project to disseminate profitable soil management recommendations for acid soils, determining which practices are likely to be profitable (there are no guarantees) is a very complex task. It requires inputs of biophysical data from agronomists regarding the agronomic effectiveness of different soil management practices and also requires economic analysis by trained economists with access to economic data such as input costs and crop prices in markets.*

Management of soil acidity in tree-based agroecosystems was reviewed by Wong et al. (2004)<sup>52</sup> in a paper in SCRIPTORIA. They refer to an experiment carried out in collaboration with the World AgroForestry Centre (ICRAF) on an Oxisol at Karuzi in Burundi in which maize and bean crops were given adequate fertilizer and application of 3 and 6 t/ha of the pruned material; the increased yield was attributed to amelioration of soil acidity and lowered aluminum saturation. These rates of addition appear feasible in agroforestry systems. *In the CATALIST*

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<sup>51</sup>Mathieu, C., C. Otoul, and A. Bruyere. 1992. "Influences de la Fertilization sur un Sol Acide Désaturé et sur le Rendement en Blé Dans le Bututsi (Burundi)," *Pedologie*, XLII-1, p. 39–56, 11 tab., Gand, 1992.

<sup>52</sup>Wong, M.T.F., K. Hairiah, and J. Alegre. 2004. "Managing Soil Acidity and Aluminum Toxicity in Tree-Based Agroecosystems," Chapter 8 IN SCRIPTORIA IN *Below-Ground Interactions in Tropical Agroecosystems Concept and Model With Multiple Plants Components*, Wallingford, UK. CABI. p. 143–156, M. van Noordwijk, G. Cadisch, and C. K. Ong (Eds.).

*project, applications of 3–6 t/ha of pruned material will depend upon the availability of both the pruned material and labor.*

## **Democratic Republic of Congo**

There are many opportunities for soil management in South Kivu.<sup>53</sup> The most important lime deposits are at Katana, north of Bukavu, and at Mushinga, south of Bukavu. These are not used for agriculture but are used principally in the construction industry and for production of pharmaceuticals by PHARMAKINA. In North Kivu, there are lime deposits at Kasugho, southwest of Lubero, and at Katana. *Participants in the CATALIST project should be able to use these sources of lime to raise soil pH.*

## **Rwanda**

Two previous consultancies of IFDC soil scientists provided brief references to the problems of soil acidity in Rwanda. Based upon information obtained during her consultancy in Rwanda during January 12–27, 2007, Dr. D. T. Hellums<sup>54</sup> recommended that to raise the pH of acid soils on which Irish potato, maize, soybeans, and wheat are cultivated: “Correct soil pH to 6 with incorporation of 2.5 t/ha of lime (every 2 years) or 10 t/ha of organic manure (annually) 4 weeks prior to planting.” Based upon information obtained during his subsequent fact-gathering consultancy in Rwanda, Dr. U. Singh<sup>55</sup> noted that nutrient imbalances between Ca and Mg, on one hand, and K, on the other, can occur if lime is applied to raise the pH of acid soils, resulting in disproportionately large amounts of available Ca and Mg, compared with the amount of available K. He also noted that an imbalance can occur in an opposite manner if K fertilizer is applied to an acid soil with very little Ca or Mg, resulting in a disproportionately higher availability of K than Ca and Mg to plants growing in the soil. During Dr. Singh’s consultancy, soil samples from the CATALIST office were analyzed by Ms. Laurence Mukamana, Agronomist at IFDC-Rwanda, and Mr. Chiruzo, Agronomist at IFDC-DRC. They found that very low levels of K were evident in all soils tested, and N and P levels were low in most soils tested. The effect of lime applied in the top 30 cm of soil was restricted to that depth. *The present literature review provides deeper insights into the extent to which soil acidity is a problem in the CATALIST implementation areas and provides further insight into the chemistry of liming and fertilization, which needs to be taken into account before CATALIST staff make recommendations for liming or fertilizing soils within the areas of project implementation.*

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<sup>53</sup>Lubanga, L. “Possibilités de Gestion de la Fertilité de Sol au Sud-Kivu Montagneux.” <[http://209.85.165.104/search?q=cache:1iMFaTVRW20J:129.194.252.80/catfiles/2083.pdf+sol+acide+burundi&hl=en&ct=clnk&cd=9&gl=us&lr=lang\\_fr](http://209.85.165.104/search?q=cache:1iMFaTVRW20J:129.194.252.80/catfiles/2083.pdf+sol+acide+burundi&hl=en&ct=clnk&cd=9&gl=us&lr=lang_fr)>.

<sup>54</sup>Hellums, D. T. January 27, 2007. Presentation entitled “Fertilizer Use by Farmers in the Great Lakes Region.”

<sup>55</sup>Singh, U. July 2007. “Consultancy Report: Developing a Terms of Reference on Fertilizer Recommendations for Crops in the Great Lakes Region for CATALIST PROJECT - A Regional Project to Intensify Agricultural Productivity and Improve Product Marketing.”

The effectiveness of alley cropping with leguminous shrubs in acid soils was investigated in Rwanda between 1983 and 1989.<sup>56</sup> *Cassia spectabilis*, *Calliandra calothyrsus*, and *Sesbania sesban* grew well on acid soils that were infertile in a semiarid zone. *Calliandra calothyrsus* nodulated spontaneously and was infected with mycorrhizae, which enabled good absorption of phosphorus. With 5-m wide alleys and four cuttings per year, *Cassia spectabilis* was the best performing, followed by two species of *Lucaena* and *Calliandra calothyrsus*. *Sesbania sesban* did not survive four cuttings and was judged unsuitable for alley cropping in an arid environment. The average annual production of nutrients in the biomass harvested was 72–119 kg/ha of N, 2–3 kg/ha of P, 47–94 kg/ha of Ca, 8–19 kg/ha of Mg, and 29–60 kg/ha of K. This production was equivalent to the contribution of mineral nutrients from 10 t/ha of farmyard manure. During a 5-year period, compared with the untreated control, percentage increases from incorporation of OM from the cuttings in the acid soils were in the following ranges: 2%–20% C, 3%–7% K, 4%–51% Ca, 7%–31% Mg, and 3%–47% CEC. Yield increases of common bean (*Phaseolus vulgaris* L.) and sorghum (*Sorghum bicolor* L.) were greatest with *Cassia spectabilis*; maize (*Zea mays* L.) was weak; and the yield of sweet potato (*Ipomoea batatas* (L.) Lam) was less with the alley cropping treatments than it was with the control. *The results of this research show that alley cropping with leguminous species can be used to bring mineral nutrients from deep in the soil to the vegetative parts of the plant that can be periodically cut and incorporated in the soil, increasing C, K, Ca, Mg, and CEC. When developing ISFM recommendations, CATALIST agronomic staff should consider alley cropping with leguminous species in acid soils within semiarid zones as one way to increase availability of essential plant nutrients to improve soil quality and yield of common bean and sorghum.*

Soil erosion in Rwanda continues to result from conversion of land use from forests and pastures to cultivation.<sup>57</sup> On steep slopes, as much as 100 t of soil per ha per year have been observed. Based on a review of research on soil erosion in Rwanda, Koenig recommends using biological means such as alley cropping, instead of mechanical means such as building rock walls, to control erosion and recycle nutrients in cropping systems on steep slopes. *A combination of both mechanical and biological means of erosion control offers flexibility to provide appropriate erosion control in different locations in Rwanda. CATALIST agronomic staff with Helpage colleagues should weigh the costs and benefits of mechanical and biological means of erosion control on cropped slopes of different steepness and with different soil characteristics.*

Agroforestry was examined by field experimentation as a means of restoring eroding, acid soils in the Central Plateau (Rubona station of ISAR near Butaré) and in savannahs in the east (Karama station of ISAR) at lower altitudes in Rwanda.<sup>58</sup> The ferralitic soils of these two regions are generally low in base saturation; a pH between 3.8 and 5 is common; and deficiencies of N and P are widespread. Many of the soils in these two regions appear to be very permeable, have

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<sup>56</sup>Balasumbranian, V., and L. Sekayange. 1992. "Effets de la Culture en Couloirs sur les Propriétés du Sol et les Performances des Arbustes et les Cultures Vivrières Dans un Environnement Semi-Aride au Rwanda. [*Réseau Erosion*, 12:180–190. <[http://www.ruralpovertyportal.org/english/regions/africa/rwa/agriculture\\_in\\_rwanda/Menu.htm#\\_Rapports\\_et\\_articles](http://www.ruralpovertyportal.org/english/regions/africa/rwa/agriculture_in_rwanda/Menu.htm#_Rapports_et_articles)>.

<sup>57</sup>Koenig, D. 1994. "Dégradation et Erosion des Sols au Rwanda," *Cah. Outre-mer*, XLVII:185, 1–3:1994, pp. 35–48.

<sup>58</sup>Roose, E., F. Ndayizigiye, and L. Sekayange. 1993. "L'agroforesterie et la G-CES au Rwanda – Comment Restaurer la Productivité des Terres Acides Dans une Région Tropicale de Montagne à Forte Densité de Population?" *Cah. Orstom sér Pédol.*, vol XXVIII, no. 2, 1993, 327–349.

low water-holding capacity (1 mm per cm), and have low cation exchange capacity (1–5 meq/100 g). Figure 1 shows agroecological zones, and Figure 2 shows effects of erosion and deposition of soils in landscapes of Rwanda. Significant decreases in erosion are shown in Figure 3 (after Köenig) as evidence that agroforestry can reduce erosion from on the order of 550 t/ha/year for bare soil to less than 100 t/ha/year using agroforestry. Also shown in Figure 3, based on Köenig's data, are reductions of erosion with cassava production utilizing agroforestry. The rest of the paper contains many tables of data, figures, and diagrams. Key conclusions of the paper are: 1) agroforestry reduced runoff and erosion to >2 t/ha/yr; and 2) after 2 years, hedges produced 2–9t/ha/yr of green forage and 2–4 t/ha/yr of fuel wood. Joined with crop residues, this biomass brought to the surface of the soil 80–120 kg/ha/yr of N, 2–12 kg/ha/yr of P<sub>2</sub>O<sub>5</sub>, and 20–80 kg/ha/yr of K<sub>2</sub>O, CaO, and MgO, depending upon bush species and soil fertility. Even after adding 10 t/ha/yr of manure to these agroforestry systems, production of maize and beans (600 kg/ha/yr) and sorghum grain (800 kg/ha/yr) remained low. To achieve higher production of maize and bean grains (2,300 kg/ha/yr) and sorghum grain (1,500 kg/ha/yr), it was necessary to correct the pH (3 t/ha/3yrs of lime), and add 3–10 t/ha/2 years of manure and fertilizer (40–100 kg/ha/yr of N, 30–80 kg/ha/yr of P<sub>2</sub>O<sub>5</sub>, and 20–200 kg/ha of K<sub>2</sub>O, depending upon plant needs and soil deficiencies). Roose and his colleagues observed that in the Central Plateau and low savannahs of Rwanda, agroforestry can stabilize slopes and bring some mineral nutrients and OM to the surface of the soil; however, they concluded that addition of up to 10 t/ha/year of manure was ineffective at increasing yields. Their results show that addition of lime and fertilizers are necessary to raise yields significantly in acid soils of the two regions. *This research indicates that in the CATALIST project, because needs for plant nutrients depend upon both soil conditions and the nutrient needs of the crop to achieve a target yield, soil testing should be used to determine needs for lime and plant nutrients to be applied using fertilizers. Agroforestry and manure can contribute to ISFM, but lime and fertilizers can bring significant increases to crop yields.*

Further research by Roose et al. (1988)<sup>59</sup> reinforces conclusions presented above and adds new insights to the problems associated with managing acid soils, which they estimate comprise two-thirds of the cultivated soils of Rwanda. Because vegetable biomass from agroforestry is insufficient to meet the nutritional needs of plants grown on acid soils (particularly Ca and Mg from lime and P), Roose and his colleagues recommend lime, mineral fertilizers, and animal biomass (bone meal and blood meal). Since the use of vegetable biomass (agroforestry, green manure, manure, compost, and crop residues from cereals) has proven insufficient to provide sufficient mineral nutrients to plants grown in acid soils, Roose and his colleagues recommend massive applications of manure (10 t/ha every 2 years), lime (2–4 t/ha every 3 years), and NPK fertilizer (50–100 kg/ha/yr of N, 40–100 kg/ha of P, and 30–200 kg/ha/yr of K, depending upon soil nutrient content and yield target of specific crops). To restore the productivity of degraded soils, they recommend six steps. One of the steps is to apply and mix 10–20 t/ha of manure or compost to “revitalize” the soil, 1–5 t/ha of lime to bring the pH to >4.8, at which point toxicity of aluminum and manganese disappears, and fertilization to avoid fixation or precipitation with free iron or aluminum. *Treatments of acid soils in the CATALIST project should include application of mineral nutrients from both organic and inorganic sources. OM and lime provide*

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<sup>59</sup>Roose, E., F. Ndayizigiye, L. Sekayange, and J. Nsengimana. 1988. “La Gestion Conservatoire de l'Eau et la Fertilité des Sols (G.CES) – Une Nouvelle Stratégie pour l'Intensification de la Production et de la Restauration de l'Environnement en Montagne,” *Bull. Agric. Rwanda* 21(4): 264–277. <[http://horizon.documentation.ird.fr/exl-doc/pleins\\_textes/pleins\\_textes\\_7/bre/36046.pdf](http://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_7/bre/36046.pdf)>.

*essential plant nutrients; additions of OM add cation exchange capacity and buffer soil pH, and additions of lime neutralize acidity.*

Using the SFCC and ACID4 computer models to assess problems of acid soils in the Buberuka Highlands and Central Plateau of Rwanda, Yamoah et al. (1990)<sup>60</sup> divided the study area into three agroecological zones: (1) high elevation >2,000 m; low rainfall <1,200 mm; parent material – granite and schists complex; (2) medium to high elevation, 1,800–2,000 m; 1,200 mm < rainfall <1,400 mm; parent material – granite and schists complex; and (3) low elevation, 1,500–1,800 m; high rainfall, >1,400 mm; parent material – quartzite and schists complex. Soil samples were taken, and the lime requirement was estimated using the ACID4 program. Data from each soil sample were used to compute lime requirement per field, and an Al-sensitive crop (bean) was used as a test crop in the model. Using the estimated lime requirement as the dependent variable, regression analyses were run with Al and pH as independent variables to obtain prediction equations. The soils were very low to low in N, P, and K and marginal in Ca and Mg. The pH of all soils was <5.5, indicating possible Al toxicity in Al-sensitive crops. Exchangeable acidity (Al + H) was >2 meq/100g, and mean Al saturation of the cation exchange complex was <50%, but as high as 70% in some soils. These Al-saturation levels affect beans and other Al-sensitive legumes more than maize or potatoes. Effective cation exchange capacity (ECEC) is a measure of soils' ability to retain nutrients under conditions of leaching. The low ECEC of the soil samples of this study implies that application of Ca and Mg could be used to displace Al and H from the cation exchange complex deeper than in soils with higher ECEC. Lime requirement for the soils ranged between 0–6 t/ha of CaCO<sub>3</sub>. The correlation coefficient for the equation predicting lime requirement from exchangeable Al was  $r=0.95^{**}$ , as opposed to  $r=0.73^{*}$  for pH. While several investigators referenced by Yamoah and his colleagues see exchangeable Al as a better predictor of lime requirement, from a practical standpoint, pH is easier to measure and may, therefore, be preferable as the basis on which to estimate lime requirement. In most cases, liming is required once every 3 years.<sup>61</sup> According to the SFCC, 75% of the soils were acidic, and 55% were low in K reserves. Soil acidity was associated with high exchangeable Al and Al saturation, which exceeded 50% at pH <5.2. Lime is available locally in what was, in 1990, the Ruhengeri Province. Yamoah and colleagues recommend the SFCC and ACID4 computer programs as quick and cost-effective means of evaluating soil fertility-related problems and recommending remedial measures to overcome them. *It is recommended that the Soil and Nutrient Dynamics Program rapidly evaluate these two programs. If they are quick and useful to use, they should be used to analyze soil data of the CATALIST project to provide recommendations for liming and fertilizer applications.*

Yamoah et al. conducted a study of early growth of alley shrubs in the Highland Region of Rwanda.<sup>62</sup> The paper provides some information on the establishment of alley shrubs and their response to manure and liming. Growth of *Sesbania* was retarded by intercropped pea.

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<sup>60</sup>Yamoah, C. F., J. R. Burleigh, and M. R. Malcolm. 1990. "Application of Expert Systems to Study of Acid Soils in Rwanda," *Agric. Ecosystems Environ.*, 30:203–218.

<sup>61</sup>Tropsoils. 1987. "ACID4: An Expert System to Manage Soil Acidity in the Humid Tropics." The Center for Soils Research, Bogor Indonesia, Univ. of Hawaii, and North Carolina State University.

<sup>62</sup>Yamoah, C., R. Grosz, and E. Nizeyimana. 1989. "Early Growth of Alley Shrubs in the Highland Region of Rwanda," *Agroforestry Systems*, 9:171–184.

## **Tanzania**

Based on systems analysis of soils and agriculture for a 30-year period in Tanzania, it is predicted that the productivity of Tanzanian soils will decline unless steps are taken to reverse several processes.<sup>63</sup> The main factor causing decline in productivity is the reduction in nutrient availability through soil mining and erosion. A buildup of soil acidity is also a threat to agricultural productivity, especially if strongly acidifying fertilizers are used.

## **Uganda**

Information about Uganda is in the main body of the text.

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<sup>63</sup>Aune, J. B. 1995. "Predicting Soil Degradation in Tanzania—A Systems Analysis Approach," *Norwegian J. Agric. Sci.*, 21:47–60.

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