PBL Netherlands Environmental
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Micronutrients for agricultural intensification

Is Sub-Saharan Africa at risk?

Policy Study

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MAIN FINDINGS

Summary

In Sub-Saharan Africa, population growth, associated food demand and pressure on natural areas have all increased greatly. Agricultural intensification – more production from the same acreage – remains a key solution to these challenges. Main trends in agriculture show that, in most Sub-Saharan African countries, agricultural area expansion has outpaced crop yield increases. Though considerable diversity between countries exists, Sub-Saharan Africa as a whole is at risk of continuing on a path of low agricultural intensification, mounting further pressure on natural areas.

One of the cornerstones of intensification is that of a higher and more productive use of inputs, such as chemical fertilisers, yet the average uptake of fertiliser and yield increases have remained low. Most chemical fertilisers contain macronutrients only (nitrogen, potassium and phosphorous). Recently, attention for the role of soil micronutrient deficiencies as a possible explanation for low productivity has increased. Compared with macronutrients, micronutrients are required in smaller quantities for optimal plant growth, but are indispensable nonetheless. They are, however, often insufficiently available in soils. Opportunities for improving crop growth lie in development and application of fertilisers enriched with the lacking micronutrients. This may concurrently increase the efficiency of fertiliser use and thus stimulate its uptake, raising productivity and farm income and slowing down the current, unabated agricultural expansion into natural ecosystems. In other words, it could be a means to stimulate agricultural intensification and Inclusive Green Growth.

In addition, it could play a role in reducing incidences of malnutrition. Reduced availability of these micronutrients, leading to insufficient levels in human diets, invokes a range developmental problems. The consequences of zinc deficiency are one of the best documented. It is a leading cause of mortality amongst young children in Sub-Saharan Africa. Nutritional quality – the sufficient intake of all essential nutrients – also plays a key role in child cognitive development. Increasing soil concentrations of these essential nutrients potentially leads to an increased nutrient content of food crops and, in this way, reduces these issues of malnutrition.

Increasing nutrient application through fertilisers may require large amounts of these elements and metals, which currently are mostly used in industrial sectors, potentially increasing competition for already scarce elements. This links intensification directly to global and often volatile markets for these elements. Many of these elements are currently not mined in Africa, and African countries may not have the means to procure them.

Motivated by these issues, we investigated the impact of the potential demand from intensified agricultural production in Sub-Saharan Africa on sometimes overstretched markets. Considering future food demand, how large do volumes of nutrients need to be to satisfy potential demand from the agricultural sector? Is there a risk that scarcity of certain elements, and associated high prices, curb or jeopardise the Sub-Saharan African quest for agricultural intensification?

In order to answer these questions, detailed insights into the magnitude of nutrient deficiencies in Sub-Saharan Africa are essential. Therefore, PBL commissioned World Soil Information (ISRIC) to synthesise available information and estimate soil nutrient stocks across Sub-Saharan Africa. The resulting maps, at a resolution of 250m, currently constitute the most detailed available that cover the African continent fully.

Merging these novel data with scenarios on agricultural development, we approximate potential volumes that are required to sustain a more intensified agriculture.
These volumes account for both nutrient applications to raise current stocks to levels suitable for more intensified agricultural production, and to replace nutrients continuously being removed in harvested crop and livestock products. Considerable uncertainties in the exact

relations between nutrient availability and crop uptake remain, next to variation in local agricultural practices. Both are reflected in relatively wide ranges computed.

Next, as a first assessment we contrast the estimated ranges of minerals and metals with global supplies. The outcome suggests that for most nutrients volumes are relatively small compared with reserves and annual production. Main exceptions are manganese, magnesium and potassium. We extend this assessment to account for additional factors shaping the supply risk of these elements, further taking into account global reserves, and the location in which mining operations take place (the level of economic and human development and geopolitical concentration). We find that supply risks are highest for manganese and zinc.

On the other hand, we assess the vulnerability of African countries to supply restrictions. The required volumes may differ considerably from one country to another. Countries may substitute global supply squeezes from own production or may have ample foreign currency reserves to source lacking nutrients. The results highlight an elevated vulnerability across the continent, but also shows considerable diversity between countries. The high vulnerability to potassium supply risk is most apparent, namely because of the lack of potassium mines. The most vulnerable are those countries already dependent on net agricultural imports, despite having a dominant agricultural sector.

The results of this report raise a number of implications for policy-making. Foremost, it should be reiterated that the nutrients considered are essential for agriculture as well as human health. Unlike in many industrial applications, they are not substitutable in crop growth or human nutrition. Keeping this in mind, we identify three key focus areas for policymakers and link these to specific policy options. Firstly, in order to address potential scarcities, non-agricultural demand and agricultural demand should be kept as low as possible, for instance by stimulating substitution and recycling and minimising losses. Secondly, fertiliser product innovation needs to be fostered. In order to reach this, field trials and systemised data collection are indispensable to induce public, private or public–private research and development on developing and testing novel fertiliser products. Thirdly, in order to bring impact to scale, farmgate fertiliser prices need to decrease. In some cases, mandatory application of lacking nutrients could be desirable. This approach is geared towards the goal of profitably getting the right nutrient in the right amount to African farmers in a specific place. It raises crop yields, production levels and incomes, and could ease existing pressure on pristine areas. In the medium to long run it may serve to reduce incidences of malnutrition.

FULL RESULTS

Introduction

The burgeoning population in Sub-Saharan Africa creates an additional demand for food of at least 140% to possibly 170%, up to 2050 (FAO, 2009; Tilman et al., 2011; Ray et al., 2013; PBL, 2012). Meanwhile, the pressure on the remaining natural areas in Sub-Saharan Africa is high. In recent years, substantial tracts of forests have been cleared and converted into agricultural areas (Brink and Eva, 2009; Brink et al., 2014). Agricultural intensification – more production from the same acreage – remains a key solution to increase food supply and raise rural incomes, while safeguarding pristine ecosystems from being converted into cropland. A cornerstone of intensification is a higher and more productive use of inputs such as chemical fertilisers. Notwithstanding considerable diversity across countries, average uptake of fertilisers and growth in crop yields have remained weak.

A multitude of technical, social, and institutional explanations all have their merit in explaining parts of this shortfall in expectations. Of recent, an appreciation of the role of micronutrients, and the impact of micronutrient deficiencies across Sub-Saharan Africa, has emerged (Lyons and Cakmak, 2012; Voortman, 2012; Dimkpa and Bindraban, 2016; F&KBF, 2016; VFRC, 2017). The old and weathered soils in Sub-Saharan Africa may be particularly prone to such deficiencies. A wide array of nutrients (minerals and metals) are indispensable in supporting a healthy growth of both humans and plants (Table 1). This includes some well-known minerals, such as potassium and calcium (macronutrients), but also various metals, including boron, manganese and zinc (micronutrients)[1].

A limited availability of micronutrients impairs crop growth and may jointly explain the low efficiency and low profitability of regularly promoted fertilisers. The latter typically contain nitrogen, to which phosphorus and potassium are added in some blends. When other essential micronutrients/macronutrients are neither sufficiently available in soils, nor included in these fertilisers, crop responses to fertiliser application will be low.

Hence, even though levels of fertiliser use across Sub-Saharan Africa are considered low by global standards, they may well be close to actual economic optima at prevailing crop responses and prices (Suri, 2011; Beaman et al., 2013; Sheahan et al., 2013).

Effective interventions need to focus on further reducing fertiliser prices but also on increasing crop responses to fertilisers. One promising avenue is to enrich fertilisers with lacking micronutrients. It may concurrently raise the efficiency of fertiliser use and stimulate its uptake, raising productivity and farmer incomes and slow down agricultural expansion, continuing unabatedly into natural ecosystems. In other words, it could be a means to stimulate agricultural intensification and Inclusive Green Growth.

At the same time, it could play a role in reducing incidences of malnutrition. Shortfalls in availability and human consumption of these elements invoke a range developmental problems. With respect to human diets, the case of zinc deficiency is one of the best documented. Zinc deficiency is a leading cause of mortality amongst young children in Africa; for instance, due to more frequent and prolonged incidences of diarrhoea (Berti et al., 2014). Nutritional quality (i.e. sufficient intake of all the essential nutrients) also plays a key role in child cognitive development (Black et al., 2013; Berti et al., 2014). Benefit-cost ratios for combatting malnutrition in the developing world are particularly large because they have such large societal multipliers (Horton and Hoddinott, 2014). The agricultural sector is thereby well placed to abate this crisis. In some countries nutrient-enriched fertilisers are understood to have greatly reduced deficiencies in soils and human consumption (Cakmak, 2008; Ros et al., 2016).

This reasoning also implies that further intensification of the agricultural sector in Sub-Saharan Africa requires an external supply of various minerals and metals. This links this sector, and the sufficient availability of nutritious

Table 1

Essential building blocks for plant and human development

	Essential for:	
	Plants:	**Humans:**
Nutrients considered in this report:		
Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), zinc (Zn), boron (B), iron (Fe), manganese (Mn), copper (Cu)	√	√
Other essential nutrients not considered[2]**:**		
Molybdenum (Mo), chlorine (Cl)	√	√
Nickel (Ni)	√	
Cobalt (Co), chromium (Cr), iodine (I), selenium (Se), silicon (Si), sodium (Na)		√

food in Sub-Saharan Africa, directly to global and often volatile markets for elements such as manganese and zinc (e.g. Prins et al., 2011). For instance, over 90% of US consumption of these metals is in industrial applications (e.g. galvanising steel and producing ferroalloys) (USGS, 2017).

Debate on the finiteness of resources and raw materials has been recurrent (Meadows et al., 1972; Meadows et al., 2004; Henckens, 2016), but attention has shifted from concerns over physical depletion towards resource access and price volatility. This publication builds on various studies on raw materials' criticality (Erdmann and Graedel, 2011; Prins et al., 2011; Achzet and Helbig, 2013; Helbig et al., 2016). These studies consider geological reserves as one of a broader range of institutional and economic factors that determine supply and price stability. This Note investigates the impact of potential and additional demand from intensified agricultural production in Sub-Saharan Africa on already overstretched markets. Thus, considering future food demand, how many nutrients will be needed to satisfy potential demand from the agricultural sector? Is there a risk of supply restrictions of certain elements, and associated high prices, curbing or jeopardising the Sub-Saharan Africa quest for agricultural intensification?

To answer these questions, we revisit trends in the current use of inputs and productivity in Sub-Saharan African agriculture in Section 2 and contrast these with socially and environmentally desired changes. Section 3 presents new data on nutrient densities in soils and graphically shows were nutrient shortages are most likely to impact agricultural production. Section 4 expands on these insights, to accommodate linkages to global markets. For which elements are supply risks the greatest and which Sub-Saharan African countries are the most vulnerable to such risks? Section 5 reiterates the main findings and presents effective and efficient avenues for policymakers and researchers to address nutrient deficiencies in Sub-Saharan Africa.

Notes

1 The reference to 'macro' and 'micro' extends solely to differences in the absolute amounts of nutrients contained in plant tissue, and the terms do not contain any information on their importance. Both types of nutrients are essential and non-substitutable for healthy plant growth, with each individual chemical element serving a different function in this process. In line with many other studies, we refer to nitrogen, phosphorus, potassium, calcium, magnesium and sulphur as macronutrients, while all other nutrients are collectively considered as micronutrients.

2 Selection of the data used in this report strongly depended on their availability. Their inclusion, therefore, has no relationship with their level of importance. For the nutrients included, it proved possible to construct estimates of densities in soils across Sub-Saharan Africa. Next, the impact of malnutrition is relatively well-documented for some of these nutrients.

TWO

Main trends in Sub-Saharan African Agriculture

The Sub-Saharan African population increased at a relatively high annual rate of 2.75%, between 1970 and 2015, to a total of nearly one billion, which is triple that of 1970. To provide food for the growing population, agricultural production has increased but the continent has become increasingly reliant on food imports nevertheless (Rakotoarisoa et al., 2011). Undernourishment continues to be a serious problem in many countries, even though the share of undernourished in total population declined gradually (e.g. FAO, 2017b). In order to close the per capita gap in undernourishment, food demand is thus bound to increase stronger than population numbers. Moreover, diets are changing, with the share of animal products in diets increasing. The production chain of livestock is far less efficient than that of food crops, as animals require substantial amounts of food intake to sustain their lives, digestive tracts, and to reproduce themselves.

Crop yields increased slowly across Sub-Saharan Africa from 1980 onwards, so agricultural intensification lagged behind production. Substantial tracts of forested and other natural areas have been converted into agricultural lands (Brink and Eva, 2009; Brink et al., 2014). The average cereal yield in Sub-Saharan Africa increased from around 1,131 kg/ha to 1,548 kg/ha (1980–2013; Figure 1, top panel). In itself, this reflects a considerable increase of 37%, but is still substantially lower than the global average cereal yield in 2013 (3,840 kg/ha) as well as the global growth rate (78%) over that period. However, individual countries experienced trends very different from the average. Ranging from no or negligible yield increases and vast area expansions, to constant or even slightly smaller cultivated areas with varying yield trends.

The diversity across countries displayed in Figure 1 illustrates that actual crop yields depend on a range of factors, including climatic conditions, soil quality, sophistication of technical and management skills, access to markets and finance, etc. A well-balanced mix of these factors is required in order to raise yields effectively, as these strategies are only substitutable to a point. For example, while on average labour productivity increased in Sub-Saharan Africa (Wiggins, 2014) this has not translated into significant yield enhancements. One probable cause is that fertiliser use remains relatively low (Morris et al., 2007).

Recognising the increasing pressure to raise food production in Sub-Saharan Africa to overcome already current shortfalls and a growing future population, food demand is projected to increase strongly, in the next decades. Production of food crops is projected to grow, from 510 Mt in 2015, by a factor of 2.4 to 2.7, by 2050 (IMAGE model data used in: Kok et al., 2014). In the same period, production of animal products will grow from 51 Mt in 2015 to around 165 Mt by 2050, 3.2 times the 2015 level.

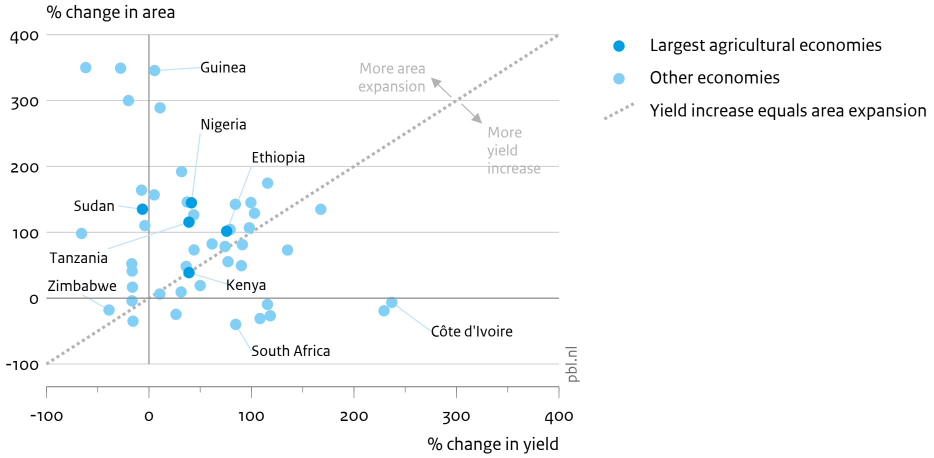
But, in order to support farm income and to constrain expansion of agricultural land, average yields will need to improve drastically. While on the whole, large tracts of currently uncultivated, suitable land for agriculture exist in Sub-Saharan Africa, this land is very unevenly distributed across the continent, matches poorly with spatial population distribution, and occupies valuable ecosystems including rain forests. In one PBL study (Kok et al., 2014), projections were explored that aim to match different goals and ambitions for food security, climate resilience, and nature conservation. Depending on the choice of pathway, the development of agricultural area and yield over time show a very different trend than the historical average trend, see Figure 1 (bottom panel).

Figure 1 also shows that even the baseline trajectory ('Trend scenario') assumes a larger yield improvement and slower area expansion than the historical trend. A scenario with accelerated human development projection, enabled by technical and managerial progress and enhanced access to markets ('Global Technology scenario') displays the strongest levels of intensification. In the projections, it is assumed that future nutrient

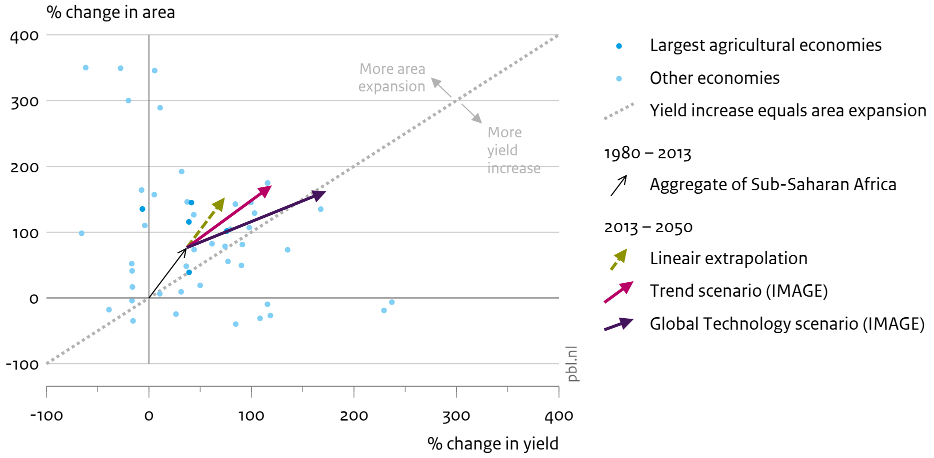
Figure 1

Changes in cereal yield and area expansion in Sub-Saharan Africa

1980 – 2013



2013 – 2050



Source: FAO; PBL/IMAGE; Worldbank

management including fertiliser application is adequate to sustain the yield improvements. While climate change and basic soil quality were considered explicitly, no specific attention was paid growth constraining factors such as micronutrient deficiencies as is the focus in this note.

Various factors may explain the diversity across countries (Figure 1; top panel) of which differences in soil fertility could be one. Low densities of essential soil nutrients could form a plausible explanation for farmers preferring an area increase over intensification in order to increase production volumes. If true, this implies that agricultural intensification in these areas can only be achieved through the supply of nutrients from external sources. The next sections take this reasoning a step further and presents first approximations on the volumes of nutrients required to further scale up agricultural intensification.

THREE

Variation in soil nutrient densities

Gaining more insight into the magnitude of nutrient deficiencies, and the potential demand that correcting such deficiencies may incur, is thus a high priority. But, most data on soil nutrient stocks are either site-specific or very general estimates of nutrient availability across the continent. It is for these reasons that PBL commissioned ISRIC – World Soil Information to synthesise available information and estimate soil nutrient stocks across Sub-Saharan Africa in more detail. The resulting maps, at a resolution of 250 m, currently constitute the most detailed map available, fully covering Sub-Saharan Africa[1].

This Section highlights the main results, notably the distribution of nutrient densities across the continent, thereby identifying those regions where soil macronutrient and micronutrient levels may be problematic. Secondly, a first order approximation of required volumes in order to stimulate agricultural intensification is computed. These computations are carried out using data on critical thresholds for agricultural production, crop and livestock production scenarios, and resulting rates of nutrient depletion.

3.1 Distribution of soil nutrient densities across Sub-Saharan Africa

In order to better estimate soil nutrient stocks across Sub-Saharan Africa, various databases of soil sample data were merged, yielding a database with soil data from about 59,000 locations. Fifteen nutrients were considered: organic carbon (C), organic nitrogen (N), extractable and total phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), sodium (Na), aluminium (Al), boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn).

A statistical model is used to explain the observed soil nutrient densities from a wide range of remote sensing covariates, capturing soil formation processes (climate, landform, lithology, and vegetation). Insights into the methodology used and the main results obtained are reported elsewhere (Hengl et al., in press). For most nutrients, the predictive quality (R-squared) of nutrient densities was high to very high (scores of R-squared ranging from 40% to 85%). Only the variation in soil densities of phosphorus and sulphur turned out difficult to explain. For this reason, these elements are not considered further in this study. The estimated model is subsequently used to predict soil nutrient densities in locations where no actual soil samples were taken. Examples of predicted soil nutrient densities, for zinc and manganese across Sub-Saharan Africa, are given in Figure 2.

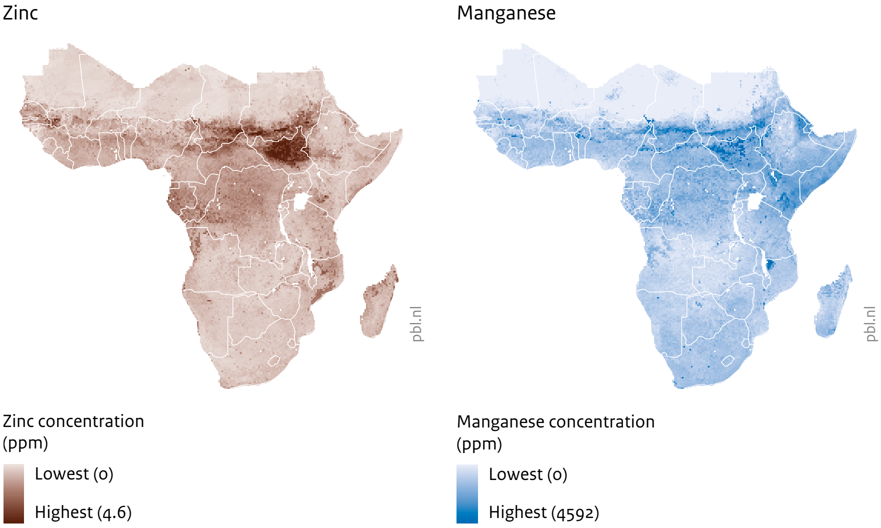
In a first assessment of the dispersion of nutrient availability and potential deficiencies across Sub-Saharan Africa, the lower end of the distribution of each nutrient was considered. For each grid cell, Figure 3 displays the count of nutrients that fall within the lower 25% range of each nutrient distribution, for micronutrients (B, Cu, Fe, Mn, Zn) and macronutrients (Ca, K, Mg, and N). Information on critical thresholds for different levels of agricultural production is scarce (see next section). Therefore, Figure 3 should be interpreted as depicting regions (in red) with the greatest *likelihood* of having one or more nutrient deficiencies, limiting a more intensified agricultural production. One such region is at the northern edge of the Sahel in West Africa, a region where the prevalence of malnutrition is equally high.

3.2 Potential volumes of nutrients required by agriculture up to 2050

This understanding about the distribution of soil nutrient densities in Sub-Saharan African soils can be used to compute the potential volumes that are required to sustain a more intensified agriculture. Here, the term *demand* is avoided, intentionally. A proper calculation of

Figure 2

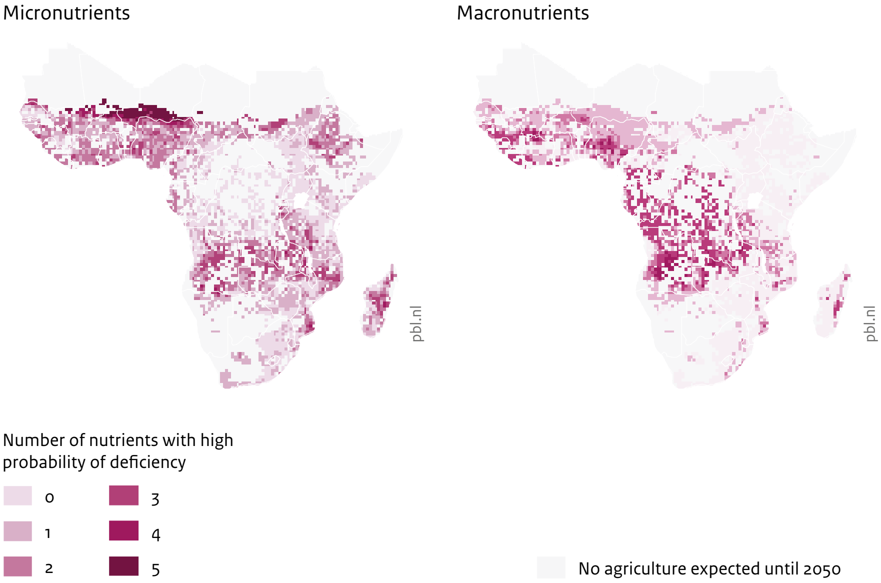
Variation in zinc and manganese concentrations in Sub-Saharan Africa



Source: ISRIC

Figure 3

Likelihood of soil nutrient deficiencies across Sub-Saharan Africa



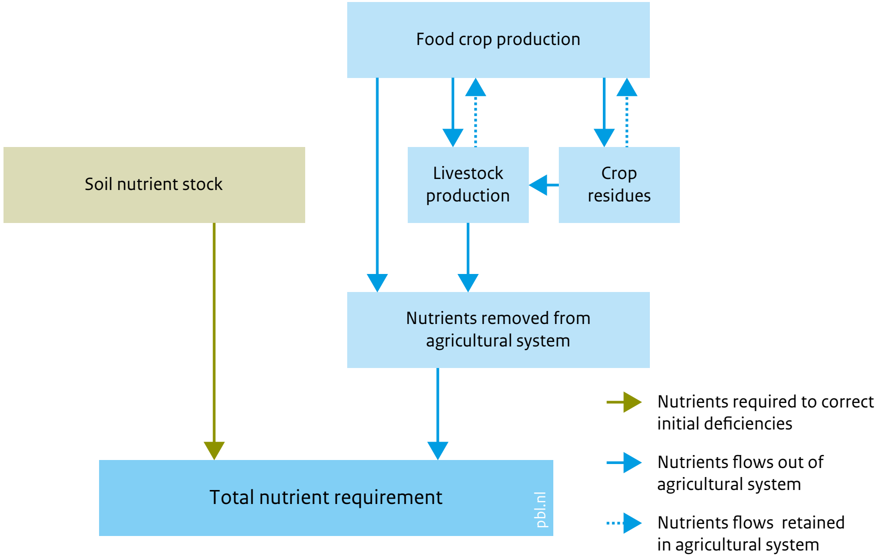
Source: ISRIC; PBL/IMAGE

demand requires detailed information on demand elasticities as a function of price changes. Data on such elasticities are non-existent, since micronutrients are rarely included in African fertiliser blends, to start with. Nonetheless, in the next section, the approach followed in this section is extended by including cost estimates of the volumes of nutrients. There, the estimated volumes are put in perspective, by considering a range of economic indicators, on a country level, and assessing whether required volumes could be critically high.

Potential volumes required consist of two separate streams as captured by Figure 4. First, given the low nutrient densities across much of the continent, an initial

Figure 4

Components of total nutrient requirement as estimated in this analysis



Source: PBL

application can be envisioned to raise current stocks to levels suitable for more intensified agricultural production (Section 3.2.1). Second, nutrients removed through harvested crop and livestock products need to be replaced in sufficient quantities (Section 3.2.2). Both of these components can be approximated, albeit conditional on a number of assumptions as explained below. Full details on the assumptions underlying the computations are provided in Appendix A.

3.2.1 Addressing inherent soil deficiencies

Underlying these computations are forecasts of the development of the Sub-Saharan African agricultural sector, in terms of yield and area increases, up until 2050. These spatially disaggregated forecasts come from the global assessment model PBL-IMAGE (Stehfest et al., 2014). In the calculations throughout this section we rely on the 'Trend' scenario (Kok et al., 2014; see also discussion in Section 2). As discussed, other scenarios are available but these would necessitate a substantial altering of policy-making. And even though these scenarios imply different trends in crop yield and area under agriculture, these differences are not large enough as to invalidate calculations hereafter substantially.

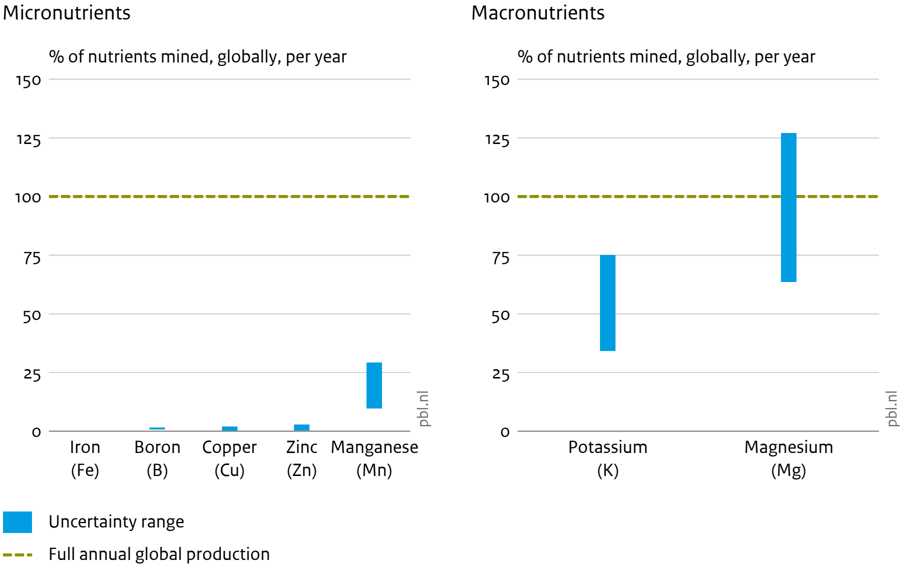
The approximation proceeds by calculating, per grid cell and per nutrient, the difference between a nutrient's threshold level and the current stock. Here, the assumed threshold, below which soil nutrient densities are insufficient to sustain desired production levels, is critical. But, relevant information about such threshold levels is not generally available, in an African setting, and thresholds depend on a variety of environmental conditions. In fact, such data are scarce altogether[1]. ISRIC- World Soil Information (2017a) identifies only one source, covering insights for Ethiopia. The individual nutrient ranges from this source are considerable (see Appendix A). Zinc, for instance, ranges from 6.3 kg/ha to 34.5 kg/ha[2]. This large range reflects a substantial variation in local factors, such as soil acidity and organic carbon content, determining which nutrients are actually available to crops. Availability can also be determined by nutrient ratios, which may prove to be either synergetic or antagonistic for plant availability. Two further assumptions were made; one about thresholds not differing per crop type, and one about nutrients being applied with 100% efficiency (e.g. in fertiliser).[3]

Altogether, these uncertainties are not directly problematic for the main purpose of this report, which is namely to gain insight into the order of magnitude of macronutrients and micronutrients that may be needed to sustain Sub-Saharan African agriculture. They translate into an uncertainty range with lower and upper bounds, likely containing the true potential requirements. However, it is considerably more difficult to use such data for accurate farm- or plot-level fertiliser recommendations, under varying local conditions and crop types; which points to a need for further scientific research.

The approximation proceeds by identifying the grid cells for which current estimates on soil nutrient content are lower than the identified threshold values. For these grid cells the amount of nutrients required to elevate the soil

Figure 5

Calculated ranges of micronutrient and macronutrient requirements in Sub-Saharan Africa



Source: ISRIC; PBL/IMAGE; USDA; USGS; adaptation by PBL

nutrient content to either threshold value is calculated. These requirements are subsequently aggregated both country wise as well as for the full continent.

3.2.2 Removal of nutrients in harvested products

To maintain soil fertility, it is desirable to replace the *nutrients removed from the system*. The exact volumes of nutrients removed are shaped by consumption patterns of harvested produce (Figure 4). A dominant component of agricultural production concerns the production of food crops, a fraction of which is destined for human consumption, and the remainder for livestock feed. Nutrients are further stored in crop residues, of which a fraction is consumed by livestock, a fraction has various domestic uses such as thatching, and a fraction is retained in agricultural production systems as mulch or compost. Part of the fraction destined for livestock feeding is retained in agricultural production systems through manure flows. The exact values of these fractions are shaped by local and cultural practices and variations in market prices of food, feed and livestock products. An exact determination of quantities removed from agricultural systems is therefore not possible[5].

A range is therefore used that most likely captures the true use of crop residues and overall quantities of nutrients removed from agricultural systems (see details in Appendix A). The lower bound considers nutrient losses as only arising from the human consumption of end products (food grains and livestock), while the upper bound considers losses arising from export of all harvested produce (food grains and crop residues). The actual values will lie somewhere in between.

Forecasts of harvested produce by year are derived from IMAGE production scenarios up until 2050. The volumes of nutrients stored therein are computed by combining estimates on harvest indices, dry weight (data from PBL-IMAGE) and the relative crop nutrient content (ISRIC, 2017a). Data on livestock inputs (food grains) and outputs (meat and dairy products) are those as forecasted by IMAGE. Livestock feed and nutrient intake from grazing and scavenging are not considered as it is unlikely that nutrients removed from such sources would be replenished actively.

3.2.3 Full estimates for Sub-Saharan Africa

A range of nutrient volumes, thus, was estimated for the period from 2015 to 2050. The overall lower bound was derived from lower-bound estimates of the quantities required to replenish soil nutrient deficiencies (Section 3.2.1) and those to replace nutrients removed annually from the system (Section 3.2.2). The upper bound was calculated in a similar way, by also adding estimates of upper bounds. Finally, an annual average range in required volumes was estimated by dividing the full estimates by 36. The uncertainty ranges provided are large and reflect both variation in local conditions and practices as well as uncertainty in precise crop responses to micronutrient applications. They are based on the best available insights and most likely include the actual required volumes.

As a final step in this section, the obtained ranges of annually required volumes are contrasted with annual average supplies (USGS, 2017) of the elements considered (Figure 5)[6]. This gives a first insight into whether current production levels are sufficient to meet these potentially required volumes of nutrients, or whether global markets could wreak havoc, in an effort to intensify production across Sub-Saharan Africa, in a sustainable way.

For the majority of elements, potential requirements, as a fraction of annual supplies, are relatively small. For zinc, for instance, this ranges from 0.3% to 2.7%. Notable, however, are the ranges for manganese (the highest amongst the micronutrients), with a lower bound at 10% of the annual supply. With respect to the macronutrients, the ranges for magnesium and potassium stand out. For magnesium, the upper bound exceeds the full (100%) annual supply.

These data, thus, provide a snapshot of whether concerns about metal and mineral scarcity, as a potential constraint to the Sub-Saharan African agricultural sector are warranted. A first inspection would suggest such concerns to be relatively minor, with small computed volumes for most micronutrients, with the possible exception of manganese. The volumes are larger for magnesium and potassium. But, markets for these elements are not solely shaped by geological reserves, or the relative scarcity thereof. In line with other studies on the *criticality* of raw materials (Prins et al., 2011; Graedel et al., 2015), the next section considers a broader range of factors shaping global supply, as well as the characteristics of individual countries that determine their vulnerability to supply restrictions.

Notes

1 The data has been disclosed publicly and can be downloaded from: http://gsif.isric.org/doku.php/wiki:africa_nutrient_maps

2 Relatively more information is available for various regions in the United States.

3 Assuming a target yield of 5000 kg/ha.

4 Even though it is highly unlikely that these assumptions actually hold, it would be unrealistic to make further assumptions given the paucity of data encountered.

5 The scenarios from PBL-IMAGE do forecast quantities of food grains used in either human or livestock consumption, but not for quantities of crop residues used in livestock consumption.

6 Only considering minable resources, thus excluding nitrogen (N).

FOUR

A region vulnerable to supply restrictions?

In many agricultural regions, supplementation of macro- and micronutrients is a necessary precondition for fostering agricultural intensification. Yet, the required volumes may differ, considerably, from one region or country to another. Meanwhile, Sub-Saharan African mining reserves could be limited, and global supplies may be tight due to competing demand from other economic sectors. The implication is that agricultural intensification could be a feat that is intrinsically more difficult, or easy, to achieve in particular regions.

Ideally, an investigation proceeds with a detailed analysis using price elasticities based on underlying supply and demand functions. Such information, however, is scarce and incomplete. This section therefore follows the methodology introduced and used by Graedel et al. (2012; 2015), albeit with a few minor modifications as outlined below. It entails a broader characterisation of factors shaping global supply (*Supply Risk* (SR)) of the nutrients under consideration as well as the *Vulnerability to Supply Restriction* (VSR) of individual Sub-Saharan African countries for each of these elements[1]. Both indicators are calculated on a scale ranging from 0 (no supply risk, or no vulnerability to restrictions) to 100 (high supply risks; or very high vulnerability to restrictions). The indicators and computations in this Section Full details of the indicators and sub-indicators considered and data sources used are provided in Appendix B.

4.1 Supply Risks

Supply risk captures the vagaries of the supply side of global mineral and metal markets. Three sub-indicators add up to the composite indicator. First, a sub-indicator captures the relative abundance of the elements in global mine reserves and fractions recovered from recycling processes, with tighter reserves signalling greater risks. Second, the average (weighed) level of economic and human development of producing countries is calculated. Somewhat perversely, higher levels of development signal greater supply risks as pressure to close or downscale impactful mining operations may mount amongst citizens. Third, geopolitical risks increase when mines are concentrated in a smaller number of countries and/or in politically unstable countries. The final Supply Risk (SR) indicator is the arithmetic mean of these three sub-indicators. Data sources are listed in Appendix B, while Table 1 provides the final SR-scores for the elements considered.

Supply risks are highest for manganese and zinc, an outcome first and foremost driven by relatively small reserves. At current supply and demand, mining reserves will suffice for 35 years for manganese and 17 years for zinc. That said, the SR calculations use higher estimates to account for supply from recycling of waste streams. While copper reserves are also not abundant, limited reserves are partially offset by a relatively favourable spread of mining operations across various countries. Conversely, mining concentrations of Magnesite and phosphorus are unfavourably concentrated in a select set of countries. Yet, this oligopolistic concentration is largely offset by relatively ample reserves. Still, compared with elements such as Bismuth or Antimony, the supply risks in Table 2 are relatively low (Graedel et al., 2015). But, a low supply risk can nevertheless be problematic when countries are highly vulnerable.

4.2 Vulnerability to Supply Restriction

The vulnerability of individual Sub-Saharan African countries to supply restrictions of these elements is thus computed. The calculations make use of the midpoint of each uncertainty range for each element and for each country in Sub-Saharan Africa as estimated in Section 3. The approach deviates from the framework outlined by

Table 2

Computed Supply Risk indicators. Indicators are expressed on a range from 0 (no supply risk) to 100 (very high supply risks).

	Boron (B)	Copper (Cu)	Iron (Fe)	Magnesium (Mg)	Manganese (Mn)	Potassium (K)	Zinc (Zn)
Average Supply Risk	43	50	42	47	56	40	57

Graedel et al. (2012) in a few aspects. First, most Sub-Saharan African countries do not yet actually propagate supplementation of most elements considered, except for phosphorus and potassium. As such, the indicators first and foremost capture the potential difficulty encountered in turning this situation around, rather than measuring the actual current vulnerability to supply restriction. Second, the indicators proposed are specifically adapted to the agricultural sector in Sub-Saharan African countries.

VSR is calculated as the arithmetic mean of two sub-indicators on *importance* and *susceptibility*[2]. *Importance* is thereby measured as the mean of the market value of estimated required volumes (Section 3) as a fraction of agricultural GDP and the share of the agricultural sector in overall economic output. It thus captures the potential impact that changes in market prices for these elements would render on the agricultural sector and national economies.

The indicator on *susceptibility* also comprises two components. First, is the share of volumes that can be met by own mining capacity. Ample domestic mining reserves would dampen supply risks rising in the global market. Second, is the share of the estimated value of nutrient volumes (after deducting own reserves) that can be covered financially from own agricultural exports. The reasoning is that (foreign currency denominated) costs of nutrient imports, are primarily paid from receipts of agricultural exports. Countries with few agricultural exports, or net-importing countries, are then particularly vulnerable to fluctuations in nutrient prices.

Again, all indicators are normalised on a scale of 0 (no VSR) to 100 (very high VSR) a full description of the indicators, calculation and data sources are provided in Appendix B. Figure 5 shows the distribution of the VSR indicators across Sub-Saharan Africa. The maps point to a sizeable diversity between countries as well as elements considered. Consider, for example, manganese. South Africa, with low VSR, is the largest global manganese producer (32% of global production) and has ample supplies to supply its own agricultural sector. Moreover, the South African economy is well diversified with agricultural output only making up 2.5% of total GDP. Despite this relatively small size, the absolute value of net agricultural exports is considerable and sufficient, by and large, to cover the procurement of elements not mined domestically.

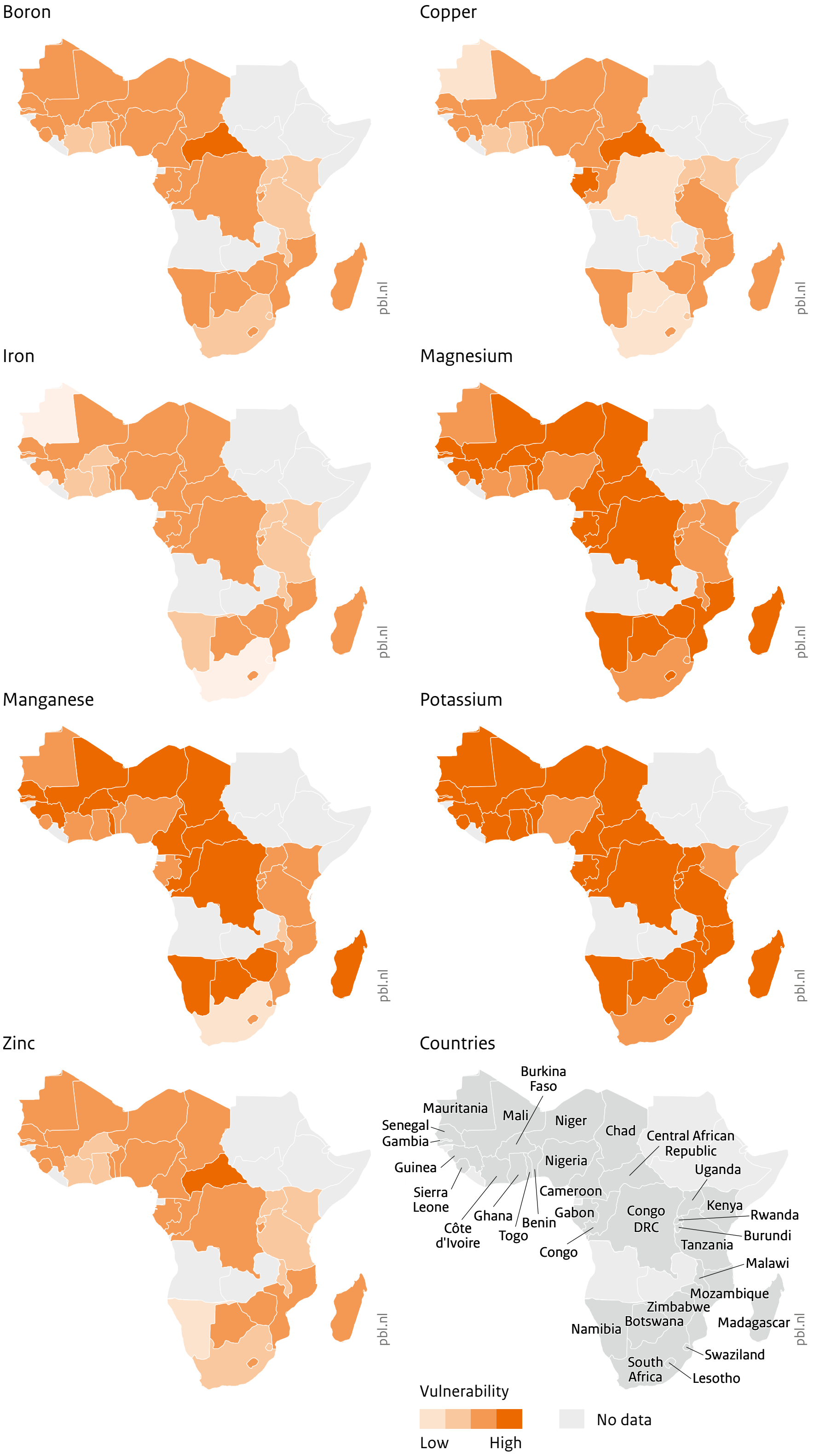
But South Africa proves to be an African exception. Sometimes considerable quantities of elements are recovered from African mines, such as manganese in Gabon and Cote d'Ivoire, copper in Mauritania and Zambia, phosphorus in Togo and Senegal, and zinc in Burkina Faso and Namibia. But these quantities are rarely sufficient, at least in the short run, to cover the estimated volumes even within these countries. Other elements, such as boron or potassium, are currently not being produced in Sub-Saharan Africa, at all. The high vulnerability of nearly all Sub-Saharan African countries to potassium supply restrictions is apparent. In this case, it is not only lack of supplies from Sub-Saharan African mines, but also the relatively large volumes under consideration (potassium being a macronutrient).

Therefore, most countries, for the majority of nutrients, depend on global market supply. Again, there are some marked differences. Some countries are in a better position, because of a relatively small agricultural sector or because of positive net agricultural exports. Examples of the former include countries mostly dependent on other natural resources, such as Guinea and Nigeria, while, for example, Kenya, Malawi and Cote d'Ivoire are countries with robust net agricultural exports.
These latter are in a better position with regard to securing and paying for nutrients necessary for enhancing agricultural production and intensification.

However, this also points to a group of countries in peril, notably those which are both net food importers, despite having a dominant agricultural sector, and have no own mining reserves to speak of. This set covers most countries around the Sahel, such as Chad, the Central African Republic, Niger and Mali. Membership of this unfavourable group is also partially driven by the fact that estimated volumes (see Figure 3 in Section 3) are particularly high for these countries.

Figure 6

Vulnerability to Supply Restriction across Sub-Saharan Africa



Calculations based on Graedel et al. (2011)

Source: FAO; ISRIC; London Metal Exchange; PBL/IMAGE; USGS; World Bank

Underlying these calculations is the assumption that countries place a considerable effort in redressing low nutrient stocks in the near future. For various reasons, not least being the current low levels of fertiliser use, incremental changes could be more realistic. This will lower the VSR for many countries, those with small own nutrient reserves, or smaller net positive agricultural receipts. However, it will not change the ranking between countries and importantly – it does not alter the sobering outlook for very high VSR countries (agriculturally dominant and net food importers).

Notes

1 Graedel et al. (2012) consider 'Environmental Implications' as a third indicator to capture the full vagaries of supply and demand. Due to data-limitations we discard this indicator in this analysis.

2 We do not include the substitutability indicator proposed by Graedel et al. (2012). Nutrients are non-substitutable in plant growth and agricultural production (or in human health for that matter). Instead of including a third indicator that would uniformly scale the vulnerability for all elements and countries, we choose to leave it out of the calculation without altering the key insights.

Getting the right nutrient at the right place

Stimulating agricultural intensification – a more productive use of current and future agricultural land – serves three distinctive purposes. First, increased productivity is an important means to stimulate income growth and reduce poverty amongst rural smallholders. Second, a more productive use of current agricultural land is paramount for safeguarding pristine ecosystems for future generations. Across Sub-Saharan Africa, such areas are already under great pressure. Third, targeting lacking nutrients (for agricultural intensification) could serve to alleviate the burden of malnutrition, currently a major contributor to child mortality and lagged cognitive development.

In other words, agricultural intensification is a means to stimulate Inclusive Green Growth and to achieve the vital Sustainable Development Goals on eradicating hunger and malnutrition. It thus merits close attention by policymakers for devising ways of accomplishing these goals in the most efficient way. A key question emanating is then how to get the right nutrient, in the right amount to the right place, and how to do so at a reasonable price.

In order to answer this question, this policy note first sought to provide a first order estimate of required volumes of macronutrients and micronutrients for stimulating agricultural intensification across Sub-Saharan Africa. The main motivations for conducting this research were concern about the scarcity of certain nutrients, which may shape the optimal policy response, profoundly. Even though concerns over physical scarcity are warranted, in some cases, concerns over cost-effective access for countries with limited financial resources dominate.

Moving towards the design of effective policy interventions, three further questions arise. First, how to address possible scarcities? Second, how to stimulate the development of fertiliser products for the right environment? And third, how to achieve impact to scale for agricultural intensification and possibly for fighting malnutrition? In the remainder, effective options are discussed for each category and summarised in Table 3. But, none of these categories are mutually exclusive and an effective strategy to raise agricultural intensification requires efforts across all three.

5.1 An element of scarcity

For manganese, magnesium and potassium the estimated intervals of volumes are relatively high. For magnesium, the interval even exceeds the full annual supply, suggesting that in the worst case agricultural requirements from Sub-Saharan Africa alone may exceed the full annual global mining supply. For most other nutrients considered[1] physical scarcity, as an impediment for agricultural intensification in the region, is not of direct concern. In most instances concerns mount over institutional and economic factors elevating supply risk or countries' vulnerability to supply restrictions.
But concerns over scarcity should not be dismissed altogether. A recent study on physical scarcities labelled overall zinc reserves as scarce and copper, boron and iron as moderately scarce (Henckes, 2017).
Moreover, calculations in this policy note only consider the case of Africa, whereas concerns over zinc-deficient soils in India and China are equally prompting action in, and likely raise demand from, these regions.

Evidently, the magnitude of such volumes, combined with the fact that the Sub-Saharan African agricultural sector competes with other economic sectors, may place a substantial upward pressure on prices. This upward price shift may imperil efforts to stimulate inclusion of these lacking nutrients in fertiliser. Policies should thus aim to keep such price increases at bay, both by stimulating substitution in competing sectors and by keeping actual demand from the agricultural sector as low as possible.

The main premise underlying any strategy for reducing demand in other sectors relates to non-substitutability. Each of the nutrients considered is essential to plant growth and human health, but the vast majority of their

Table 3

Overview of possible policy interventions

Area of focus:	Sub-goal:	Possible policy interventions:
Address potential scarcities	Keep non-agricultural demand as low as possible	- Stimulate substitution, reuse and recycling in non-agricultural sectors
	Keep agricultural demand at a sufficient yet low level, through increased efficiency of fertiliser use	- Recycling (for agricultural reuse) of agricultural waste streams
Stimulate fertiliser product innovation	Increase marginal crop responses to fertiliser	- Stimulate field trials and soil data collection and disclosure of data in public domains - Stimulate public, private or public–private R&D on developing and testing of novel fertiliser products
Bringing impact to scale	Keep farmgate fertiliser prices low	- Subsidise use of novel fertiliser products to overcome learning costs - Interventions aimed at lower transport costs (better infrastructure, reduced corruption) - Stimulate competition in fertiliser sector (anti-trust regulation)
	Enforce application of lacking nutrients	- Mandate inclusion of lacking nutrients in fertilisers • in low-VSR countries • for export crops only in high-VSR countries

use is in industrial applications. For instance, the high volumes of magnesium may be relatively unproblematic, as there are substitution options for in many applications. Moreover, geological reserves are large, even though these are concentrated in only a few countries. The picture is somewhat less favourable for other elements. In the United States, less than 10% of primary zinc supply is used in applications other than galvanising steel or the production of various ferroalloys, and only a fraction is used in fertilisers (or animal feed) (USGS, 2017).

Still, ample options exist to substitute for zinc in industrial applications, unlike manganese. The vast majority of the latter element is used in iron, steel and aluminium production for increasing corrosion resistance. It is also used in batteries and its demand may further rise with increased battery use (USGS, 2017). For manganese, a key avenue to keep prices low (at rising agricultural demand) is therefore to stimulate circular economies. This refers to measures stimulating reuse and recycling (another major end use of manganese is the production of beverage cans) thereby reducing demand for raw materials (e.g. Rood and Hanemaaijer, 2016).

Second, policies should aim to keep the actual demand from the agricultural sector sufficient, but as low as possible. One area with scope for intervention relates to minimising nutrient losses in the agricultural cycle.
Part of the uncertainty underlying the broad intervals in this analysis stems from uncertainty on the assumptions of the exact share of crop residues, and the nutrients contained in it, removed from the agricultural production cycle. Strategies could include measures to stimulate recycling of crop residues at farms, and reverting urban waste streams for agricultural use (Rood et al., 2017). These could steer required volumes to the lower end of the estimated ranges. Such strategies are particularly important for safeguarding potassium resources, which sees little use outside agriculture but for which the estimated requirements are nevertheless considerable.

Such efforts keep demand from non-agricultural sectors at bay and prices of these elements for inclusion in fertilisers within reasonable ranges. A key challenge then rests with the development of efficient fertiliser blends and types that, for a particular site and crop, efficiently target the lacking nutrient.

5.2 Stimulating fertiliser product innovation

The question on how to stimulate fertiliser use amongst smallholders in Africa is one that has merited great attention from researchers and policymakers. And despite frequent outcries that African farmers should apply more fertiliser, evidence from several studies suggest that farmers do in fact apply it at rates close to economic optima (Suri, 2011; Beaman et al., 2013; Sheahan et al., 2013). These are nonetheless lower than recommendations set per country. Crop responses to fertiliser under farmer-managed conditions may indeed be much lower than recommendations presume. Meanwhile, farmgate fertiliser prices are often high. Changing this unfavourable situation around necessitates ways to increase marginal crop responses to fertiliser application (this section) and further reductions in fertiliser costs (next section).

Low responses to fertiliser arise when lacking nutrients are not sufficiently available from soil stocks or not included in applied fertilisers. This has been the main premise underlying this research and highlights the need to stimulate the development of a wider range of fertilisers. Clearly, product development and, ultimately, large-scale production are the main responsibility of the fertiliser industry. Considerable innovation does take place, but most efforts seem geared towards realising efficiency gains in production processes, rather than to the development of novel products suitable for use under various African conditions (Bindraban, et al., 2015; Dimkpa and Bindraban, 2016). This insight hints at the need for stronger public-sector involvement, for which there are some additional compelling arguments.

First, choices on actual product development (which nutrients, for which crops in which locations) requires detailed soil information. The data used in this note (and the original source: Hengl, et al., in press) provide important guidelines, but should be groundtruthed with actual soil measurements and eventual product trials. The incentives for large-scale soil testing by fertiliser companies may well be limited as the risk of free-riding on such efforts by competitors are large. Some companies do provide farmers with the option, at a fee, to test local soil conditions and recommend effective fertiliser use (e.g. Soilcares). Such efforts are commendable, but, from a broader policy perspective, run the risk of yielding information from selected settings only.

Moreover, the broad requirement intervals (Section 3) reflect that information on critical thresholds for specific crops under varying growing conditions in Africa is scarce. Altogether it hints at fundamental agronomic knowledge gaps with respect to the role of micronutrients in crop production. Given the magnitude of the agricultural intensification effort required, and potentially large societal impacts, it is most desirable to disclose outcomes from additional soil data and knowledge development in public domains. Semi-public institutions (universities and international research consortia) have a key role to play.

Finally, there exist concerns on health that warrant a strong public role. Even though the elements considered are essential building blocks for plants and humans, concentrations too high turn many of these elements toxic. Application through fertilisers, and subsequent build-up in soils requires continuous monitoring by national agencies in order to prevent rendering agricultural areas toxic and unsuitable for agricultural production altogether.

5.3 Bringing impact to scale

Unmistakably, the development and availability of new fertiliser products is an essential precondition for achieving impact, i.e. raising production per acreage of crop land across Africa. Yet, only product innovation may not suffice and additional measures are required to keep fertiliser cost of both existing and new products at bay.

To start with, farmers are often reluctant to use new products, certainly when these are relatively expensive, for instance, due to the more expensive nutrients included. The application of a new product involves a sometimes costly trial and adaptation phase. Some studies even suggest that farmers strategically delay experimentation in order to free-ride on the learning experiences of neighbours (Bandiera and Rasul, 2006; Conley and Udry, 2010).

Such arguments justify well-targeted government subsidisation of fertilisers for an initial period of time, thereby overcoming social learning constraints and building common knowledge on the most appropriate use of novel fertiliser products. But subsidisation should eventually culminate into a situation in which the unsubsidised product becomes economically remunerative. Otherwise, subsidies run the risk of draining scarce public resources while foregoing other sound public investments (Jayne et al., 2013).
The detailed soil data underlying this research provide entry points for field trials on specific combinations of lacking nutrients, crops and locations. Such trials will yield valuable information on the more precise estimates of crop responses and the price ranges of minerals and metals for which these remain profitable. Where and for which nutrients and crops, profitability will ultimately hold is difficult to ascertain a priori and requires continuous trials throughout the continent.

If the economics of using a novel fertiliser works out positively, governments may choose to regulate its use further through mandating specific fertiliser blends. Various countries have resorted to such mandates. Public health concerns, particularly a too low human intake of Selenium, in Finland prompted a mandatory inclusion of the element in Finnish fertilisers, even though it is not an essential nutrient for plant growth (Ros et al., 2016). Similar regulations, for the inclusion of zinc in fertiliser, exist in Turkey (Cakmak, 2008).
Yet, this may not be a feasible strategy for some African countries, particularly those with a high Vulnerability to Supply Restriction (VSR) for specific elements.

The computed volumes and values for nutrients in these locations are large relative to the size of agricultural economies. Some of these countries already have sizeable net food imports, despite a dominant agricultural sector, and are thus extremely vulnerable to supply and price distortions. Mandating such elements would jeopardise both the use of fertiliser and food production when prices of the elements rise. Conversely, mandatory inclusion could be a relatively risk-free strategy in countries with low VSRs. These countries have a healthy agricultural sector, sufficient domestic nutrient supply, or sufficient foreign currency reserves.

This would suggest a rather bleak picture and limited options for high VSR countries. Yet, options do exist. Some countries that are ranked as having a high VSR (Mali, Burkina Faso, Benin), for certain elements, do specify fertiliser types to be used in cotton production. They mandate the inclusion of boron and sulphur (Gregory and Bumb, 2006). It may not be a coincidence that such specifications exist only for main export commodities. After all, it is easier to recover the costs of added nutrients through export receipts. Meanwhile, soil residues of cotton fertilisers benefit food crops planted in following seasons. In other words, setting regulations for export crops could be a viable strategy for high VSR countries to move forward. Nevertheless, the overall challenge remains daunting for these countries.

Novel product development, and a most appropriate strategy for disseminating these, does not negate the need to address other looming constraints in fertiliser markets. Without the pretence of being complete, a few factors merit attention here. Notably, overall costs to local farmers in Africa are considerably higher than going world market prices. Poor infrastructure coupled with ubiquitous road checkpoints and bribes being taken make the transport of fertilisers from sea ports to end users much more expensive than it should be (Omamo, 2003; Stifel and Minten, 2008; Minten et al., 2013).

Meanwhile, concerns on price collusion merit further attention. The number of global fertiliser producers is relatively small. Some studies suggest the global fertiliser market to display oligopolistic pricing behaviour (Taylor and Moss, 2013; Gnutzmann and Spiewanowski, 2014). Moreover, oligopolies may be present at national import levels (Bumb et al., 2011) and at local markets (Falcao, 2016). These could further inflate the local price of fertiliser but also limit the pass-through of reductions in transport costs to farmers. Altogether these insights call for institutions, globally and nationally, that monitor such markets and enforce anti-trust regulation when and where needed. Finally, some countries label fertilisers enriched with micronutrients as luxury products, attracting higher VAT rates. Such regulations clearly need revision.

This stepped and stacked approach is thus geared towards a goal of profitably getting the right nutrient in the right amount to African farmers in a specific place, raising crop yields, income and production and ease pressures on non-agricultural lands. This process of, so-called, agronomic fortification also has a role to play in fighting malnutrition. The case of selenium-enriched fertilisers in Finland serves to make this point (Ros et al., 2016), but it also is the only existing case documenting impact on public health. As the discussion highlights, there are multiple steps to be taken for impact to scale in fertiliser use can be achieved. Possible impacts on malnutrition therefore most likely materialise in the medium to long run only. Even then, it remains to be seen whether the most vulnerable households, often the most malnourished, can be reached. The latter for instance includes large tracts of the population in high VSR countries who are not engaged in export crop production. Hence, a policymaker who seeks to address the goal of reducing malnutrition amongst highly vulnerable groups, in the short run, would do better to use other policy measures, such as food supplementation and fortification.

Note

1 Two nutrients (phosphorus and sulphur) were excluded in this note due to data limitations.

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Annex

A. Estimating nutrient volumes

The calculations underlying the results in Section 3 combine data from various sources in order to determine the range that most likely contains the potential requirements for increasing agricultural productivity across Sub-Saharan Africa, up to 2050. Two key data sets form the base for these calculations. The first includes explorations of land-use developments in Sub-Saharan Africa up till 2050 as forecasted by PBL-IMAGE (Kok et al., 2014). The second are the recent estimates of soil nutrient densities across Sub-Saharan Africa at a highly spatially disaggregated level (5 x 5 km) (Hengl et al., in press).

1. PBL-IMAGE scenarios on African land use developments

The calculations make use of the 'Trend Scenario' developed for the Global Biodiversity Outlook (Kok et al., 2014) with PBL-IMAGE. Detailed forecasts are estimated at five-year intervals, from 2015 to 2050. A forecast for a single year, say 2020, is representative for the four subsequent years (2021–2024). The 'Trend Scenario' is used in all calculations, as the other available scenarios presuppose a substantial change in policies to address malnutrition, biodiversity loss and climate change (See discussion Section 2).

The forecasts include detailed data on crop types cultivated, acreages, yields, overall production, as well as the quantities of food grains used for livestock production. Data were spatially disaggregated at approximately 50 x 50 km, and point to all regions where agriculture will take place up to 2050. Seven crop types are included in PBL-IMAGE (1: temperate cereals; 2: rice; 3; maize; 4: tropical cereals; 5: pulses; 6: roots and tubers; 7: oil crops). Without loss of generality, crop types 1 to 4 are aggregated to obtain a category 'cereals' for use in the calculations in this report.

2. Assessing inherent soil deficiencies (Section 3.2.1)

The calculations to estimate the volumes of soil nutrient deficiencies required to correct low levels of soil nutrients are based on the estimates on soil nutrient densities by Hengl et al. (in press). These estimates are at a higher resolution of 5 x 5 km. The following steps are taken to arrive at the estimates presented.

a) Preparing data set:
   a. Where necessary (for B, Cu, P, and Zn), soil nutrient densities are expressed in particles per million (ppm) by dividing by 100; All nutrient densities are converted from ppm to kg/ha according to the formula below. Thickness is set at 0.3 m, estimates of bulk density and coarse fragments are from ISRIC (ISRIC, 2017b):

      *Nutrient stock [kg/ha] = Nutrient content. [ppm] / 100 * BD [kg/m*^{3}*]/1000 * (1 - CF) * thickness [m]*

   b. The maps are converted from a resolution of 5 x 5 km to match the resolution of PBL-IMAGE data (50 x 50 km), by using the *resample* function of the *raster* package in statistical software package R;

b) Calculations are only carried out for grid cells in which agriculture is expected to be practiced in 2050 (as per the Trend scenario). These grid cells are selected using the *mask* function of the *raster* package in statistical software package R;
c) Nutrient thresholds are based on a study by ISRIC (2017a) and are provided at a 0.20 m depth interval. These thresholds are converted from 0.20 m into 0.30 m depth, assuming that nutrients are proportionally distributed (Table A.1);
d) Comparing estimated soil nutrient densities with thresholds:
   a. For each nutrient, a minimum-deficiency map is constructed, using the maps with soil nutrient densities (step a above) and subtracting the minimum threshold (Table A.1);
   b. For each nutrient, a maximum-deficiency map is constructed, using the maps with soil nutrient densities (step a above) and subtracting the maximum threshold (Table A.1);
e) The maps constructed under d provide the magnitude of the nutrient deficiency per grid cell, in kg/ha. These are then used to arrive at an aggregate estimate for Sub-Saharan Africa:
   a. The grid cells for which the initial densities minus the threshold values are negative are selected;
   b. To arrive at quantities of nutrient stocks, these grid cells are multiplied with the cultivated area within each grid cell;

Table A.1

Nutrient thresholds for agricultural production, in kg/ha, for a target yield of 5,000 kg/ha (ISRIC, 2017a)

	B	Ca	Cu	Fe	K	Mg	Mn	N	P	Zn
Min. (ISRIC reported minimum)	3.3	8,400	4.2	61.5	982.5	1,512	220.5	6,300	99	6.3
Avg. (ISRIC reported average)	5.85	12,600	33	61.5	1,474.5	2,772	567	8,925	159	34.5

Table A.2

Nutrient crop content, per nutrient and crop category, in g/kg (ISRIC, 2017a)

Nutrient content per crop, g/kg											
		B	**Ca**	**Cu**	**Fe**	**K**	**Mg**	**Mn**	**N**	**P**	**Zn**
cereals	min	0.004	1.8	0.0034	0.04	14	1	0.019	15.6	1.5	0.013
	max	0.03	10	0.02	0.525	50	4.5	0.178	47.4	5.2	0.079
pulses	min	0.0191	6.8	0.0088	0.098	15	2.6	0.041	40.2	2.4	0.02
	max	0.063	20.7	0.025	0.425	37	7.7	0.396	57.4	6.2	0.12
oil crops	min	0.022	6.4	0.0051	0.055	17.1	2.8	0.028	32	2.5	0.02
	max	0.078	22.9	0.016	0.274	37	8	0.237	50	6	0.091
roots & tubers	min	0.02	8.5	0.007	0.233	35.4	2.5	0.022	48.4	2.8	0.019
	max	0.0584	17.5	0.0147	0.545	48.2	7.5	0.35	60	6	0.098

  c) The resulting figures are multiplied by 100 to convert km² into hectares.
  d) Both maps are aggregated to get total initial correction per nutrient in kg. This figure is then divided by 1,000,000 for gigagram.

3. Export of nutrients in harvested products (Section 3.2.2)

a) Estimate flows in food crops (step 1);
b) Use crop nutrient content data (ISRIC, 2017a) (Table A.2):
  a. Nutrient crop content in g/kg;
  b. Harvest index and dry matter content are used from PBL-IMAGE (Table A.3)
c) Calculate dry weight: crop nutrient content (g/kg) * harvest index * dry matter= dry matter harvestable crop nutrient content (g/kg). Divide by 1,000 to get: kg/kg;
d) Use forecasted production data (PBL-IMAGE), for the 2015–2050 period:
  a. The data in gigagrams per year are aggregated for East- West-, and Southern Africa;
  b. Crop groups maize, rice, temperate, and tropical cereals are aggregated as cereals;
  c. Production is multiplied by 1,000,000 to obtain k g/year;
e) The exact amount of harvested nutrients is computed as follows:
  a. Multiply annual production in kg with dry weight (step 3) to get the annual amount of nutrients harvested per crop
  b. Aggregate the result over all crops to obtain aggregated estimates for each nutrient.
f) Divide aggregates by 1,000,000 for annually harvested volumes of nutrients in gigagrams
g) Estimate nutrient flows in livestock production (step 2)
  a. Forecasted livestock production data from PBL-IMAGE (2015–2050). The data in gigagrams/year is aggregated for East, West and Southern Africa;
  b. Data is available on the categories: beef, milk, pork, mutton and goat, and poultry and eggs.
h) Nutrient content of animal products computed (Table A.4) on the basis of nutritional data from various sources.
  a. For each animal, the sources list the nutritional content of various products. The average over these products is taken to approximate the average nutrient content of the animal products. Furthermore, for dairy products, the nutrient content of whole milk is used. For poultry and eggs, the average of all chicken products is used. For mutton and goat, nutritional data are on lamb products only, due to data limitations.
i) Nutrient demand from livestock is calculated by multiplying production of animal products with nutrient content and aggregating the product categories for each nutrient.

Table A.3
Harvest index and dry matter content, in fractions (PBL-IMAGE)

	Harvest index	Dry matter content
Cereals	0.4	0.88
Pulses	0.49	0.9
Oil crops	0.52	0.73
Roots & tubers	0.4	0.3

Table A.4
Animal product nutrient content, in kg/gigagram, various sources

Animal product nutrient content, kg/gigagram										
	B	**Ca**	**Cu**	**Fe**	**K**	**Mg**	**Mn**	**N**	**P**	**Zn**
Beef	0.015	132.6	1.585	25.4	3,135.5	207.9	13.872	37.5	2,064.1	50.6
Milk	0.015	1,130.0	0.250	0.3	1,320.0	100.0	0.040	0.0	840.0	3.7
Pork	0.000	159.0	1.873	17.4	3,252.3	216.2	0.213	37.0	2,265.4	24.0
Mutton & Goat	0.000	139.9	3.012	23.6	2,722.9	218.7	38.728	35.3	1,989.2	38.7
Poultry & Eggs	0.015	152.3	0.893	16.2	2,231.9	210.5	0.407	35.0	1,832.5	19.5
Source	Hunt et al., 1991	USDA, 2017	USDA, 2017	USDA, 2017	USDA, 2017	USDA, 2017	USDA, 2017	Analytical Methods Committee, 2014	USDA, 2017	USDA, 2017

4 Calculating lower and upper bounds

a) Lower and upper bounds of nutrient volumes are estimated, which account for uncertainties on 1) critical soil thresholds, 2) variation in crop nutrient content, and 3) volumes of nutrients removed within livestock products;

b) The uncertainty about nutrients removed within livestock products stems from the difference in nutrient content between the final livestock products (as calculated under 3 above) and the nutrients contained in food crops and crop residues destined for livestock production:
   a. *Volumes nutrients stored in food crops as well as crop residues used for* livestock production are both forecasted by PBL-IMAGE;
   b. The lower bound of nutrients removed by livestock is determined by the nutrients contained in consumed livestock products. It assumes all animal waste products (e.g. manure, bones, hides) are recycled in the agricultural system;
   c. The upper bound is determined by all nutrients contained in food crop and crop residues used in livestock production. It assumes all animal waste products leave the agricultural production cycle;

c) Calculating upper and lower bounds accounting for all three types of uncertainty:
   a. Calculate lower bound as follows:
      - Lower bound = initial correction to correct soil deficiencies (step 2 above, minima from Table A.1) + harvested material from all food crops (step 3 above, minima from Table A.2) + nutrients stored in livestock products (fed from food crops and crop residues) – livestock nutrient demand (food crops only, to avoid double counting);
   b. Calculate upper bound as follows:
      - Upper bound = initial correction to correct soil deficiencies (step 2 above, maxima from Table A.1) + harvested material from all food crops (step 3 above, maxima from Table A.2) + crop residues used in livestock production.

B. Estimating Supply Risk and Vulnerability to Supply Restriction

Table B.1

Indicators used for calculating Supply Risk

Group of Indicators	Indicators original methodology (Graedel et al., 2012)	Modifications in this study and notes
Geological, Technical and Economic	- Depletion Time - Companion Metal Fraction	- Followed Graedel et al. (2012) - Score is calculated as the average over both sub-indicators (100: very risky; 0: not risky)
Social and Regulatory	- Weighed across producers: - Policy Potential Index - Human Development Index	- Followed Graedel et al. (2012) - A high PPI denotes a favourable regulatory environment for mining companies. The complement (100-PPI) is used in the calculations to give more weight to countries with a n unfavourable regulatory environment. - A high HDI, indicating higher development, is considered a threat to mining production. Popular resistance to mining increases with development levels - Score is calculated as the average over both sub-indicators (100: very risky; 0: not risky)
Geopolitical	- Weighed across producers: Worldwide Governance Indicators (Political Stability) - Global Supply Concentration (Herfindahl-Hirschman Index)	- Followed Graedel et al. (2012) - Score is calculated as the average over both sub-indicators (100: very risky; 0: not risky)
Supply risk	- Unweighted average over three groups above	- Unweighted average over three groups above

Table B.2

Data sources used for calculating Supply Risk

Group	Indicator	Data sources, assumptions and values
Geological, Technical and Economic	Depletion Time	- Copper, selenium: Nassar et al., 2012; - Iron, manganese: Nuss et al., 2014; - Copper, zinc, aluminium: Harper et al., 2015; - Boron, magnesium: Graedel et al., 2015. No exact data were obtained, only ranges. Midpoints in ranges were used for boron and magnesium (5 for both); - Phosphorus, potash, sulphur: set at 0, USGS reserves (2017)>100 years.
	Companion Metal Fraction	- Data were obtained from the same sources as listed above - Companion fractions for phosphorus, potash and sulphur set at 0.
		- Global mining production data (2014) from the World Mining Database (World Mining Congress, 2016) to calculate the PPI, HDI, HHI and WGI-PV scores.
Social and Regulatory	Policy Potential Index (PPI)	- Data on Policy Potential Index (now Policy Perception Index) (Fraser Institute, 2016); - Data on certain countries (Canada, United States, Argentina) were disaggregated to provincial or state level, then unweighed average across states/provinces were used; - Data on certain countries were lacking. Inserted midpoint of score: 50; - The complement was calculated (100 PPI) to reflect a higher score for countries with a less favourable regulatory environment; - Calculated as weighed score: (% share of world production * (100 PPI)) and summed over all countries. Calculated for each metal and mineral, separately.
	Human Development Index (HDI)	- Data from United Nations Development Program (UNDP), 2015; - Data on certain countries were lacking (Taiwan, North Korea, Kosovo, Nauru). Alternative HDI scores as reported on Wikipedia (2017) were added; - Calculated as weighed score: (% share of world production * 100 * HDI) and summed over all countries. Calculated for each metal and mineral, separately.

Group	Indicator	Data sources, assumptions and values
Geopolitical	Herfindahl-Hirschman Index (HHI)	- HHI = (% share of world production)^2, summed over all countries; - Rescaled to [0, 100] following Graedel et al. (2012): 17.5* LN (10,000 * HHI) – 61.18; - Calculated for each metal and mineral, separately.
	Worldwide Governance Indicators (Political Stability)	- Worldbank data on governance were used, in particular, the score (WGIpv) (World Bank, 2017b) on political stability and absence of violence: - Used the complement (100 – WGIpv) to reflect a higher score for countries with lower stability and higher incidences of violence; - Calculated as weighed score: (% share of world production * (100 – WGIpv)) and summed over all countries. Calculated for each metal and mineral, separately.

Table B.3

Indicators used for calculating Vulnerability to Supply Restriction

Vulnerability to Supply Restriction		
Group of Indicators	**Indicators original methodology (Graedel et al., 2012)**	**Modifications in this study and notes**
Importance	- National Economic Importance - Percentage of the population using the resource considered	The following two *importance* indices were used (weighted average): - Value of estimated average demand / agricultural GDP (i.e. importance in agricultural production); - Share of agricultural GDP in overall GDP (importance of this sector in the national economy).
Substitutability	- Substitute Performance - Substitute Availability - Environmental Impact Ratio (of substitute) - Net import reliance ratio of substitute	Given the focus on agriculture and health and the fact that no substitutes exist, this category was omitted.
Susceptibility	- Net import reliance - Global innovation Index	The following two *susceptibility* indices were used (weighted average): - Net import reliance (fraction of demand that can be filled from own production); - Balance of payment ratio, indicating whether net earnings from agriculture suffice to cover costs for nutrient imports: value of imports / net agricultural exports (index was set at 100 for countries that are net importers).
Vulnerability to Supply Restriction (per country)	- Unweighted average over Importance, Substitutability and Susceptibility (see above)	- Unweighted average over Importance, Substitutability and Susceptibility (see above)

Table B.4:

Data sources used for calculating Vulnerability to Supply Restriction

Group	Indicator	Data sources, assumptions and values
Economic Importance		- Price data on pure, refined metals and minerals (not being ores) were used when available. Exceptions listed below, as well as data sources: - London Metal Exchange (spot prices, January 2017) (London Metal Exchange, 2017): aluminium, copper, iron, zinc, (molybdenum); - Boron (United States Geological Survey, 2015a). Price of borax ore, most commonly boron fertiliser in agriculture, Boron content of 11%. Price converted to reflect price of ore needed to produce one tonne of boron; - Magnesium (United States Geological Survey, 2015b). Price of caustic calcined magnesia. Typical purity of 85% to 95% MgO. We used 90% to calculate the amount of caustic calcined magnesia needed to produce one tonne of magnesium; - Manganese (United States Geological Survey, 2013). - Potash (United States Geological Survey, 2016). Prices per tonne of K_2O; - Phosphorus (United States Geological Survey, 2015c). Price of phosphate rock with a phosphate content of 20%. Price converted to reflect price of ore needed to produce one tonne of phosphate; - Sulphur (United States Geological Survey, 2014). Prices for elemental sulphur charged by the Abu Dhabi National Oil company (considered best indicator of world sulphur price).
	Share of agricultural GDP in overall GDP	- Data on the 2014 share of the agricultural sector in overall GDP (World Bank, 2017a).
	Value of estimated mineral and metal demand as % of agricultural GDP	- Estimated value of demand, per country and aggregated for Sub-Saharan Africa – own calculations, based on ISRIC data and IMAGE scenarios; - Demand was calculated as average annual demand over the 2015–2050 period; - Price data was used to value the demand for minerals and metals. Sources of and assumptions on price data as above; - Data on the 2014 share of the agricultural sector in overall GDP (World Bank, 2017a); - Data above used to calculate percentage: value of estimated average annual demand / Value of agricultural GDP.
Susceptibility	Net import reliance	- Share of estimated demand (not value) that could potentially be met from domestic sources: estimated average annual demand / Annual domestic production; - Data on mining production from World Mining Database (World Mining Congress, 2016).
	Balance of payment ratio	- Share of net agricultural exports needed to cover the estimated annual average demand for metals and minerals: estimated average annual demand / net agricultural exports. The value was set at 100%, for countries that are net agricultural importers; - Net agricultural exports were estimated using FAO data (2017a) on agricultural imports and exports (2014 data).

Note

1 Selection of the data used in this report strongly depended on their availability. Their inclusion, therefore, has no relationship with their level of importance. For the nutrients included, it proved possible to construct estimates of densities in soils across Sub-Saharan Africa. Next, the impact of malnutrition is relatively well-documented for some of these nutrients.

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