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ABSTRACT

Cereal production in Sub Saharan Africa (SSA) is inadequate for supporting population nutritional demands. Nutrient mining of nitrogen (N) has taken place in all areas where cereals are produced in SSA. This review reports on the nitrogen use efficiency (NUE) of Sub Saharan Africa cereal grain production. For SSA, NUE's exceed 100%. In light of the low N application rates, high NUE's speak to a much bigger and potentially damaging situation for cereal production in SSA. Limited supplies of N, the continual rise in prices and elevated economic risk of N fertilization, combined with existing low yield levels of cereal production reiterates the importance of NUE in SSA and the importance of aiding this region in overcoming its dysfunctional agriculture production systems. High NUE's for SSA are a direct result of applying so little fertilizer N, at the ultimate expense of mining an already depleted soil resource.

Keywords: nitrogen, rice, wheat, corn, nutrient uptake, fertilizers, soil fertility

INTRODUCTION

Current production of cereal grains in Sub Saharan Africa (SSA) is inadequate for supplying the nutritional demands of the rapidly growing African

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population. Sanchez et al. (1997) linked the origin of declining per capita food production in SSA to soil nutrient management and further noted that production will undoubtedly fail to meet the nutritional needs of the African people until issues within soil fertility are addressed. Furthermore, their findings showed, until recently, the primary focus of research and extension in SSA was not soil nutrient management, but rather the development of higher yielding varieties, adoption of conservation tillage, and minimization of soil erosion. The failure to improve soil fertility and nutrient use efficiency has fueled environmental degradation, food insecurity, and the need for outside aid (Mafongoya et al., 2006).

Cereal Production in Sub Saharan Africa

Agriculture is the largest economic sector in SSA, engaging 70% of all Africans (Sanchez, 2002). The most widely cultivated cereal crops in SSA are maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), millet (*Pennisetum glaucum* L.), and rice (*Oryza sativa* L.). Being the largest crop produced, maize has cultural, economic, and political significance in SSA and is the dominant staple food for much of eastern and southern Africa while greater dependence on millet, rice, and sorghum is found in western Africa (Doward et. al., 2004). Sorghum and millet are the second and third, respectively, largest produced crops in SSA, while rice is a relatively new crop for the region (Maredia et al., 2000).

Maize is the most widely cultivated crop in SSA and is the most important food staple, accounting for up to 70% of the total human caloric intake (Byerlee and Heisey, 1996; Martin et al., 2000). Maize is high yielding, affordable, and easily digestible. Grains, cobs, stalk and tassel are used for both food and non-food products. The grain is commonly eaten as a starchy base in the form of porridges, pastes, and grits. Throughout the dry season, green cobs are eaten in an attempt to solve hunger problems. Almost all maize produced in SSA is used for human consumption with less than five percent used for animal feed; the exception being South Africa which uses half as animal feed (Byerlee and Eicher, 1997).

Sorghum is the traditional staple grain food for SSA and is the second largest cereal grain produced. It is grown throughout SSA; this is important because sorghum can produce yields under climate conditions where most other crops fail (Djurfeldt, 2005). Sorghum is used in porridges, pastes, and beverages, and has begun to be used for instant soft porridge and malt extracts (Taylor, 2003).

The third largest cereal grain crop produced in SSA is millet. Millet, which can tolerate a wide variety of climates, is another traditional staple grain crop for SSA. It is a valuable energy source in the diet with a protein content ranging from nine to 21%. Of the millet produced, 78% is used as a food source for human consumption, while 20% is used for beverages and other purposes. Approximately two percent of the production is used as animal feed.

The fourth largest cereal crop produced in SSA is rice. Production in east and west African regions accounts for 95% of the total production in SSA and is cultivated in dry land, paddy, and floating cropping systems. Approximately 20 million SSA farmers grow rice and nearly 100 million Africans depend on rice as their source of income.

Import—Export Considerations

Over the next two decades global food demand is expected to increase by around 50%; 80% of this originating from developing countries, particularly those in SSA (Dar and Twomlow, 2007). The growth rate of food production in SSA is two percent which is lower than the annual population growth rate of three percent. As a result, the percentage of the population undernourished and living in poverty (earning less than US $1 per day) has increased in SSA. During a 12 year period, the number of undernourished persons rose from 170 to 204 million, comprising almost one-third of SSA's population, of which 45 percent is under the age of 15 (Kidane et al., 2006).

Imports account for 25% of total cereal consumption and 15% of maize consumption in SSA (Kidane et al., 2006). Cereal deficits in SSA are the largest in the world and this problem is exacerbated by rapid population growth, low productivity of local varieties, and declining soil fertility. For example, due to low productivity of local rice varieties, local markets are dominated by imported rice varieties (Nwanze et al., 2006). Furthermore, cereal imports in SSA are increasing at an annual rate of more than 20% (Saverimuttu and Rempel, 2004), serving to supplement inadequate local grain production. In addition to imports, food aid accounts for five percent of the total cereal consumption of SSA (Kidane et al., 2006).

Non-Governmental Organizations

Nongovernmental organizations (NGO) and community based organizations are active parties in the quest to improve the nutritional status and well being of SSA through agricultural research and related activities, thereby reducing the need for imports and food aid. Increased agricultural production in a sustainable manner would improve the lives of women and children, the dominant population of SSA (FAO, 1996; Pingali, 2001). For example, the International Institute of Tropical Agriculture (IITA), together with other NGO's and community based organizations, are currently active in promoting the conservation and utilization of plant genetic resources among local farmers. Reports from 39 SSA countries show 77% of the countries have operating agricultural extension services. Many of the NGO's are highly involved in agricultural extension and in promoting sustainable production. One focus of NGO programs is the lack of a reliable seed production system and poor quality seed from traders. As a result of the efforts of NGOs, 25% of SSA countries have passed a Seed Act, stipulating specific seed quality regulations. The remaining 75% of SSA countries do not have legislation governing the sale and distribution of seeds (FAO, 1998).

Fertilizer Use—Nitrogen (N) and Nitrogen Use Efficiency (NUE)

Grain yields from improved plant varieties have stopped rising as fast, and plant scientists agree that they are approaching physical limits to producing increasing amounts of a plant's weight in grain (Mann, 1997). Since the 1990s, it has become apparent that to increase crop production to the yields needed to sustain the growing population, especially in SSA, without further degradation of the natural resource base, inorganic fertilizer additions are required (Sanginga, 2003). Nitrogen Use Efficiency $\{\text{NUE} = [(\text{total cereal N removed}) - (\text{N coming from the soil} + \text{N deposited in rainfall})]/(\text{fertilizer N applied to cereals})\}$ (Raun and Johnson, 1999), is vital to be able to meet global demands for food, animal feed and fiber, and for minimizing environmental problems (Mosier et al., 2005).

Inorganic fertilizer has played an important role in increased crop production and consequently in feeding the growing world population. The Green Revolution which combined higher yielding grain varieties with increased use of chemical fertilizers enabled much of Asia and Latin America to achieve agricultural self-sufficiency in the 1960s and 1970s (Mann, 1997). However, the Green Revolution has never been fully applied to some of the world's poorest areas, especially SSA. Sub Saharan Africa agricultural production is characterized by eroded soil, N deprivation, and a lack of soil organic matter. With sufficient water and fertilizer, these deficiencies can be overcome (Mann, 1997).

The increase in human population and soil degradation has lead to a significant decrease in the per person available area for food production. In 1960, an average of 0.5 hectares per person of agricultural land was available worldwide, but by 2002 the area per person had decreased to 0.23 hectares. In developing countries, as is the case for SSA, available land for conversion to agricultural use is limited (Tan et al., 2005). The conversion of land to agricultural use accelerates land degradation and is threatening biological resources and agricultural productivity which is the mainstay of the economy for much of SSA. The deforestation and subsequent cultivation of land in SSA has led to the exponential decline of total N in the 0–10 centimeter soil layer. The nutrient balance for arable and permanent crop land in Africa from 1961–1998 showed that nutrient depletion has been increasing and for 1998 was 3.5 million metric tons of N (17.4 kg N ha^{-1} yr^{-1}). Nutrient audits for six SSA countries (Kenya, Malawi, Nigeria, Uganda, Zambia, and Zimbabwe) for the period 1961–1998 show that for most countries N, phosphorus (P), and potassium (K) nutrient depletion rates have increased (Sheldrick and Lingard, 2004). Increasing fertilizer use is essential to preventing soil degradation and increasing global yields (Lal, 2000), especially those of SSA.

Fertilizer use in developing countries has changed significantly in the last decades. For developed countries, the peak in fertilizer use was around 1980, but for developing countries as a whole it has been increasing and has not peaked. Bumb and Baanante (1996) estimate an increase in fertilizer use of 130 million tons of nutrients by 2020. However, this increase will be concentrated in parts of Asia and Latin America. Fertilizer use in SSA is predicted to increase by 10 million tons in the same period. Globally, higher cereal yields are likely to be achieved through a combination of increased N applications in regions with low N fertilizer use such as SSA and parts of Asia and Latin America, and improved NUE in countries where current N fertilizer use is already high (Dobermann, 2006).

Major Obstacles to Nitrogen Management in SSA

High external input technologies, lack of infrastructure, research, development, and extension are major obstacles to increasing fertilizer application rates in SSA (Howard et al., 1999). The fertilizer supply is limited and the cost is prohibitive for SSA farmers because fertilizer may cost as much as five times the global market price (Mosier et al., 2005). As a result of high fertilizer costs, application rates in SSA are the lowest in the world and continue to decline even though soils in SSA are considered as poor as those in Latin America and Asia (Kidane et al., 2006). The high cost of fertilizer necessitates the need for NUE to be maximized as it is vital to increase farmer profits derived from the application of fertilizer at the correct time in the correct amounts (Wong and Nortcliff, 1995).

The lack of infrastructure is a major factor influencing the cost of agricultural inputs in SSA. For a successful and sustainable increase in grain production to occur, an investment in infrastructure will have to occur (Mann, 1997). Infrastructure is needed to provide access to fertilizers and other inputs and for the delivery of products to local, national, and international markets (Mosier et al., 2005). The lack of infrastructure contributes to the existing food insecurity in SSA. Harvested crops do not move at reasonable rates from food surplus to food deficient areas resulting in food emergencies (Kidane et al., 2006). As a result of the inability to maintain infrastructure, instability for access to agricultural inputs and markets has occurred. Infrastructure would increase the opportunity for SSA to revive its economy (Mbwana, 1997), along with new technology, which would be a stepping stone in furthering the possibility of SSA becoming a part of the global community.

The greatest challenge to increasing grain yields in SSA is an overall lack of access to improved agricultural technologies and inputs that are combined with inadequate agricultural supporting services, created by a lack of funding and a lack of expert knowledge in the region (Kidane et al., 2006). Due to the belief that technology was not making a difference, funds that were provided by organizations such as the United States Agency for International Development (USAID) dropped between 1986 and 1991 (Oehmke and Crawford, 1996). Worldwide agricultural research funding is diminishing (Mann, 1997). However, agricultural research is absolutely vital to producing enough food for the world's growing population while sustaining the natural resource base on which agriculture depends (Pardey et al., 1996). Better technology and marketing is vital to solving the food issues of SSA (Djurfeldt and Larsson, 2004). Grain yields can at least be doubled, frequently tripled, and in some cases quadrupled through the application of the best technology (Mann, 1997). Creating partnerships and maintaining engagement in the process is the single most important challenge to bringing science and technology to farmers and thereby increase the agricultural productivity and raise the standard of living for all people residing in SSA (FAO, 1996). The result is improved food security and economic growth that can in turn reduce political instability and conflict within the region that leads to pressure on developed countries in the form of humanitarian crisis, emergency aid and military interventions (Pardey et al., 1996).

RESULTS

For this analysis, South Africa was included in all Sub Saharan Africa statistics, consistent with that recognized by the World Bank (World Bank, 1993).

Sub Saharan Africa currently has a population approaching 800 million people. It is growing annually by an alarming 19 million people per year (Figure 1). Despite this significant increase, it is somewhat misleading since SSA incurs 2 million deaths per year due to acquired immune deficiency syndrome (AIDS), and a total population of 24,500,000 people are living with the disease (AVERT, 2008). For comparative purposes, malnutrition and/or other diseases are responsible for 8.8 million deaths in this region per year (Jamison et al., 2006). Feeding an additional 19 million people in a currently depressed society further compromises the effectiveness that over-stretched assistance agencies can deliver.

While population has increased in SSA in the last 10 years, fertilizer N consumption decreased over this same time period (Figure 2). This statistic, like many others for SSA, is extremely disturbing since without N, protein simply cannot be produced. Adequately feeding the current population of 800+ million people with the Food and Agriculture Organization (FAO) minimum of 2500

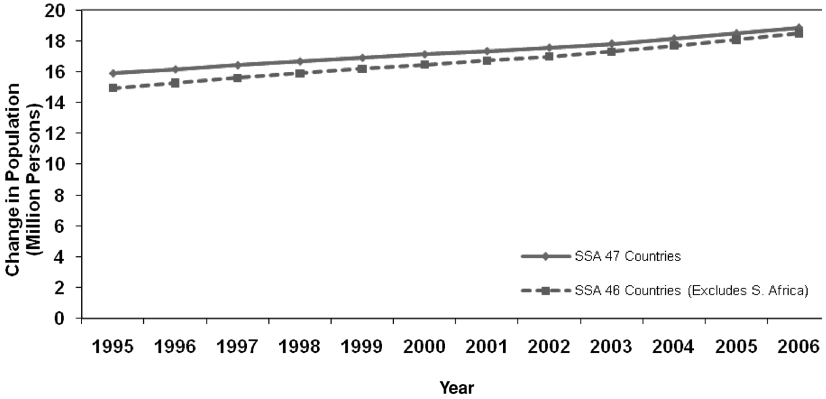

Figure 1. Change in population in Sub Saharan Africa from 1995 to 2006.

calories per day (FAO, 1950) is not being achieved, and further exacerbated with the additional mouths that need to be fed each year. Furthermore, the World Health Organization reports approximately 206 million SSA people have iron deficiencies, 86 million are affected by iodine deficiencies, and up to 31 million have vitamin A deficiencies. These deficiencies are due in large part to the low consumption of most vitamins based on the daily recommended intake rate (van Heeden and Schonfeldt, 2004).

Despite the decrease in fertilizer N consumption in SSA, cereal production from 1994 to 2006 has increased (Figure 3). It should be noted, however, that the increases from year to year have been highly variable, partly due to the

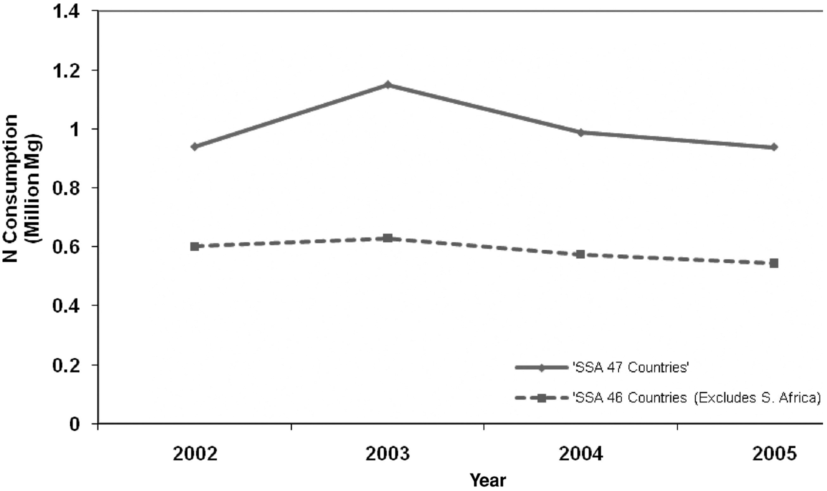

Figure 2. Total fertilizer N consumed in Sub Saharan Africa, 2002 to 2005.

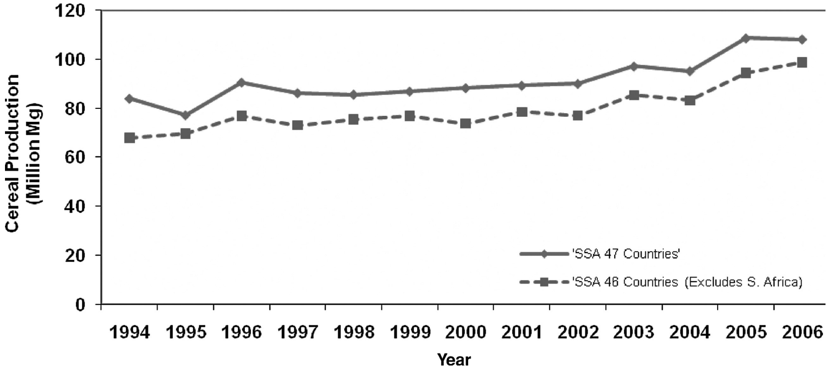

Figure 3. Total cereal grain production in Sub Saharan Africa, 1994–2006.

environmental changes and political instability (data not reported). This is possibly due to slight increases in the area that has come under production, and an overall increase in production per unit area for this region (Figure 4). The latter is due to improved varieties and hybrids and the adoption of more sustainable production practices.

Maize

Maize production in SSA increased from 1994 to 2006 (Figure 5), while the area harvested has remained steady at 25 million hectares over the same time period. Production per unit area increased from 1198 kg ha^{-1} to 1557 kg ha^{-1} in this same 13 year span. This is comparable with changes in maize production noted in other third world countries over the past decade. Thus, in order to feed 19 million additional people per year in SSA with 2500 calories per person

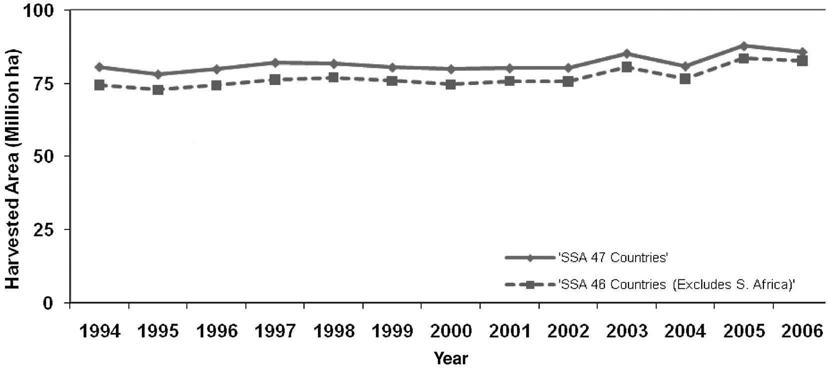

Figure 4. Total harvested area for cereal production in Sub Saharan Africa, 1994–2006.

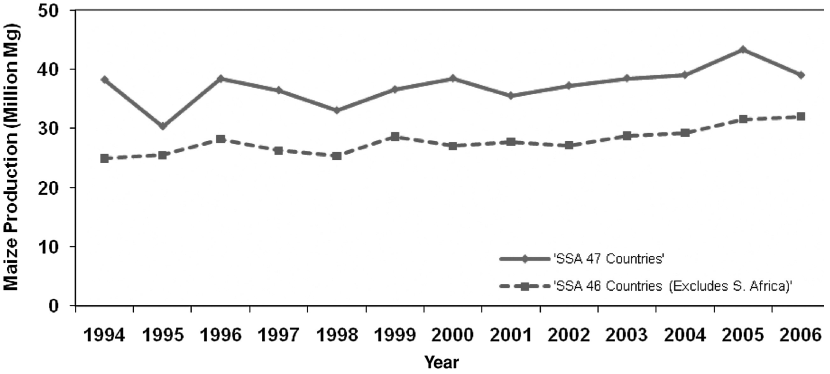

Figure 5. Total maize production in Sub Saharan Africa, 1994–2006.

per day using a 70 percent maize diet as the caloric source, an increase of 3,622,761 tons per year would need to be produced. This in turn would require 90,569 additional tons of N fertilizer at an NUE of 50%, and assuming a 1.25% total N value in the maize grain. Work conducted by Fofana et al. (2005) in Togo would support this endeavor in which they found an increase from 0.4 to 2.8 ton ha^{-1} of maize grain yield due to N application.

Sorghum

Sorghum production in SSA increased from 1994 to 2006 (Figure 6) as has the area harvested. Production per unit area has increased overall from 775 kg ha^{-1} to 890 kg ha^{-1}; however, it is highly variable from year to year. Overall, sorghum yields are low when compared with other similar dryland regions. However, Ouedraogo et al. (2007) working in Burkina Faso showed that

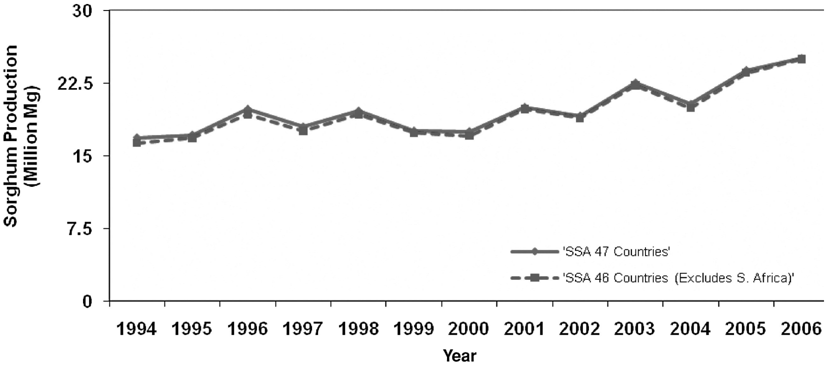

Figure 6. Total sorghum production in Sub Saharan Africa, 1994–2006.

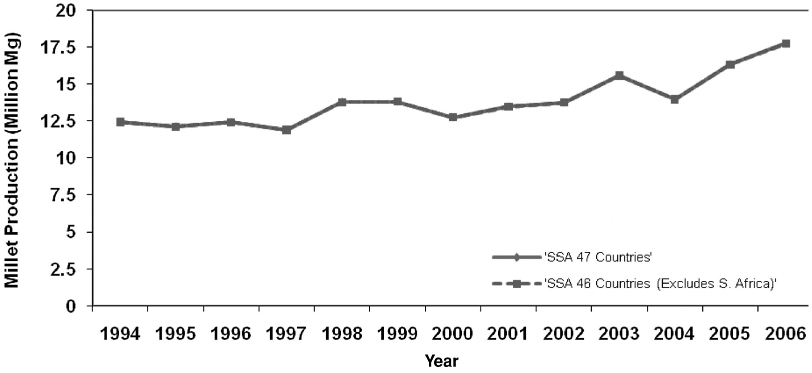

Figure 7. Total millet production for Sub Saharan Africa, 1994–2006.

moderate rates of sheep manure (40 kg ha^{-1}) and urea (40 kg ha^{-1}) could produce yields up to 8,300 kg ha^{-1}. Thus sorghum responds well to low or moderate rates of additional N fertilizer.

Millet and Rice

Although the harvested area for millet has remained steady at 20 million hectares from 1994 through 2006, production has increased (Figure 7). This is due to increases in production per unit area. As with other crops, low millet yields can be attributed to nutrient deficient soils. Bationo et al. (1992) reported millet yield per unit area increases of 125% on farmer's fields when adequate P was added, and increases of 185% when both N and P were added.

Rice production in SSA has increased slightly for the time period 1994 to 2006 (Figure 8). This is due to increases in harvested area and to increases in

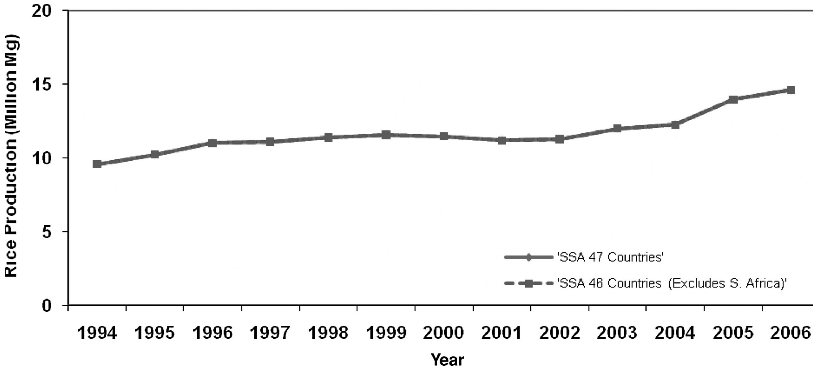

Figure 8. Total rice production for Sub Saharan Africa, 1994–2006.

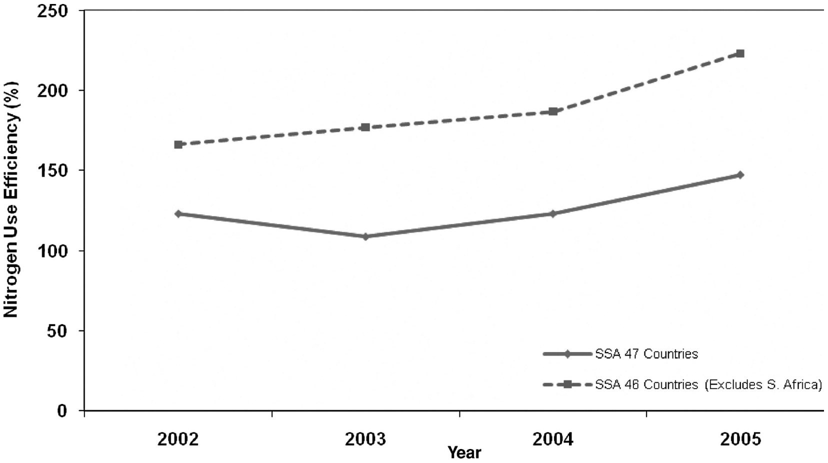

Figure 9. Estimated nitrogen use efficiency for cereal production in Sub Saharan Africa including and excluding South Africa, 2002–2005.

production per unit area. For the 13 year period, harvested area has increased from slightly more than 63 million hectares to more than 82 million hectares. For the same time period, production per unit area has also increased from 1841 kg ha^{-1} in 1994 to 2142 kg ha^{-1} in 2006.

Estimated Nitrogen Use Efficiency in Sub Saharan Africa

From 2002 to 2005, estimated cereal nitrogen use efficiency for sub Saharan Africa including and excluding South Africa is reported in Figure 9. Whether or not South Africa was included, estimated NUE's exceed 100 percent. On the surface this would suggest that SSA is doing a remarkable job of managing fertilizer N. However, the reality is that so little fertilizer N is used (average of 4 kg N ha^{-1}) that the estimates of NUE using the difference method (Varvel and Peterson, 1991) are grossly exaggerated (Table 1). Furthermore, this is misconstrued because nutrient mining, particularly N has taken place in virtually all areas where cereals are produced in SSA, and as a result, the natural soil resource is on the brink of exhaustion. Reporting on these high NUE's is important, but their levels in light of N application rates speak to a much bigger and potentially damaging/explosive situation for cereal production in this region.

This situation is very much like the symptoms noted in starving children who ironically show bloated stomachs when in fact they are nutrient deprived. Farmers in SSA have removed large quantities of nutrients from the soil over the course of decades, without using sufficient quantities of manure or fertilizers

Table 1
Nitrogen use efficiency for cereal production in Sub Saharan Africa, 2002–2005

	2002		2003		2004		2005	
Nitrogen Use Efficiency	SSA 47 (Mg)	SSA 46 (Mg)	SSA 47 (Mg)	SSA 46 (Mg)	SSA 47 (Mg)	SSA 46 (Mg)	SSA 47 (Mg)	SSA 46 (Mg)
SSA Fertilizer N Consumption								
*TOTAL	939449	600906	1150553	629172	986811	574342	938301	544759
**Cereals (60%)	563669	360544	690332	377503	592087	344605	562981	326855
SSA Cereal Production								
Maize	37182828	27106828	38436174	28731174	38996782	29286712	43273041	31557093
Sorghum	19129883	18871883	22533453	22273453	20319981	19946981	23828396	23568396
Millet	13762138	13750138	15586991	15574991	13982438	13970921	16353036	16341796
Rice	11253954	11250754	11987907	11984707	12249340	12246172	13950170	13947012
Wheat	4923590	2485845	4464549	2917709	5149229	3462229	5560270	3655270
Oat	98771	40554	77159	44159	100232	63232	96249	62249
Rye	700	0	230	0	620	0	1400	0
Barley	1490903	1310903	1401124	1161124	1644196	1459196	1711591	1486591
TOTAL	87842767	74816905	94487587	82687317	92442818	80435443	104774153	90618407
SSA Cereal Grain N Removal								
Maize (12.6 g/kg)	468504	341546	484296	362013	491359	369013	545240	397619
Sorghum (19.2 g/kg)	367294	362340	432642	427650	390144	382982	457505	452513
Millet (20.1 g/kg)	276619	276378	313299	313057	281047	280816	328696	328470
Rice (12.3 g/kg)	138424	138384	147451	147412	150667	150628	171587	171548
Wheat (21.3 g/kg)	104872	52948	95095	62147	109679	73745	118434	77857
Oat (19.3 g/kg)	1906	783	1489	852	1934	1220	1858	1201
Rye (22.1 g/kg)	15	0	5	0	14	0	31	0
Barley (20.2 g/kg)	30116	26480	28303	23455	33213	29476	34574	30029
TOTAL	1387750	1198860	1502580	1336586	1458056	1287880	1657925	1459239
N removed in Cereals from soil								
50% of total	693875	599430	751290	668293	729028	643940	828963	729619
SSA Estimated NUE	123	166	109	177	123	187	147	223

to replenish the soil (Sanchez, 2002). The extensive nutrient mining of soils in SSA and full knowledge of the lack of nutrient additions has led to a very similar "false interpretation" of the situation at hand.

DISCUSSION AND CONCLUSIONS

Nitrogen use efficiency in SSA is estimated at more than 100%. The high NUE is a misleading characterization of the SSA cereal production system and results from the low average application rates of N. The increasing gap between population and cereal production is influenced by low fertilizer use and difficulties associated with implementing external input technologies, which in turn result in low productivity and diminished soil quality.

Sanchez (2000) states that crop production needs to be increased by 40 percent and meat production by 58% by 2020 in developing nations in order to meet the demand of an ever growing population. Furthermore, Sanchez and Leakey (1997) report that high post harvest losses, decreased rainfall and increased temperatures, pest and disease, soil erosion, nutrient mining, and declining human health are among the problems facing SSA and that challenge even more its capacity to improve agriculture. Limited supplies of N, the continual rise in prices and elevated economic risk of N fertilization, combined with the existing low yield levels of cereal production systems reiterates the importance of NUE in SSA and the importance of aiding this region in overcoming the challenges its agriculture production systems must take on.

REFERENCES

AVERT (AVERTing HIV and AIDS). 2008. Sub Saharan Africa HIV & AIDS Statistics. Available at http://www.avert.org/subaadults.htm. (Accessed 23 April 2008).

Bationo, A., C. B. Christianson, W. E. Baethgen, and A. U. Mokwunye. 1992. A farm level evaluation of nitrogen and phosphorus fertilizer use and planting density for pearl millet production in Niger. *Fertilizer Research* 31: 175–185.

Bumb, B., and B. C. Baanante. 1996. World trends in fertilizer use and projections to 2020. 2020 Brief No. 38, International Food Policy Research Institute. 2020 Vision Brief 38:1–4

Byerlee, D., and P. W. Eicher. 1997. *Africa's Emerging Maize Revolution*. Boulder, CO: Lynee Rienner Publishers.

Byerlee, D., and P. W. Heisey. 1996. Past and potential impacts of maize research in Sub-Saharan Africa: A critical assessment. *Food Policy* 21: 255–277.

Dar, W. D., and S. J. Twomlow. 2007. Managing agriculture intensification: The role of international research. *Crop Protection* 26: 399–407.

Djurfeldt, G. 2005. The African food crisis: Lessons from the Asian green revolution. Wallingford, UK: CABI Publishing.

Djurfeldt, G., and R. Larsson. 2004. Food security, agricultural technology, and policy—The case of maize in sub Saharan Africa. In: *African Development and Poverty Reduction: The Macro-Micro Linkage Forum Paper 2004*. Pretoria: TIPS. Available at: http://www.tips.org.za/files/Djurfeldt_Larsson_Food_security.pdf.

Dobermann, A. 2006. Nitrogen use efficiency in cereal systems. Available at http://www.regional.org.au/au/asa/2006/plenary/soil/dobermannad.htm#TopOfPage (Accessed 24 April 2008).

Doward, A., J. Kydd, and M. Stockbridge. 2004. Agricultural liberalization in Sub Saharan Africa. Inception Report for ECPrep. Rome: FAO.

FAO. 1950. Calorie requirements: Report of the Committee on Calorie Requirements. FAO Nutritional Studies No. 5. Washington, DC: FAO.

FAO. 1996. Report of the fourth external programme and management review of the International Institute of Tropical Agriculture (IITA). Available at: http://www.fao.org/Wairdocs/TAC/X5806E/x5806e09.htm (Accessed 23 April 2008).

FAO. 1998. Seed production and improvement: assessment for sub Saharan Africa. Available at http://www.fao.org/AG/AGp/AGPS/abidjan/Tabcont.htm#Table (Accessed 23 April 2008).

Fofana, B., A. Tamelkpo, M. S. C. Wopereis, H. Breman, K. Dzotsi, and R. J. Carsky. 2005. Nitrogen use efficiency by maize as affected by mucuna short fallow and P application in the coastal savanna of West Africa. *Nutrient Cycling in Agroecosystems* 71: 227–237.

Howard, J., V. Kelly, M. Maredia, J. Stepanek, and W. C. Eric. 1999. Progress and problems in promoting high external technologies in sub Saharan Africa: The Sasakawa global 2000 experience in Ethiopia and Mozambique. In: *Annual Meetings of the American Agricultural Economics Association*. East Lansing, MI: Michigan State University. Available at: http://ageconsearch.umn.edu/bitstream/21570/1/sp99ho01.pdf.

Jamison, D. T., R. G. Feachem, M. W. Makgoba, E. R. Bos, F. K. Baingana, K. J. Hofman, and K. O. Rogo. 2006. Disease and mortality in Sub-Saharan Africa. Washington, DC: The World Bank.

Kidane, W., M. Maetz, and P. Dardel. 2006. Food security and agricultural development in sub Saharan Africa. Rome: FAO.

Lal, R. 2000. Soil management in developing countries. *Soil Science* 165: 57–72.

Mafongoya, P. L., A. Bationa, J. Kihara, and B. S. Waswa. 2006. Appropriate technologies to replenish soil fertility in southern Africa. *Nutrient Cycling Agroecosystems* 76: 137–151.

Mann, C. 1997. Reseeding the green revolution. *Science* 277:1038–1043.

Maredia, M., D. Byerlee, and P. Pee. 2000. Impacts of food crop improvement research in Africa. *Food Policy* 25: 531–559.

Martin, R. V., R. Washington, and T. E. Downing. 2000. Seasonal maize forecasting for South Africa and Zimbabwe derived from an agroclimatological model. *Journal of Applied Meteorology* 39: 473–1479.

Mbwana, J. 1997. Transport infrastructure in sub Saharan Africa. *Africa Notes* 1997(November):1.

Mosier, A. R., J. K. Syers, and J. R. Freney. 2005. Global assessment of nitrogen fertilizer: The SCOPE/IGBP nitrogen fertilizer rapid assessment project. *Science in China Series C-Life Sciences* 48: 795–766.

Nwanze, K. F., S. Mohapatra, P. Kormawa, S. Keya, and S. B. Oliver. 2006. Perspective rice development in sub Saharan Africa. *Journal of the Science of Food and Agriculture* 86: 675–677.

Oehmke, J. F., and E. R. Crawford. 1996. Payoffs to investments in agriculture technology in sub Saharan Africa. *Policy Synthesis for USAID—Bureau for Africa Office of Sustainable Development* No. 20:1.

Ouedraogo, E., A. Mando, L. Brussaard, and L. Stroosnijder. 2007. Tillage and fertility management effect on soil organic matter and sorghum yield in semi-arid West Africa. *Soil and Tillage Research* 94: 64–74.

Pardey, P., J. M. Alston, J. E. Christian, and S. Fan. 1996. Hidden harvests: U.S. benefits from international research aid. Food Policy Report. Washington, D.C.: The International Food Policy Research Institute.

Pingali, P. L. 2001. 1999–2000 World maize facts and trends, meeting world maize needs: Technology opportunities and priorities for the public sector. Mexico City: The International Maize and Wheat Improvement Center.

Raun, W. R., and G. V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. *Agronomy Journal* 91: 357–363.

Sanchez, P. A. 2000. Linking climate change research with food security and poverty reduction in the tropics. *Agriculture, Ecosystems and Environment* 82: 371–383.

Sanchez, P. A. 2002. Ecology—Soil fertility and hunger in Africa. *Science* 295: 2019–2020.

Sanchez, P. A., R. J. Buresh, A. N. Izac, F. R. Kwesiga, A. U. Mokwunye, C. G. Ndiritu, F. M. Place, K. D. Shepherd, M. J. Soule, and P. L. Woomer. 1997. Soil fertility replenishment in Africa: An investment in natural resource capital. SSSA Special Publication 51. Madison, WI: SSSA.

Sanchez, P. A., and R. R. B. Leakey. 1997. Land use transformation in Africa: Three determinants for balancing food security with natural resources utilization. *European Journal of Agronomy* 7: 15–23.

Sanginga, N. 2003. Role of biological nitrogen fixation in legume based cropping systems: A case study of West African farming systems. *Plant and Soil* 252: 25–39.

Saverimuttu, V., and H. Rempel. 2004. The determinats of cereal grain imports: Sub-Saharan Africa, 1970–1997. *African Development Review* 10: 525–548.

Sheldrick, W. F., and J. Lingard. 2004. The use of nutrient audits to determine nutrient balance in Africa. *Science Direct—Food Policy* 29: 61–98.

Tan, Z. X., R. Lal, and K. D. Wiebe. 2005. Global soil nutrient depletion and yield reduction. *Journal of Sustainable Agriculture* 26: 123–146.

Taylor, J. R. N. 2003. Overview: Importance of sorghum in Africa. Available at http://www.afripro.org.uk/papers/paper01Taylor.pdf (Accessed 17 April 2008).

van Heeden, S. M., and H. C. Schonfeldt. 2004. The need for food composition table for southern Africa. *Journal of Food Composition and Analysis* 17: 531–537.

Varvel, G. E., and T. A. Peterson. 1991. Nitrogen fertilizer recovery by grain sorghum in monoculture and rotation systems. *Agronomy Journal* 83: 617–622.

Wong, M. T. F., and S. Nortcliff. 1995. Seasonal fluctuations of native available N and soil management implications. *Fertilizer Research* 42: 13–26.

World Bank. 1993. A strategy to develop agriculture in sub Saharan Africa and a focus for the World Bank. Washington, DC: World Bank.