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SOILS

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1. Soybean in 'African Soils'

There is no such thing as a "tropical soil" or an "African soil". Regardless of the pitfalls of referring to soils by their climate or geographic region (Hartemink, 2015), such labels egregiously dismiss the tremendous soil diversity in sub-Saharan Africa (Pedro A Sanchez, 2002; Pedro A. Sanchez & Logan, 1992). The diversity of soils in the subcontinent challenge one-size-fits-all blanket recommendations for any crop. Understanding and adapting to soil context is thus critical for effective development and delivery of agricultural intensification technologies such as soybean.

Recent and accelerating cultivation of soybean across sub-Saharan Africa has raised prospects of a "soybean bonanza" (Foyer et al., 2019; Sinclair, Marrou, Soltani, Vadez, & Chandolu, 2014). From production largely as niche crop in the 1960s to nearly 1.5 million acres in 2016, soybean production is increasing in Africa despite decreasing consumption of other legumes (Foyer et al., 2019). Diversification of cropping systems with legumes such as soybean can increase food security due to beneficial impacts on pest and disease cycles, soil fertility, and as a source of human and/or livestock dietary protein (Snapp, Blackie, Gilbert, Bezner-Kerr, & Kanyama- Phiri, 2010). Harnessing the potential of Nitrogen fixation of legumes is a promising strategy for sustainable intensification of smallholder agricultural systems predicted on multiple soil-plant interactions, which for soybean in the African context may require unique consideration (Franke, van den Brand, Vanlauwe, & Giller, 2018; Snapp et al., 2010).

Soybean, like other legumes, can also offer a means to improve soil fertility and cropping system productivity beyond the soybean crop phase. Nitrogen (N) fixed by a soybean crop can contribute significantly to the N needs of ensuing grain crops such as maize. For example, up to 22 kg N ha-1 derived from soybean were taken up by following maize crops in Guinea (Sanginga, Okogun, Vanlauwe, & Dashiell, 2002), which is higher than estimated mean N inputs across SSA of 10 kg ha-1 (van der Velde et al., 2014). Soil fertility interventions that target soybean productivity – such as the SIL input bundles – can be therefore leveraged by soybean to the benefit of other crops important for food security and profitability.

However, soil fertility constraints to N fixation by legumes such as soybean can hamstring potential entry point of this crop to act as a fulcrum for improved production. In the smallholder agricultural systems that dominate production in much of sub-Saharan Africa (Pedro A Sanchez et al., 1997; Smaling, Nandwa, & Janssen, 1997), such soil constraints can be especially obstructive. To address these, SIL has focused on input bundles to maximize returns on soybean technology.

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2. The (Soil) Science Behind Bundling: Making the most of soybean's potential

Three key components of bundled inputs are: phosphorus, inoculum, and lime. Each component targets a specific soil-related constraint in order to maximize the yield potential of soybean. Additionally, all components can synergize to amplify investments in two or more components.

2.1. Phosphorus

Phosphorus (P) is a building block of the genetic code (RNA, DNA), a structural component of all cells (lipid membrane), and drives energy transactions in cells (ATP, NADPH). As for most crops, sufficient soil P availability is critical to support soybean growth and yield (Dodd & Mallarino, 2005; Jones, Lutz, & Smith, 1977). Since soybean is thought to be able to meet a majority of its N needs via biological N fixation (Gelfand & Philip Robertson, 2015; Salvagiotti et al., 2008) and given generally high crop demand for P compared to other nutrients (Havlin, Tisdale, Nelson, & Beaton, 2013), P can be a key yield-limiting soil nutrient for soybean.

However, the occurrence of weathered soils (Margenot, Singh, Rao, & Sommer, 2016) and socioeconomic constraints to smallholder access to P inputs (Nziguheba et al., 2015) in sub-Saharan Africa means soybean productivity may be especially constrained by this macronutrient. Additionally, soybean has a relatively high P harvest index, with up to 80% of P uptake allocated to grain (Bender, Haegele, & Below, 2015). Thus, replenishing P exported by soybean grain harvest using P inputs is essential for long-term agroecosystem sustainability.

When soils are managed to offer soybean sufficient P, N fixation can be maximized (van Vugt, Franke, & Giller, 2018), and coupled use of P and inoculants can increase grain yield (van Vugt et al., 2018). Legumes such as soybean may also be able to preferentially scavenge non-available P contained in organic forms via secretion of phosphatases (Lelei & Onwonga, 2014; Oberson, Friesen, Tiessen, Morel, & Stahel, 1999; Rao, Borrero, Ricaurte, Garcia, & Ayarza, 1997). Meta-analysis suggests improved soil P availability to grain crops with the addition of a legume rotation explains non-N effects of legumes on non-legume grain yield increases across sub- Saharan Africa (Franke et al., 2018).

2.2. Inoculum

As with any other legume, biological N fixation by soybean requires a compatible symbiotic rhizobacteria generally from the genus *Bradyrhizobium*. Given its Asian origins and historically recent introduction to Africa (Mpepereki, Javaheri, Davis, & Giller, 2000), the soybean symbiotic *Bradyrhizobium japonicum* is generally thought to not be present in soils in the continent (van Heerwaarden et al., 2018). Pioneering field trials in sub- Saharan Africa attributed limited N fixation by soybean to the absence of compatible *B. japonicum* (Kueneman, Root, Dashiell, & Hohenberg, 1984). Native or indigenous *Rhizobium* strains appear to have generally limited symbiotic effectiveness for soybean (Abaidoo, Keyser, Singleton, Dashiell, & Sanginga, 2007). Thus, inoculation with appropriate *Rhizobium* offers a means to enhance soil biological fertility for maximizing soybean production in this sub-Sahara Africa. For example, across more than 2,000 trials in ten sub-Saharan African countries, inoculation was found to increase soybean yield from a mean of nearly 9% from 1.22 to 1.34 Mg ha- 1, albeit with highly variable site-specific response (van Heerwaarden et al., 2018). However, emerging evidence suggests that indigenous *Rhizobium* are able to colonize and effectively symbiose with soybean in certain soils in the subcontinent (Jaiswal & Dakora, 2019). Though indigenous soil *Rhizobium* in sub-Saharan Africa appear to differ from those found in other subcontinents, it has been proposed that potentially high *Rhizobium* diversity may be harbored in Africa (Grönemeyer & Reinhold-Hurek, 2018) that could serve as a rich genetic resource for comparable or even improved inoculants for soybean and other leguminous crops in Africa and globally (Jaiswal & Dakora, 2019).

2.3. Lime

Lime works through multiple mechanisms to alleviate co-constraints to crop production, most notably decreasing aluminum toxicity to roots and enhancing the availability of soil nutrients already present. While not a nutrient, soil pH is critical for soybean growth indirectly via its effects on the availability of nutrients, in particular P and micronutrients, and directly via aluminum toxicity. Both of these constraints occur at low pH values (acidic soils) making liming an important strategy to enable soybean use of nutrients already present or applied to the soil. Soybean is responsive to liming applications that increase pH above the threshold of aluminum toxicity (Slaton, Roberts, & Ross, 2011), generally thought to be pH > 5.5 (Havlin et al., 2013).

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