Acta Agriculturae Scandinavica, Section B — Soil & Plant Science

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/sagb20

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To cite this article: Getachew Agegnehu, Tilahun Amede, Teklu Erkossa, Chilot Yirga, Carol Henry, Robert Tyler, Matthew G. Nosworthy, Sheleme Beyene & Gudeta W. Sileshi (2021): Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: a review, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, DOI: 10.1080/09064710.2021.1954239

To link to this article: https://doi.org/10.1080/09064710.2021.1954239

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https://doi.org/10.1080/09064710.2021.1954239

REVIEW

Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: a review

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ABSTRACT
Increasing areas of agricultural land in high rainfall areas of Sub-Saharan Africa (SSA), where crop production used to be reliable, are affected by soil acidity. This review focuses on the extent, causes and effect of soil acidity on soil properties and crop yield and its management from the context of SSA. Studies showed that the detrimental effects of soil acidity can be mitigated through liming, integrated acid soil management and the use of acid-tolerant germplasms. Application of lime resulted in yield increments of 34–252% in wheat, barley and tef, 29–53% in faba bean and soybean, and 42–332% in potato in Ethiopia, 111–182% in maize in Kenya, and 45–103% in Mucuna in Nigeria under moderate to severe acid soil conditions. This was accompanied by a corresponding increase in soil pH up to 1.9 units and a decrease in exchangeable acidity and aluminum up to 2.1 cmol kg^{-1}. Use of acid-tolerant crop varieties such as maize expressing superior tolerance to Al toxicity resulted in a yield increase of 51% under low soil pH in Cameroon and Kenya. Overall, soil acidity covering ~35% of SSA should be reclaimed with lime and integrated acid soil management interventions, which could significantly increase crop yield and enhance the resilience of the tropical agroecosystems. .

ARTICLE HISTORY
Received 11 May 2021
Accepted 7 July 2021

KEYWORDS
Aluminum toxicity; food security; liming; phosphorus sorption; soil acidity; yield loss

Introduction

Soil degradation is recognized as a key factor underlying poor agricultural productivity in sub-Saharan Africa (SSA) affecting the livelihoods of farmers and their environment (Sanchez 2002; Amede and Whitbread 2020). About 65% of the agricultural land (2.3 billion ha) is degraded in Africa, mainly due to poor soil fertility management practices, soil erosion, and soil acidification (Zingore et al. 2015). Severely degraded soils account for about 350 million ha or 20–25% of the total land area, of which about 100 million ha is estimated to be acutely degraded mainly due to improper agricultural activities. According to Sanchez (2002), soil degradation costs SSA about U.S. $68 billion per year and reduces the annual agricultural GDP of SSA by 3%. The productivity of land in Africa ranks amongst the lowest in the world. Around two-thirds of the land in SSA are considered unfavourable for agriculture compared to one-third for South America and 40% for Asia (Vlek et al. 2008). As a result, the average yields of a good indicator crop such as maize stood below 2 t ha^{-1} in Africa compared to 5.5 t ha^{-1} for Asia and 8.0 t ha^{-1} for Americas (FAO 2019). The sustainable use of these soils requires adequate nutrient inputs such as fertilisers, inorganic and organic amendments such as lime, compost, manure and biochar, as soil health or fertility is a manageable soil property, and its management is of utmost importance for optimising crop nutrition to achieve sustainable crop production (Zeleke et al. 2010; Zingore et al. 2015; Agegnehu and Amede 2017).

Soil degradation processes vary according to land-use types. The human impact on the productive capacity of agricultural land in SSA is largely related to unsustainable soil management, such as removal of crop residues, application of very low external inputs, monocropping and shifts to more demanding crops (Vlek et al. 2010). The consequences are soil acidification, loss of soil organic matter (SOM), nutrient mining and soil erosion. Soil acidity increases with the build-up of hydrogen (H^+) and aluminum (Al^{3+}) cations in the soil or when base cations such as potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and sodium (Na^+) are leached and

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replaced by H^+ or Al^{3+} (Von Uexküll and Mutert 1995). According to Sanchez and Logan (1992), one-third of the tropics (1.7 billion ha) is acid enough for soluble Al to be toxic for most crops. Similarly, acid soils cover more than a third of SSA (Pauw 1994) and the productivity of these soils is low and declines rapidly due to their poor fertility, Al toxicity and fragile structure (Aviles et al. 2020). These soils are mostly common on old, stable surfaces that have been exposed to tropical weathering. According to Vlek et al. (2008), the SSA was divided into three zones, i.e. dry [mean annual precipitation, MAP<800 mm yr^{-1}, sub-humid (800 mm yr^{-1}<MAP < 1300 mm yr^{-1}), and humid areas (MAP>1300 mm yr^{-1})]. Based on this classification, acid soils predominantly occur in the humid and sub-humid regions of east and central Africa, west and South Africa as most of the acid soils in SSA have been influenced by a wet tropical climate, and slightly by the vegetation cover. High rainfall results in more acid soils, including Ferralsols, Alisols, Plinthisols, Acrisols, and Podzols (FAO and ITPS 2015).

Increasing area of agricultural land in high rainfall areas of Sub-Saharan Africa (SSA), where crop production used to be reliable, is affected by soil acidity and the productivity of these soils is low and declines rapidly. There is unprecedented overlap of high rainfall areas with soil acidity. Rain-fed farming system is mainly practiced in humid and sub-humid areas where acid soils are common, using dominant annual and perennial crops (Dixon et al. 2019). Most of the acid soil areas, which used to be covered by woodlands and forests, have been rapidly diminishing and replaced by various smallholder farmers varying from shifting cultivation to more intensive fallow systems. Where population pressure is most intense, permanent cultivation systems have evolved as in parts of central and East Africa. Hence, to reduce the impacts of agriculture on the environment, great effort needs to be made on underperforming lands to decrease agricultural land expansion by closing yield gaps through sustainable intensification, increasing cropping efficiency and reducing food waste (Foley et al. 2011). Soil acidity has also been affecting large-scale farms by reducing yield and quality of cash crops such as coffee, tea, pineapple, oil palm, rubber and sisal, which are important sources of foreign exchange for several African economies (Vlek et al. 2010). The key issue of management of acid soils is that the intensification of land use necessitated by the increase in Africa's population is severely hindered by the inherent fragile nature of these soils. Sustainable increases in productivity can only be achieved by a gradual transformation of traditional farming systems through development pathways that consider socioeconomic and agroecological diversity (Pauw 1994; Fageria and Nascente 2014).

Acid soil management is becoming one of the major strategies to achieve food and nutrition security in SSA. On the other hand, the management of acid soils is still a major challenge that calls for investment. An in-depth analysis and knowledge are required to design, adopt and scale up a suitable acid soil management approach. Several studies have been conducted on acid soils in South America (Fageria and Baligar 2008), Africa (Eswaran et al. 1997a; Tully et al. 2015), Asia and Australia (Eswaran et al. 1997b; Bai et al. 2008). However, there is limited understanding of the scope of the problems and the management of acid soils in many SSA countries. The gap in experience related to the management of acidic soils can be bridged by learning from other success stories countries. For instance, the experience of Cerrado region in Brazil in converting large areas of acid soils to productive use through employing integrated solutions could be adapted in SSA through south–south collaborations, though there is limited knowledge transfer and technologies to farmers or scientific communities. Brazil has been able to develop over 60 million ha of the Cerrado with crops and improved pasture with the implementation of appropriate technologies and inputs, infrastructure, and policy support (Klink 2014). This review attempts to capture lessons learned in other continents in managing acid soils and how these best practices could be integrated into the African context. The objectives of this review are, therefore, (1) to provide a synthesis of the current extent, distribution, causes and effects of soil acidity in SSA and (2) inventory and characterise existing differing acid soil management options and their integration modalities in SSA.

Literature search and data processing

Literature search was conducted through the Web of Science (apps.webofknowledge.com), Google Scholar (scholar.google.com), Scopus (www.scopus.com), AGRIS (agris.fao.org) and ResearchGate (https://www.researchgate.net). We searched the literature published up to 2020, using 'soil acidity', 'acid soil management', 'integrated acid soil management', and 'liming' as key terms. Although over 900 publications were retrieved, about 112 publications that provide empirical evidence on problems and management of soil acidity were reviewed in this paper.

First, the papers were grouped relating to their research objectives and experimental types. These were further categorised into studies focusing on organic and inorganic nutrient sources, including lime and the use of acid-tolerant crop species and varieties. Crops tested for soil acidity tolerance in the field were cereals (grain crops, such as wheat, maize, and barley), food legumes (faba bean, soybean, etc.), and root crops (potato). For some data, statistical analysis was performed using SAS-STAT software and some results were graphically presented using Microsoft Excel 2016. In the literature reviewed soil types were given in different soil classifications (USDA, FAO, and WRB). To ensure uniformity, we converted soil types into the World Reference Base (WRB) for soil resources classification and correlation system (IUSS Working Group WRB 2015). Soil types were verified by referring to the dominant soil types in the harmonised soil atlas of Africa (Dewitte et al. 2013).

Synthesis and discussions

Extent and distribution of acidic soils

Acidic soils belongs to Ferralsols and Acrisols and to a smaller extent the Plinthisols, Alisols and Nitisols (IUSS Working Group WRB 2015). Acrisols cover 87.8 million ha or 2.9% and Ferralsols about 312.4 million ha or 10.3% of the total land area of Africa (Tully et al. 2015). Nearly 10.8 million km^2 or 35% of the total area of land in Africa is characterised by slight to high phosphorus (P) fixation, of which 8.2 million km^2 is typified by high P fixation due to soil acidity (Eswaran et al. 1997b).

Soil acidity is expanding both in area and level of acidity in SSA (Figure 1). Major areas of SSA affected by soil acidity include East and Central Africa (Ethiopia, Kenya, Tanzania, Uganda, Rwanda, Brundi, Malawi, Central African Republic, Democratic republic of Congo), West Africa (Ghana, Nigeria, Ivory Coast, Liberia, Sierra Leone, Guinea) and southern Africa (south Africa, Zimbabwe, Mozambique) (Leenaars et al. 2014). For example, in Ethiopia, ~43% of the cultivated land is affected by soil acidity (ATA 2014), of which about 28% is strongly acidic (pH 4.1–5.5) (Abebe 2007). Soils developed on non-calcareous parent materials such as Nitisols and Acrisols are inherently acidic in Ethiopia. The predominant acidic soil associations in Ethiopia are Dystric Nitisols and Orthic Acrisols with inclusions of Leptosols (Abebe 2007), unlike many African countries where Acrisols and Ferralsols dominate the acidic soils. Nitisols have very good potential for agriculture; they have a stable structure and a high-water storage capacity. Workability of these soils is not a problem even shortly after precipitation or in the dry season (IUSS Working Group WRB 2015). They have

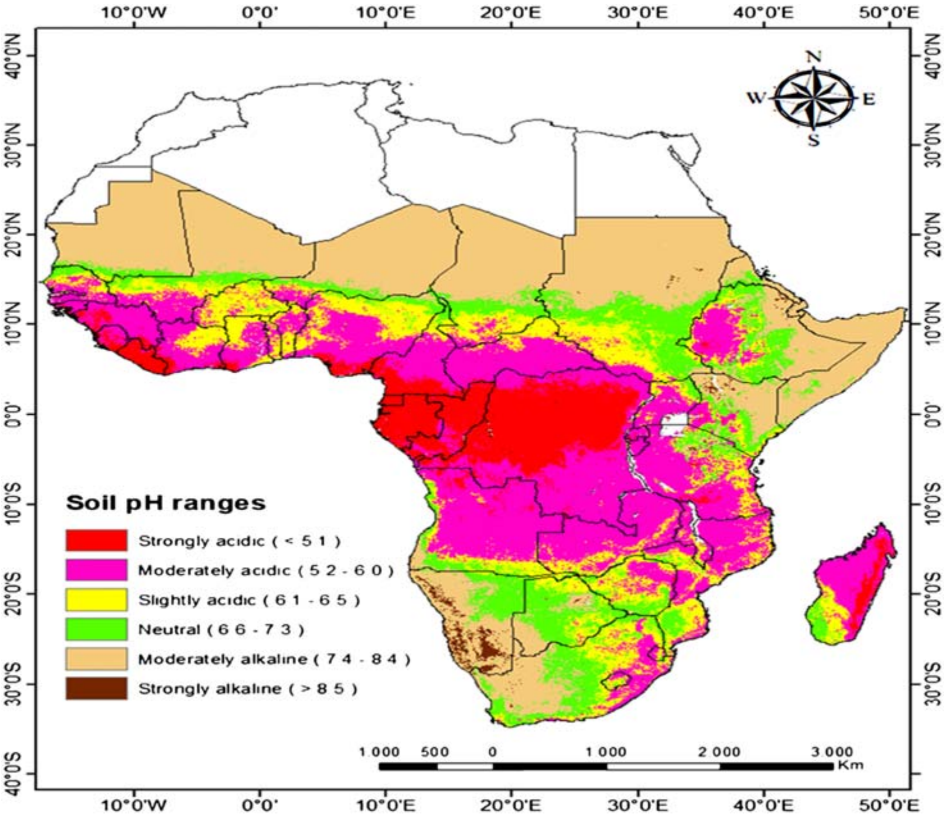

Figure 1. Extent and distribution of soil acidity in Sub-Saharan Africa extracted from Horneck et al. (2011); Leenaars et al. (2014).

low CEC and available P is usually very low (Sertsu and Ali 1983; Abebe 2007; Regassa and Agegnehu 2011). Strongly acidic soils are infertile because of Ca, Mg, P and Mo deficiencies and the possible Al and Mn toxicities (Barber 1984; Fageria and Nascente 2014).

Acidic soils contain high concentration of aluminum (Al), manganese (Mn), and iron (Fe). At pH below 5.0, Al is soluble in water and becomes the dominant ion in the soil solution. In acid soils, excess Al primarily injures the root apex and inhibits root elongation (Sivaguru and Horst 1998). The poor root growth leads to reduced water and nutrient uptake, and as a result crops grown on acid soils are constrained with poor nutrients and water availability leading to reduced growth and yield of crops (Wang et al. 2006; Marschner 2011). Acidic soils such as Acrisols and Ferralsols contain toxic levels of Al and Mn, which have low availability of nutrients, but with good physical properties (IUSS Working Group WRB 2015). The low nutrient content of soils such as Ferralsols and Acrisols is due to the predominance of 1:1 clay minerals, and Fe and Al oxides in the fraction (de Sant-Anna et al. 2017).

Causes of soil acidity

Generally, there are two types of soil acidity: (1) Active acidity which occurs because of high H^+ ion concentration in the soil solution which is attributable to carbonic acid (H_2CO_3), water-soluble organic acids and hydrolytically acid salts; and (2) exchangeable acidity which refers to those H and Al ions adsorbed on soil colloids. There exists an equilibrium between the adsorbed and soil solution ions (i.e. active and exchange acidity), permitting the ready movement from one form to another. Such an equilibrium state is of great practical significance since it provides the basis for the soil buffering capacity or its resistance to change in pH. Since the adsorbed H and Al ions move into the soil solution then its acidity is also referred to as adsorbed or potential or reserve acidity. Reactions of bases (e.g. lime) added to the soil occur first with the active acidity in the soil solution. Subsequently, the pool of reserve acidity gradually releases acidity into the active form. According to Somani (1996), the equilibrium relationship between exchange (reserve) and solution (active) acidity, and acid or base inputs has been illustrated as follows:

Soil acidification is a complex process and there are several causes of soil acidity. Generally, it can be considered as the summation of natural and anthropogenic processes that decrease the pH of the soil solution (Krug and Frink 1983). Naturally, soil acidification takes place due to carbonic acid-triggered leaching of basic cations, weathering of acidic parent materials, decomposition of organic matter, and deposition of atmospheric gases such as SO_2, NH_3, HNO_3, and HCl (Goulding 2016; Rahman et al. 2018). Anthropogenic activities such as continuous application of acid-forming fertilisers including sulfur or ammonium salt and contact exchange between exchangeable hydrogen on root surfaces and the bases in exchangeable form on soils, microbial production of nitric and sulfuric acids accelerate the process of soil acidification that could lead to increased soluble Al^{+3} concentrations in the soil solution (Fageria and Nascente 2014; Behera and Shukla 2015). The decomposition of organic matter produces H^+ ions, which are responsible for acidity (Kochian et al. 2004; Paul 2014), but the development of soil acidity from the decomposition of organic matter is insignificant in the short term. Low buffer capacity from clay and organic matter is another source of soil acidity, i.e. contact exchange between exchangeable H^+ on root surfaces and the bases in exchangeable form on soils. Microbial production of nitric and sulfuric acids also occurs, where leaching is limited. The buffering or CEC is related to the amount of clay and organic matter present, the larger the amount, the greater the buffer capacity.

Removal of cations, especially from soils with small reservoir of bases due to the harvest of high-yielding crops is responsible for soil acidity (Von Uexküll and Mutert 1995; Eswaran et al. 1997b; Vitousek et al. 2009;). Harvest of high-yielding crops plays the most significant role in increasing soil acidity. During growth, crops absorb basic elements such as Ca, Mg, and K to satisfy their nutritional requirements. As crop yields increase, more of these lime-like nutrients are removed from the field. Compared to the leaf and stem portions of the plant, grain contains lower amounts of basic nutrients. Thus, harvesting high-yielding forages affects soil acidity more than harvesting grain does (Fageria and Baligar 2008; Rengel 2011). Soil acidification continues until a balance is reached between removal and replacement of the basic cations such as Ca and Mg that are removed through leaching and crop harvest and replaced due to organic matter decomposition and from weathering of minerals (Abebe 2007; Regassa and Agegnehu 2011). With further increase in rainfall, a point is reached at which the rate of removal of bases exceeds the rate of their liberation from non-exchangeable forms. Hence, wet climates have a greater potential for acidic soils (Sanchez and Logan 1992). Over time, excessive rainfall leaches soluble nutrients such as Ca, Mg and K that prevent soil acidity which are replaced by Al from the exchange sites (Thomas and William 1984; Brady and Weil 2016).

Long-term application of high rates of N fertilisers, loss of cations via leaching, and land use change, i.e. continuous cropping without organic inputs are among the anthropogenic factors that increase soil acidity (Scheffer et al. 2001; Tully et al. 2015). Hydrogen is added in the form of ammonia-based fertilisers (NH_4), urea-based fertilisers $CO(NH_2)_2$, and proteins (amino acid) in organic fertilisers. Transformation of such sources of N fertilisers into nitrate (NO_3^-) releases hydrogen ions (H^+) to create soil acidity. Besides, N fertiliser increases soil acidity by increasing crop yields, thereby increasing the extent of basic elements being removed. Hence, application of fertilisers containing NH_4^+ to soil can ultimately increase soil acidity and lower pH (Hue 1992; Guo et al. 2010). Inefficient use of N is another cause of soil acidification, followed by the export of alkalinity (Guo et al. 2010).

Changes in land use and management practices often modify most soil physicochemical and biological properties to the extent reflected in agricultural productivity (Gebrekidan and Negassa 2006). Soil properties such as bulk density, soil organic matter (SOM) content and CEC deteriorate (Conant et al. 2003) due to the conversion of native forest and range lands into cultivated land (Lemenih et al. 2005). For example, the amount of SOM in grazing and cultivated lands has depleted by 42.6 and 76.5%, respectively, compared to the forest soil. Similarly, Agoumé and Birang (2009) reported the negative effect of land use or land cover change on some physicochemical properties of Ferralsols, such as clay, silt and sand fractions in the humid forest zone of southern Cameroon. Sand and silt decreased with soil depth, but clay increased. Soil pH, total N, organic C, available P, exchangeable cations, exchangeable Al, effective CEC, and Al saturation varied across land-use systems. Aluminum saturation increased with soil depth, and the top soils presented acidity problems while the sub-soils exhibited Al toxicity. Chimdi et al. (2012) also indicated that a decline in total porosity in soils of grazing and cultivated land in comparison to soils of forest land was attributed to a reduction in pore size distribution and the magnitude of SOM loss, in turn, depends on the intensity of soil management practices.

Effect of soil acidity on availability of plant nutrients

Soil acidity and associated low nutrient availability is the major constraint to crop production on acid soils. One of the detrimental effects of soil acidity is P sorption, which is affected by clay mineralogy, pH, oxides and hydroxides of Fe and Al content of amorphous materials. The mechanism of P sorption is considered to be mainly through replacement of hydroxyl ions on crystal lattices, and hydrated Fe and Al by phosphate ions (Adams 1990; Abebe 2007). The P sorption capacity increases with the increase in acidity. For instance, soils from the rift valley of Ethiopia (e.g. Melkassa with a pH value of 7.8) had the lowest P sorption, which are the least weathered (Table 1). However, in the case of highly weathered soils, where the dominant minerals are Gibbsite, Goethite, Kaolinite and desilicated amorphous materials, P sorption is high to very high (Sertsu and Ali 1983). According to Duffera and Robarge (1999), 70–75% of Nitisols in Ethiopian are highly deficient in phosphorus.

The solubility and availability of nutrients to plants is closely related to the pH of the soil (Marschner 2011). Soil acidity converts available soil nutrients into unavailable forms. High soil acidity is related to shortage of available Ca, K, Mg, P and Mo on the one hand (Somani 1996; Agegnehu and Sommer 2000) and excess of soluble Al, Mn and other metallic ions on the other (Rahman et al. 2018). Soil acidity and Al toxicity limit soil enzyme activities, resulting in suppressed microbially mediated nutrient cycling, and that Al toxicity and a reduced availability of organic matter due to Al and Fe binding, may protect a substantial pool of organic C from microbial degradation in acidic soils (Kunito et al. 2016). Soil acidity also affects the movement of soil organisms that are important for plants health. If pH of a soil is less than 5.5, phosphate can readily be rendered unavailable to plants as it is the most immobile of the major plant nutrients (Sanchez and Logan 1992; Agegnehu and Sommer 2000), which results in low crop yield. The quantity of P in soil solution needed for optimum growth of crops ranges between 0.13 and 1.31 kg P ha^{-1} as growing crops absorb about 0.44 kg P ha^{-1} per day. The labile fraction in the

Table 1. Amount of P sorbed by some Ethiopian soils at the standard solution P of 0.2 ppm.

Soil origin	Soil type	Sorbed *P* mg kg^{-1}	Sorbed *P* kg ha^{-1}	pH	Fe_2O_3 (%)	Exch. Al (cmol (+) kg^{-1})	Amorphous material (%)	Gibbsite and Goethite (%)
Chencha	Alisol	1200	2400	4.5	11.7	0.40	51	10
Nedjo	Nitisol	950	1900	4.4	16.1	6.16	32	12
Indibir	Nitisol	800	1600	4.8	11.7	1.69	61	0
Melko	Nitisol	600	1200	5.2	15.8	0.37	ND	ND
Bako	Nitisol	400	900	6.6	14.4	0.02	41	15
Melkassa	Andosol	150	300	7.8	0.20	Trace	ND	ND

Source: Regassa and Agegnehu (2011); Sertsu and Ali (1983); ND: Not determined.

topsoil layer is in the range of 65–218 kg P ha^{-1}, which could replenish P in soil solution (Mengel et al. 2001). Phosphate sorption takes place by specific adsorption and precipitation reactions (Fageria and Baligar 2008). Specific adsorption occurs when P anions replace the hydroxyl groups on the surface of Al and Fe oxides and hydrous oxides, while precipitation reaction occurs when insoluble P compounds form and precipitate. At very low soil pH (≤4.5–5.0), addition of P to soils can result in precipitation of Al and Fe phosphates, whereas at high pH (>6.5) insoluble calcium phosphates can be formed (Abebe 2007).

Effect of soil acidity on crop growth, yield and grain quality

Soil acidity and low CEC are major constraints for crop production on highly weathered tropical soils (Von Uexküll and Mutert 1995). Crops differ in their susceptibility to soil acidity. Several adverse effects such as loss of crop diversity, decline in crop yield, lack of response to N and P fertilisers, and complete failure of crops were reported. For example, yields of barley, wheat, and beans were extremely low, even under application of optimum rate of NPK fertilisers on acid soils of Bedi (Beyene 1987) and Chencha (Haile and Boke 2011) due to low pH. Some N-fixing strains of the bacteria do not thrive at pH values below 6, thus pH 6 or above is best for the legumes that require particular strains of bacteria. Although potato can grow well at higher pH, the recommended soil pH for its optimum growth is 5.0–5.5 since potato scab disease is more prevalent when soil pH is above 5.5. In contrast, plants such as azalea and camelia grow well only at pH values below 5.5 above which they suffer from Fe and Mn deficiencies. The pH of soils for best nutrient availability and crop yields is considered to be between 6.0 and 7.0, which is the most preferred range by common field crops (Duncan 2002). As indicated in Figure 2 barley grain yield and faba bean seed yield have shown strong positive relationship with soil pH level as both crops are sensitive to soil acidity, implying that an ideal soil pH is a prerequisite for attaining optimum yield of both crops, but with the application of other crop management practices.

Soil pH is the most important chemical property of the soil, which plays a significant role in plant growth. Soil acidity, at pH 5.5 or lower, can inhibit the growth of sensitive plant species, though it has little effect on insensitive species even at pH lower than 4. Crops such as cotton, alfalfa, oats, and cabbage (*Brassica oleracea*) do not tolerate acid soils and are considered suitable to neutral soils with a pH range of 7–8. Wheat, barley, maize, clover, and beans grow well on neutral to mildly acid to neutral soils (pH 6–7). Grasses tend to tolerate acid soils better than legumes, so liming to pH 5.5 may control acidity without limiting yield. Legumes, however, need more Ca and perform best between pH 6.5 and 7.5. Among crops tolerant to acid soils are millet, sorghum, sweet potato, potato, tomato, flax, tea, rye, carrot and lupine (Somani 1996). Poor plant vigour, uneven crop growth, poor nodulation of legumes, stunted root growth, persistence of acid-tolerant weeds, increased incidence of diseases and abnormal leaf colours are major symptoms of increased soil acidity which may lead to reduced yields (Somani 1996; Marschner 2011). Increased acidity is likely to

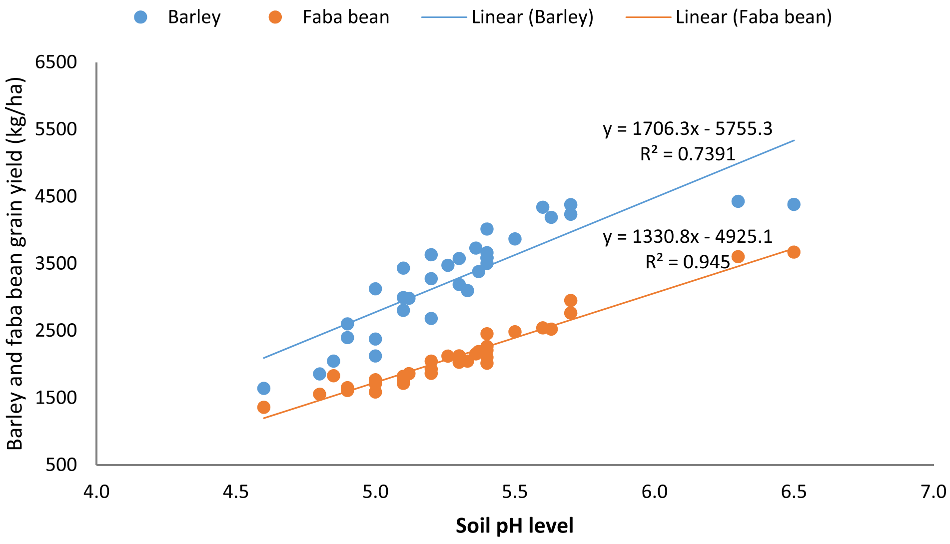

Figure 2. Relationship of soil pH status with barley grain yield and faba bean seed yield, data extracted and synthesised from different experimental findings over locations and years.

lead to poor water use efficiency due to nutrient deficiencies and imbalance and/or Al and Mn toxicity. High Al concentration also affects uptake and translocation of nutrients, especially immobilisation of P in the roots (Fageria and Baligar 2008; Baquy et al. 2017), cell division, respiration, N mobilisation and glucose phosphorylation of plants (Fox 1979; Haynes and Mokolobate 2001). At elevated Al concentrations in the soil solution, root tips and lateral roots become thickened and turn brown, and P uptake is reduced (Syers et al. 2008).

The pH effect is compounded and often surpassed by Al and Mn toxicity, Ca and Mo deficiency (Somani 1996; Baquy et al. 2017). Roots are commonly the first organs to show injury owing to acid due to Al toxicity; they become stunted, stubbly. With stunted roots, plant's ability to extract water and nutrients, particularly immobile nutrients such as P, is severely reduced (Fox 1979). Consequently, plants become susceptible to drought and prone to nutrient deficiencies. Magnesium deficiency symptoms provide a valuable indicator of acidity problems (Marschner 2011). Exchangeable Al is the dominant cation associated with soil acidity. The damage of the root growth of sensitive crop species is caused when Al in the soil solution exceeds 1 mg kg^{-1}. This often happens when 60% or more of the exchangeable capacity of the soil is occupied by Al (Fox 1979; Somani 1996). Damage may also be caused by Mn, which becomes very soluble at pH less than 5.5.

Consumption of protein is essential for normal growth and maintenance, however, the recommendation of 0.8 g of protein/kg/day is based on the protein source being 'high quality'- typically derived from an animal source. Plant proteins are usually limiting in one or more amino acids compared to human requirements and contain multiple anti-nutritive factors that further inhibit nutrient availability and absorption. In the context of acid soils, there have been several investigations into the impact of soil acidity on crop yield, however an additional consideration regarding population nutrient status is the protein content of crops grown under acid soil conditions.

Low pH soil can be detrimental to the health of crops, and so many studies highlight the effects of soil treatments on nutritional parameters. One study investigated the effect of boron and sulfur fertilisation on yield and quality of soybean grown on acid soil in India (Longkumer et al. 2017). This group identified that higher quantities of boron (0–1.5 kg ha^{-1}) and sulfur (0–60 kg ha^{-1}) in the fertiliser resulted in an increase in protein content of soybean seed from 31.7 to 40.6%. A similar study in alfalfa found that liming would increase crude protein content in shoots by up to 9% depending on season (Dugalić et al. 2012). In addition to the utilisation of agronomic treatments to increase protein content, the genetic background of the crop can play an important role. Investigations have been performed linking resistance to soil acidity and protein content in the grain of wheat (Mesdag et al. 1970) and corn (Halimi 2011), and seed of soybean (Ginting et al. 2018). This has the benefit of identifying cultivars with high protein content as well as those capable of growing in otherwise detrimental conditions, necessary information for breeders looking to optimise crops for a particular geographic region. It is worth noting that while protein content is an important parameter, there is little understanding of the impact of soil acidity on indices of protein quality such as amino acid composition or protein digestibility.

Improved acid soil management practices

The main causes and subsequent effects of soil acidity on soil properties, nutrient availability and plant growth and different acid soil management options are illustrated in Figure 3.

Liming

Management of acid soils should aim at improving the production potential of soils by applying amendments to correct the acidity and obtain optimum crop yield. Liming is the application of calcium- and magnesium-rich materials to soils in various forms. The most economical liming materials and relatively easy to manage are calcitic or dolomitic agricultural limestone (Pilbeam and Morley 2007; Rengel 2011). Calcitic limestone is mostly calcium carbonate ($CaCO_3$), while dolomitic limestone is a mixture of Ca and Mg carbonates ($CaCO_3 + MgCO_3$) which is usually more desirable as it contains both Ca and Mg. Other liming materials (byproducts or industrial products) include burned lime (CaO), hydrated lime, $Ca(OH)_2$, and wood ashes (Adams 1990).

The main effects of liming are increasing the available P through inactivation or precipitation of exchangeable and soluble Al and Fe hydroxides, increase in pH, available P, exchangeable cations and percent base saturation, and enhancing the density and length of root hairs for P uptake (Kamprath 1984; Upjohn et al. 2005). Hence, toxicity arising from excess soluble Al, Fe and Mn is corrected through liming so that root growth is promoted, and uptake of nutrients is improved. Liming also stimulates microbial activities and enhances fixation and mineralisation of N, thereby legumes

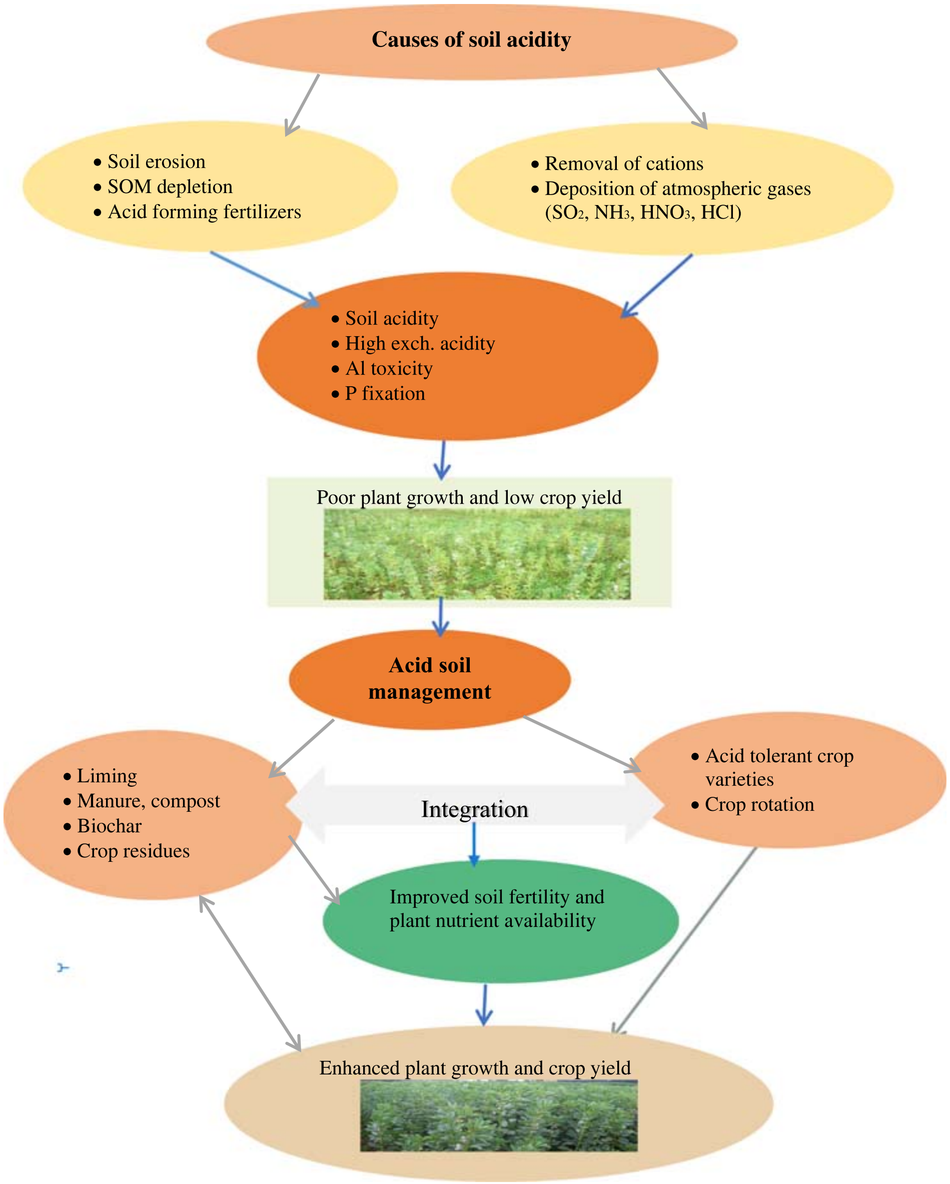

Figure 3. Illustration of causes, effects and management of acid soils in the humid tropical agroecosystems.

benefit highly from liming (Pilbeam and Morley 2007; Fageria and Baligar 2008), as Al toxicity and acidity suppresses microbial activities and nutrient cycling (Kunito et al. 2016). It should always be noted that when soils are limed plants should be sufficiently fertilised. Liming materials are normally expressed in $CaCO_3$ equivalent values (CCE) (Yang et al. 2018), and the CCE value of $CaCO_3$ is considered as a standard (100%). The acid-neutralising value of $Ca(OH)_2$ is estimated to be 135%. The higher neutralising capacity of $Ca(OH)_2$, expressed in CCE as 135%, means that when $CaCO_3$ is used in place of $Ca(OH)_2$, the weight of $Ca(OH)_2$ has to be multiplied by 135%, indicating the need for higher rates of $CaCO_3$ (Table 2).

The effectiveness of lime material is expressed by the chemical guarantee as $CaCO_3$, CaO or elemental Ca and by the particle size of the liming materials. The less the particle sizes of the liming material the higher the contact surface of the particle to react with the soil (Somani 1996). The reaction of lime with an acidic soil is described below in equation 1, which shows acidity (H^+) on the surface of the soil particles. As lime dissolves in the soil, Ca moves to the surface of soil particles, reducing soluble Al and Mn to nontoxic levels for plants. The acidity reacts with the carbonate (CO_3) to form carbon dioxide (CO_2) and water (H_2O); the result is a soil that is less acidic, with a higher pH (Adams 1990; Somani et al. 1996). The rise in soil pH is associated with the presence of basic cations (Ca^{2+}) and anions (CO_3^{-2}) in lime that are able to exchange H^+ from exchange sites to form $H_2O + CO_2$. Cations occupy the space left behind by H^+ on the exchange leading to the rise in pH

Table 2. Common liming materials and their calcium carbonate equivalent.

Name	Chemical formula	Equivalent (% $CaCO_3$)
Calcitic limestone	$CaCO_3$	90–100
Dolomitic limestone	$CaCO_3+MgCO_3$	95–110
Oxide/burned lime	CaO	130–175
Hydrated lime	$Ca(OH)_2$	120–135
Ground shells	$CaCO_3$	80–95
Basic slag	$CaSiO_3$	50–80
Wood ashes	Oxides and hydroxides	30–70

Source: Michael (2000).

(Abebe 2007; Fageria et al. 2007).

$$\text{Acid soil} + CaCO_3 = H_2O + CO_2 + Al_2O_3 \tag{1}$$

Determination of soil acidity and amount of lime requirement is associated not only to the soil pH but also to the buffer or CEC (Nelson and Su 2010). The buffering is associated with the amount of clay and organic matter present, the larger the amount, the greater the buffer capacity. Although harvested crops remove abundant lime-like elements, mainly Ca each year, the soil pH does not change much from year-to-year, implying the soil is buffered, or resistant to change. As the crop removes these elements from the soil solution, attached elements move from the soil particles to replenish the solution and over time, reserve elements are depleted enough to cause acidity. Typically clay soils and peats have a larger reservoir and higher buffer capacity than sandy ones, which means that they require more lime to achieve a suitable pH (Fageria and Baligar 2008; Rengel 2011). Coarse textured soils with little or no organic matter have low buffer capacity and, even if acid, require low lime rate. Hence, to avoid over-liming injury on coarse-textured soils, the relationship between pH and percent base saturation is important for soils with 1:1 and 2:1 clays as a much higher base saturation was required to raise the pH to 6 for montmorillonite than for kaolinite (Somani et al. 1996). Lime requirement (LR) for crops grown on acid soils is determined by the quality of liming material, status of soil acidity, crop species and varieties and their responses to lime rate, crop management practices, and economic considerations (Fageria and Nascente 2014; Li et al. 2019). Soil pH, base saturation, and Al saturation are important acidity indices which are used as a basis for determination of lime rates (Fageria and Baligar 2008; Rengel 2011). Lime requirements are expressed in terms of effective calcium carbonate equivalent (ECCE), which is established on the basis of two components: the purity of the lime, determined chemically by the calcium carbonate content in the lime material, and the fineness of the lime material, determined by how much it is ground (Ritchey et al. 2016). The more calcium carbonate and the finer the material size, the higher the ECCE, because the ECCE of lime is not always 100%, the amount of material required to provide that percentage should be calculated:

$$\begin{aligned} &\text{ECCE lime required } \times 100 \\ &\quad = \text{Lime required ECCE \%} \end{aligned} \tag{2}$$

Buffering capacity (BC) of soils is among the alternative methods for estimating lime requirement. The soil lime buffer capacity is a fundamental soil property that has many useful applications. It is the measure of the amount of soil acidity that must be neutralised to raise soil pH by one unit. According to Nelson and Su (2010), application of the sigmoid function could facilitate more accurate assessments of acidification risks, acidification rates, and potential management interventions, particularly as soils become increasingly acidic. Use of buffer curves to determine the BC of soil groups is an alternative approach to determine the LR of soil samples. It is the amount of lime required to raise the pH of an acid soil by one unit. Buffering capacity is the reciprocal of the slope of the buffer curve. Hence, the LR is determined based on the BC value, target pH, and initial soil pH using the following formula:

$$\text{LR} = \text{Target pH} - \text{Initial pH of soil sample } \times \text{BC} \tag{3}$$

The slope of the curve is determined from the part of the curve that can approximate a straight line. The intercept of the curve on the y-axis is taken as the first point to determine the changes in the pH values per unit of lime applied. The equation can provide a very good estimate of the lime requirement for the range of soil pH classes. The formula can be valid if it is applied within the ranges of soil pH values indicated in the equation. The use of BC method for the determination of lime requirement can be ambiguous for some users. To avoid confusion arising from the subjective nature of BC method, Table 3 can serve as a guide.

Frequency of liming and length of time for lime to work is vital to plan liming. Agricultural lime is not easily soluble in water as it is a natural product, even with adequate soil moisture, it may take a year or more for a measurable change in pH (Adams 1990). Normally, calcium carbonate takes more time to be soluble in water than slaked lime which consists of mostly calcium hydroxide (Somani 1996). Since neutralisation involves a reaction between soil and lime particles, mixing lime with soil increases the efficiency of acidity neutralisation (Somani 1996; Ritchey et al. 2016;). Short-term effects of lime (less than one year) are likely to be the result of physicochemical effects. On highly-weathered acidic tropical soils, where relatively low

Table 3. Estimation of lime requirements for different soil pH ranges using BC method.

pH ranges used in the curve	Curve slopes	BC (g/100 soil)	BC (kg ha^{-1})	Remark or recommendation on the use of BC values	Examples of lime rates to raise a given soil pH to target pH		
					pH ranges		Lime rate (kg ha^{-1})
					Initial	Target	
Estimation of BC values and lime rates (kg ha^{-1}) for soils with pH between 5.0 and 5.6 to raise the pH between 6.0 and 6.5							
5.17-6.12	31.61	0.0316	644	For soils with pH 5.0-5.6	5.2	6.0	530
5.17-6.4	24.87	0.0402	844	Acceptable, but less economical for one time use	5.2	6.4	1010
Estimation of BC values and lime rates (kg ha^{-1}) for soils with pH between 4.5 and 5.0 to raise the pH between 6.0 and 6.5							
4.65-6.0	11.21	0.0892	1873	For soils above pH 4.6	4.8	6.0	2250
4.65-6.30	8.26	0.1211	2544	Expensive	4.8	6.3	3820
4.63-5.61	12.24	0.0817	1716	• Cheaper for one time use, maybe with insignificant yield reduction. The rate is not recommended for split or localised application.	4.8	5.6	1370
Estimation of BC values and lime rates (kg ha^{-1}) for soils with pH between 3.8 and 4.5 to raise the pH between 6.0 and 6.5							
4.27-5.24	16.24	0.0616	1293	Cheap for one time use; perhaps, with some level of yield penalty.	4.27	5.24	1254
4.27-5.61	13.48	0.0742	1557	Acceptable for one time use; perhaps with insignificant yield reduction.	4.27	5.6	2070
4.27-5.84	11.23	0.0891	1871	Moderately acceptable.	4.27	5.8	2940
4.27-6.03	9.27	0.1079	2265	Expensive to bring the pH from below 4.3–6.0.	4.27	6.0	3918

Source: Extracted from Huluka (2005) and Sikora and Moore (2008).

lime rates are applied to neutralise exchangeable Al (usually to raise pH-H_2O to 5.3–5.6), precipitation of exchangeable Al as hydroxyl-Al species will be the main factor for improving soil structural condition (Haynes and Naidu 1998).

The residual effects of liming are usually expected to last for five to seven years. For instance, the highest yield of barley was obtained in the third year after application of lime in Ethiopia, implying that the efficiency of lime was more in the subsequent years than the first and second year of its application (Beyene 1987). Application of 200–500 kg lime ha^{-1} year^{-1} has been reported to be adequate to maintain the level of Ca and Mg in the soil while keeping a check on the release of exchangeable Al (Somani 1996). Ground limestone may have liming action for several years while hydrated lime and quick lime which are usually composed of fine particles and react quickly in the soil may have to be applied more frequently and at lower rates. Maintaining a favourable pH is extremely important in a soil fertility management plan, where periodical soil testing reveals soil pH levels and provides liming recommendations (Fageria and Nascente 2014; Ritchey et al. 2016). Inspections at intervals not greater than two to three years are advisable to economise the process of amelioration and to avoid over-liming injury to plants (Rengel 2011). The risk of over-liming is that continued increase in pH can cause Mo to become toxic. In addition, over-liming can substantially reduce the bioavailability of micronutrients such as Cu, Zn, Fe and Mn due to the low solubility of these nutrients at higher pH levels (Fageria and Baligar 2008).

Assessing the effects of lime on soil acidity and crop performance is very crucial to maximise the significance of liming. Researchers reported that soil pH increased from 5.03 to 6.72 and exchangeable acidity (EA) was significantly reduced due to the application of 3.75 t lime ha^{-1} on Nitisols with an inherent property of high P fixation in southern Ethiopia (Buni 2014). Moreover, liming significantly increased CEC and available P and decreased available micronutrients except Cu. The highest (33.34 cmol kg^{-1}) and lowest (19.18 cmol kg^{-1}) CEC values were obtained from the highest lime rate and the control treatment, respectively (Table 4). Soil pH consistently increased from 4.37 to 5.91 as lime rate increased, while the EA was significantly reduced from 1.32 to 0.12 cmol (+) kg^{-1} due to liming. Desalegn et al. (2017) showed that application of 0.55, 1.1, 1.65 and 2.2 t lime ha^{-1} decreased Al^{3+} by 0.88, 1.11, 1.20 and 1.19 cmol (+) kg^{-1}, and increased soil pH by 0.48, 0.71, 0.85 and 1.1 units, respectively, in Ethiopia. Likewise, Anetor and Akinrinde (2007) reported that liming raised soil pH (6.1–6.6), and resulted in maximum P release (15.1–17.3 mg kg^{-1}) compared to un-amended soil (4.2–7.1 mg P kg^{-1}) with pH value of 4.8. Application of lime and P also increased plant tissue P, Ca and Mg concentrations (Agegnehu and Sommer 2000).

Liming has significantly improved the response of barley and faba bean to P fertiliser application which is otherwise immobilised due to P fixation in acidic soils (Agegnehu et al. 2006; Alemu et al. 2017). For example, Desalegn et al. (2017) reported that the combined application of 1.65 t lime ha^{-1} and 30 kg P ha^{-1} resulted in 133% more barley grain yield than the

Table 4. The effect of lime on chemical properties of soils in Sodo district, southern Ethiopia.

		cmol (+) kg^{-1}		Concentration (mg kg^{-1})					
Treatment Lime (t ha^{-1})	pH	CEC	Al	EA	*P*	Fe	Mn	Cu	Zn
0	5.03d	19.18d	0.68a	0.97a	5.36b	41.96a	70.3a	0.37d	11.67a
1.25	5.64c	25.21c	0.56b	0.75b	6.70a	33.77b	58.4b	0.77b	11.19b
2.50	6.14b	31.49b	0.33c	0.51c	7.04a	25.04b	46.0c	0.99a	9.78c
3.75	6.72a	33.34a	0.24c	0.36c	6.67a	19.01c	34.5d	0.65c	9.75c
$LSD_{0.05}$	0.01	0.74	0.13	0.21	0.94	0.39	4.52	0.06	0.14
CV (%)	3.0	6.2	8.1	6.4	2.0	11.6	14.7	10.1	12.4

EA: Exchangeable acidity; LSD: Least Significant Difference at $p < 0{:}05$; CV: Coefficient of Variation. Source: Asrat et al. (2014).

control (without P and lime). According to Hillard et al. (1992), decreasing winter pasture productivity in unlimed Ultisols has been associated with increased soil acidity due to N fertiliser application. Thus, over three harvest years, rye grass yields increased 90–750% and 25–80% at the highest lime and P rates, respectively. In the second year, yield response to applied P was significantly less at the highest lime rate, indicating that liming made the soil P more plant available. Agegnehu et al. (2006) reported that addition of lime at the rates of 1–5 t ha^{-1} resulted in faba bean seed yield increments of 45–81% over the control. Mahler et al. (1988) also found that seed yields of legumes were optimal between soil pH values of 5.7 and 7.2 and yields of pea could be increased by 30% due to lime application to soils with pH values less than 5.4.

Application of NPK fertilisers with lime significantly increased potato tuber yield in Chencha (20.5 t ha^{-1}) than in Hagereselam (13.8 t ha^{-1}) (Figure 4), with 42%–279% higher yield in Chencha than in Hagereselam (Haile and Boke 2009). However, lime application alone did not significantly improve potato tuber yield, indicating that the soil in Chencha is better in fertility and more responsive to the treatments than the soil in Hagereselam which is low in soil pH, nutrient content, and yield. Liming improves the yield of crops if an acidic soil has essential nutrients rendered unavailable to crops due to low pH, but if the soils are already depleted of nutrients, crops respond to lime application only (Marschner 2011). Haile and Boke (2009) reported that application of NPK + lime resulted in the highest potato tuber yield of 30.67 in Chencha with yield increments of 332 and 73% over NP and NPK fertiliser treatments alone, respectively. However, in Hagereselam, the same treatment resulted in the highest tuber yield of 10.03 t ha^{-1} with yield increments of 82 and 59% over NP and NPK fertiliser treatments alone, respectively (Figure 4). These marked increases in potato yield is due to K application with NP, suggesting that balanced application of NPK is more efficient than applying NP alone in K deficient

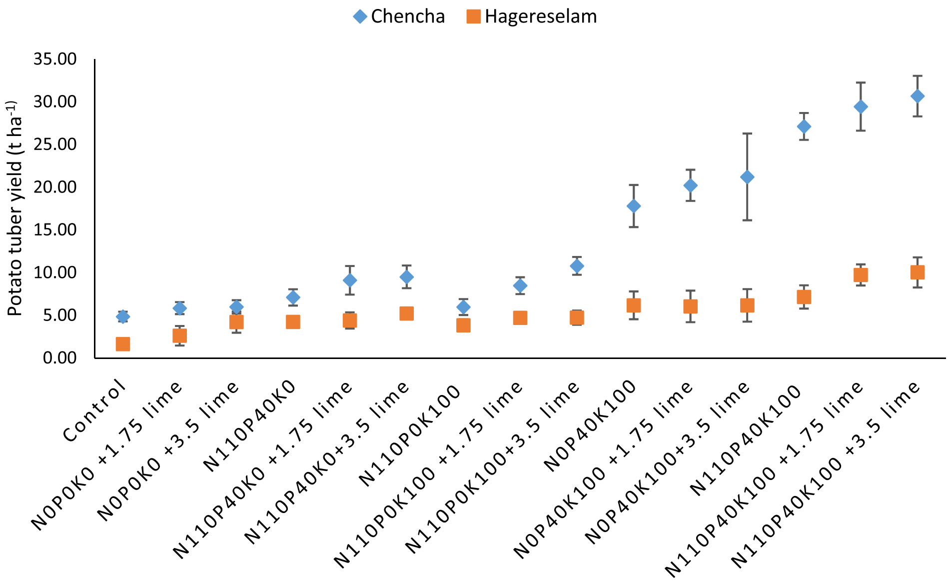

Figure 4. Lime and NPK fertilisers effects on tuber yield of Irish potato at Chencha and Hagereselam, southern Ethiopia, 2007-2009. Data synthesised and analysed from Haile and Boke (2009). Error bars represent ±1 SE. Units of lime and fertiliser are in t ha-1 and kg ha-1, respectively.

soils. Thus, to enhance crop production in acidic soils, a sustainable solution should consider a balanced application of nutrients.

Improving soil organic matter

Enhancement of soil organic matter (SOM) is one of the key approaches of current agricultural research and development is to motivate African farmers to make better use of organic resources to enhance fertility, alleviate elemental toxicity and protect the soil (Pauw 1994; Vanlauwe et al. 2015; Amede et al. 2021). Green manuring, application of compost, farmyard manure (FYM), biochar and retention of crop residues are the major organic inputs to enhance soil organic matter and recycle nutrients to the soil. Studies have shown that organic matter promotes microbial activity, improves soil structure, aeration, nutrient retention and water holding capacity (Vanlauwe et al. 2015; Agegnehu and Amede 2017; Amede et al. 2021). Crop residues can recycle nutrients removed from the soil by crops, while green manures contribute substantial amount of N to subsequent crops and at the same time protect the soil against erosion (Xu et al. 2002; Kumar and Sukul 2020). Use of organic matter in the form of crop residues, green manures, FYM, compost or biochar could also reduce the effects of toxic elements by extracting them from the soil solution and incorporating them into organic compounds (Sharma et al. 1990; Luo et al. 2017; Cornelissen et al. 2018). When organic inputs are applied, the quality, quantity and types of nutrients supplied by them should be considered as they are bulky.

Integrated acid soil management (IASM)

IASM is one of the components of the management of acid soils. In acid soils, application of FYM releases a range of organic acids that can form stable complexes with Al and Fe thereby blocking the P retention sites, and thus the availability and use efficiency of P is improved (Sharma et al. 1990; Prasad and Power 1997; Agegnehu and Amede 2017;). Organic sources such as crop residues, manures, compost and biochar can partially or wholly substitute lime (Sharma et al. 1990; Agegnehu and Amede 2017). The addition of organic amendments to acid soils has been effective in reducing phytotoxic levels of Al, thus resulting in yield increases (Haynes and Mokolobate 2001). Studies in SSA also indicated that the incorporation of biochar from different feedstock to acidic soils significantly increased soil pH, organic carbon, available P, N, exchangeable bases, reduced exchangeable acidity, and improved yield of crops (Abewa et al. 2014; Mensah and Frimpong 2018).

The practical implication of these processes is that organic residues may be used as a strategic tool to reduce the rates of lime and fertiliser P required for optimum crop production on acid soils. The application of 30/10 kg NP ha^{-1} with 50% manure and compost as N equivalence on acidic Nitisols of Ethiopian highlands increased grain yield of wheat by 129 and 68% compared to the control and 23/10 kg NP ha^{-1} (50% the recommended rate of NP fertiliser), respectively (Agegnehu et al. 2014). The same rate increased soil pH from 5.0 to 5.6, OC from 1.3 to 2.3%, total N from 0.12 to 0.18%, available P from 7.7 to 11.2 mg kg^{-1}, NO_3-N and NH_4-N 6.2–10.7 and 5.9–12.9 mg kg^{-1}, respectively. Similar studies showed that the residual effects of manure and compost applications significantly increased electrical conductivity (EC), soil pH, plant-available P and NO_3-N concentrations (Eghball et al. 2004; Walker et al. 2004). Insufficient application of one nutrient may cause the loss or the imbalance of other essential nutrients. For example, insufficient application of K fertiliser increases leaching losses of Ca, Mg and N (Poss and Saragoni 1992). Therefore, aapplication of organic residues not only increase crop yield through the release of nutrients but also improve the physicochemical and biological properties of soils.

Application of lime with other complementary agricultural practices/inputs offers substantial yield improvements. As indicated in Table 5, yield improvements ranging from 34% to over 252% in wheat, barley, and tef (Abewa et al. 2014; Asrat et al. 2014; Desalegn et al. 2017), 29-53% in faba bean and soybean (Agegnehu et al. 2006; Bekere et al. 2013), and 134–217% in potato (Haile and Boke 2011) in Ethiopia, 111–182% in maize in Kenya (Opala et al. 2018), and 45–103% in Mucuna in Nigeria (Agba et al. 2017) have been reported under moderate to severe acid soil conditions. In most cases, P, K and N fertilisers should be applied together with lime and other improved management practices to achieve significant yield increases. Moreover, a single application of lime has five to seven years of productivity benefits. In the longer term, lime-induced increases in crop yields will result in greater input of organic material and a buildup in soil organic matter and soil biological activity both of which favour improved aggregate stability and increased porosity (Haynes and Naidu 1998).

Sustainable cropping systems

Sustainable cropping system is the approach how different crops are grown considering the biophysical and socio-economic conditions to sustainably increase soil quality and crop yield. Cropping system practices are dictated by crop diversity, farming system, soil types, agroecology, and market. Crop rotation and intercropping systems are major components of a cropping

Table 5. Effect of lime and other soil fertility management practices on yield of selected crops and soil properties.

Crop	Treatment		Yield			
	Manure (t ha^{-1})	Lime (t ha^{-1})	(t ha^{-1})	% increase over control	Effect on soil properties and nutrient uptake	Source
Wheat	0-5.0	0.0–2.20	0.90–2.69	94–199		(Asrat et al. 2014)
Wheat		0–10	2.44-4.27	34–75	Liming improved soil pH and plant P uptake.	
	N/P/K (kg ha^{-1})	**Lime (t ha^{-1})**	**Yield (t ha^{-1})**	**% increase over control**		
Tef	0-46/0-26/0	0.00–2.00	0.82–2.88	99–252	Liming increased soil pH from 5.38 to 6.17 and CEC from 14.8 to 20.7	(Abewa et al. 2014)
Soybean	18/20/0	0.00–3.75			Increased soil pH from 5.03 to 6.72, and reduced Al^{3+} from 0.68 to 0.36 cmol kg^{-1}	(Buni 2014)
Soybean	18/20/0	0.00–2.60	1.58–2.31	29–46	Increased nodule dry weight by 100%.	(Bekere et al. 2013)
Barley	50/0-30/0	0.00–2.20	2.54–4.56	52–81	Lime reduced Al^{3+} by 0.88–1.19 meq 100 g^{-1} soil, and raised soil pH by 0.48–1.1 units.	(Desalegn et al. 2017)
Barley	145/00/00	0.00–7.00	2.52–4.24	15–68	Lime increased pH in the surface 15 cm and reduced Al^{3+} only in the 0-5-cm layer.	(Tabitha et al. 2008)
Barley	41/20/0	0–4.5	1.28–1.83	4.0–41	Liming increased soil pH from 4.53 to 5.61 and reduced EA from 2.2 to 0.23 cmol kg^{-1}	(Beyene 1987)
Oats/soy bean	-	0.0–2.0	0.96–1.48	5–54	Liming reduced H^{+} and Al^{3+} contents to a depth of 0.60 m.	(da Costa and Crusciol 2016)
Maize	60/26/0	0–2.0	1.77–4.99	111–182	Liming increased soil pH from 4.92 to 5.46 and reduced EA from 0.25 to 0.10 cmol kg^{-1}.	(Opala et al. 2018)
Faba bean	18/20/0	0.0–5.0	0.81–1.47	45–53	Liming increased soil pH from 5.1 to 5.9 and reduced EA from 1.31 to 0.12 cmol kg^{-1}.	(Agegnehu et al. 2006)
Mucuna flagellipes	-	0.0–4.0	1.39–2.82	45–103	Liming increased soil pH from 4.3 to 6.1.	(Agba et al. 2017)
Potato	0/0/0/-110/40/100	0.0–3.5	10.03–30.67	59–332	Liming increased soil pH from 4.8 to 5.5.	(Haile and Boke 2009)
	NPK (kg ha^{-1})	**FYM/compost (t ha^{-1})**	**Yield (t ha^{-1})**	**% increase over control**		
Wheat	23/10/0	0.0–8.0	1.2-2.9	68–129	Addition of FYM increased soil pH from 5.0 to 5.6, OC, N and P.	(Agegnehu et al. 2014)
Potato	0/0/0/-110/40/100	0–20	17–54	134–217		(Haile and Boke 2011)

system that are practiced by farmers in various ways across SSA. Improved intercropping system could maximise the complementarity between annual legume and cereal crops or annual and perennial crops (Pauw 1994). The rotation of crop species in time has long been known to increase the productivity of land and sustainability of crop yields (Xu et al. 2002). Rotations that include legumes can host N-fixing bacteria in their roots, contributing to optimum plant growth without increased GHG emissions. Crop rotations improve soil fertility, which play a key role in raising healthy and productive crops. For instance, rotating barley with legumes increased grain yield of barley by 26-93% on acidic Nitisols of Ethiopian highlands, compared to barley monocropping (Agegnehu and Amede 2017). Overall, without improving the overall condition of acid soils full intensification would be unlikely.

Matching of certain trees with specific crops as an agroforestry system can provide benefits that exceed the sum of the individual system components due to the nutrient pumping effect of agroforestry trees which bring nutrients up from the lower parts of the soil. Agroforestry enhances SOM, agricultural productivity, carbon sequestration, water retention, agrobiodiversity and farmers' income (Paul et al. 2017; Haile et al. 2021). Buresh and Tian (1998) also reported that trees could increase the supply of nutrients within the rooting zone of crops through biological N_2 fixation, retrieve nutrients from below the rooting zone of crops and reduces nutrient losses through leaching and erosion. Agroforestry is increasingly widespread for restoration of degraded lands to contribute to food security and for economic development. Where trees are key components of the system, they can greatly help restore landscapes that contribute to improve land productivity, thereby deliver multiple benefits for humans and ecosystem services (Paul et al. 2017; Haile et al. 2021).

The choice and application of the right fertiliser types at the right rates and time is one of the major acid soil management practices. Ammonium-based fertilisers increase acidity as they generate H^+ ions when NH_4 molecules are nitrified. Ammonium fertilisers can also lead to soil acidity when nitrate leaching exceeds plant uptake (Goulding 2016; Rahman et al. 2018). The fertiliser rates to be applied should be adjusted to compensate for the nutrient removals based on the target yield levels. Application of lime is important to tackle the immobilisation of P due to soil acidity. Use of cheap P sources such as rock phosphate has also additional benefit of a liming effect, increasing available Ca, raising pH and reducing exchangeable Al.

Acid-tolerant crops and varieties

Over the past decade, several researchers have focused their efforts on identifying and characterising the mechanisms employed by crop plants that enable them to tolerate Al toxic levels in acid soils. The two distinct classes of Al tolerance mechanisms are those that operate to exclude Al from the root apex and those that allow the plant to tolerate Al accumulation in the root and shoot symplasm (Ma et al. 2001; Kochian et al. 2004). Despite considerable assumptions about some different Al tolerance mechanisms, several research findings have focused on root Al exclusion based on Al-activated organic acid exudation from the root apex. Evidence is also increasing for a second tolerance mechanism based on internal detoxification of symplastic Al via complexation with organic ligands, again primarily organic acids (Barcelo and Poschenrieder 2002; Garvin and Carver 2003; Poschenrieder et al. 2008).

Several plant species of economic importance are generally regarded as tolerant to acid soil conditions. Many of them have their centre of origin in acid soil regions, suggesting that adaptation to soil constraints is part of the evolutionary process (Somani 1996). While the species generally does not tolerate, some varieties of certain species possess acid soil tolerance. Quantitative assessments of plant tolerance to acid soil stress include tolerance to high levels of Al or Mn, and to deficiencies of Ca, Mg, P, etc. Species and genotypes within a species have been reported to have considerable variation in their tolerance to Al and Mn (Somani 1996; Kochian et al. 2004). The selection of varieties or species that perform well at high Al saturation levels and thus need only a fraction of the normal lime requirement is of great practical importance (Table 6). Research on the development of acid-tolerant crop varieties, such as barley, maize, soybean, potato, etc., has been undertaken since the last decade in some SSA countries. For instance, in Cameroon, a maize yield increase of 51% was obtained with some P-efficient varieties under low soil pH, but a yield reduction of 37% was observed in other varieties (Tandzi et al. 2018). Likewise, some single cross hybrids expressing superior tolerance to Al toxicity were identified in Kenya (Tandzi et al. 2018).

Table 6. Crops and pasture species suitable for acid soils with minimum lime requirements.

Lime requirement (t ha^{-1})	Al saturation (%)	pH	Crops (using tolerant varieties)
0.25–0.5	68–75	4.5–4.7	Upland rice, cassava, mango, citrus, pineapple, sugarcane, *Desmodium*
0.5–1.0	45–58	4.7–5.0	Cowpeas, plantains
1.0–2.0	31–45	5.0–5.3	Corn, black beans

Source: Somani (1996).

Conclusions

Soil acidity and associated low nutrient availability are among the major constraints to agricultural productivity in SSA. Liming acid soils to mitigate soil acidity and reduce phytotoxic levels of Al and Mn has been recognised as necessary for optimal crop production. However, application of lime should be considered as an approach to optimise soil pH and nutrient availability for better plant growth and yield. Liming should be coupled with the applications of optimum rates of inorganic and organic fertilisers. There is also a need for identifying areas where lime application brings significant change and benefit in crop yield. The extent of soil acidification can also be reduced through integrated soil and crop management practices. Integrated soil fertility management approach can enhance soil fertility and crop yield. Application of organic residues enhances buildup of nutrients in the soil and after successive years of application, the dose of nutrients to be applied either as inorganic or organic forms will gradually decrease. Matching applied nitrogen and sulfur with crop needs may also reduce input costs while reducing acidification. Other practices involve the choice and use of less acidifying fertilisers coupled with appropriate rate and time of application.

Soil health is the basis of the productivity of farming systems, the food and nutrition security of societies, and the improvement of livelihoods and poverty alleviation in SSA. Management of acid soils needs strategic research, integrating soil and water management with improved crop varieties to generate prototypes and environmentally friendly technologies for sustainable crop production within appropriate socio-economic and policy considerations. Overall, adoption of improved soil management practices is essential to adapt to the changing climate and meeting the needs of the growing populations for food and raw materials for industries.

Acknowledgements

The authors would like to acknowledge IDRC Canada and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) of the German Federal Ministry for Economic Cooperation and Development (BMZ) for supporting this work. We also thank Dr. Steffen Schulz for editing the manuscript and Mr. Gizachew Legesse for preparing the soil acidity map of SSA.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Deutsche Geselschaft fur Internationale Zusammenarbeit.

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