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Evaluating the Dynamics of Pigeon Pea - Cereal Grain Intercropping in Sub-Saharan Africa

Introduction

Soil nutrient depletion and drought-related yield loss are major issues affecting smallholder agriculture in semi-arid regions in Africa. To maintain reasonable standards of subsistence living and to strengthen localized communities, intercropping systems have been employed in these areas for generations. By exploiting mutualistic relationships between various crops, insects, and other flora, and minimizing the effects of competition through traditional ecological knowledge, local farmers have developed tools to maintain productivity on their land. However, recent decades have brought increasing change to the African continent. Populations have risen and elements of modern, industrialized agriculture have become common in the landscape. Desertification, catalyzed by excessive livestock grazing, irresponsible development and resource consumption, and other anthropogenic factors, is now a growing problem. While the availability of chemical fertilizers and pesticides has allowed for increased yields in certain systems, these products have often created new problems for farmers, leaving them with depleted land and a dependence on unsustainable inputs. Furthermore, the application of specific, temporally significant fertilizer treatments in subsistence farming systems has the potential to greatly increase yields and improve the livelihood of families who work the land, but the adequate research necessary to advise decision making at the farm level has yet to be conducted (Saidia et al., 2019). To assist small-scale, localized farmers with the development of balanced systems that offer food and economic security, and to prevent further metastasis of environmentally destructive farming practices, it is imperative that the scientific community reexamine the traditional agricultural practices specific to each region. One such intercropping arrangement, popular for generations in areas which experience extended periods of rain followed by drought conditions, involves planting alternating rows of leguminous crops with cereal grains. Maize is the most widely planted cereal and is often chosen along with pigeon pea plants for the intercropping arrangement. If properly executed, this cereal grain – pigeon pea system improves the nutritional and economic stability of small farms by providing consistency in yields and other ecosystem services through the facilitative interactions of multiple organisms. To understand the details of the mechanics and potential variability of this system, it is necessary to elaborate on its components and how they interact in an agroecological context.

Discussion

Originating in South Asia and appearing in West Africa over 2,000 years ago, the pigeon pea (PP) has been integral to the livelihood of countless farmers throughout previous centuries. Today it is an indispensable source of protein for subsistence farmers throughout the world, with indeterminate varieties often cultivated adjacent to residences for ease of harvest throughout the season (Sharma et al., 2011). A bushy shrub, it can reach 5m in height and maintain productivity for up to five years. Valued for its high protein content, PP is often cultivated as a pulse crop in subsistence farming communities, meaning that the leguminous seeds are dried and stored for future consumption (Morton et al., 1998). In addition to protein, PP seeds contain high levels of starch, calcium, manganese, fat, and other trace minerals. A highly versatile crop, it is drought tolerant and its ability to fix atmospheric nitrogen (N) allows it to thrive in nutrient poor soil conditions (Sharma et al., 2011). Thus, the cumulative ecosystem services that PP provides to smallholder farmers makes it an excellent candidate for inclusion in future intercropping systems in semi-arid regions of Sub-Saharan Africa.

Intercropping, the practice of growing more than one crop simultaneously in the same field, has been demonstrated to increase farm productivity due to increased resource use efficiency and niche exploitation, and is widely recognized as an integral component of diverse farming systems (Brooker et al., 2015). In Africa, where land degradation and declining soil fertility are widespread problems, smallholder intensification is the key to stability (Kiwia et al., 2019). The importance of identifying productive intercrops in this region is pressing, as increased climate variability, pest and disease outbreaks, and other disruptions have resulted in conditions of food deprivation for 21% of the African population (Daryanto et al., 2020). One such intercropping system, that of PP combined with cereal grains such as maize and millet, has been widely adopted and helps to strengthen small farm resiliency in multiple ways.

Cereal grains are often the principle staple crops of African farmers, and decades of intensification with little to no replenishing nutrient inputs has created an impending fertility crisis with a wide geographic footprint. Intercropping with legumes, which fix N in their root nodules when it is not readily available in the soil, can elevate cereal yields, reduce certain pest and insect pressure, and restore depleted soil. Additionally, legumes are an advantageous intercrop because their residues contain high levels of N, a limiting nutrient in African systems. With adequate N available for uptake, microbes can perform ecosystem services such as mineralization, reducing the period of immobilization of phosphorus (P) and other nutrients in the soil (Njira et al., 2020). Under optimal conditions, PP is capable of fixing 235 kg ha-1 of atmospheric N in agroforestry systems, increasing yields and reducing the need for external inputs (Senkoro et al., 2017). It has also been demonstrated that the intercrop of maize and PP can greatly over yield equivalent monocultures, with an estimated land equivalent ratio (LER) of 1.57 in field studies (Daryanto et al., 2020). Several factors contribute to the increased productivity and consistency of this intercrop, beginning with phenological traits which allow the two species to exploit distinct niches while also exhibiting mutualistic behaviors at certain points during the growing season. While maize and other cereal grains are shallow rooted, PP has a deep rooting structure which enables it to access water during periods of prolonged drought, a common occurrence in sub-Saharan Africa. During the dry season, PP plants draw water from deep in the earth and redistribute it to surface plant and microbial communities. This transfer is facilitated by fungal networks within the soil and helps to sustain intercropped cereals during periods of harsh, dry weather (Kiwia et al., 2019).

The process by which the PP plant extracts water through multiple soil horizons via its root system is termed hydraulic lift. Occurring at night, water and other nutrients are transported from the deep soil to the other root and above ground plant biomass as well as to the dry surface soil layers. This allows PP to thrive during the dry season while at the same time providing a limiting nutrient to other shallow-rooted flora and soil microorganisms (Sekiya and Yano, 2004). Because the transfer of water by hydraulic lift recharges the topsoil, benefits intercropped plants, and prevents crop loss that would ordinarily occur under drought conditions, the process is commonly referred to as "bioirrigation" (Singh et al., 2020). While it has been demonstrated that PP can act as a deep-rooted bioirrigator when paired with cereal grains, it does not accomplish this in a vacuum, and a deeper understanding of the system is necessary to determine the efficacy of the intercrop.

The efficient transfer of deep water by PP roots to the shallow root systems of cereal grains is assisted by mycorrhizal associations within the system. Arbuscular mycorrhizal fungi (AMF) colonize root systems and facilitate mutualistic interactions in exchange for habitat and carbohydrates. They expand the root surface area and are capable of connecting multiple unrelated plant species, scavenging and distributing micronutrients, and thus creating a network of symbionts (Njira et al., 2017). AMF can also strengthen systems by increasing disease resistance and improving soil structure. Additionally, studies have shown that AMF improve the efficiency of uptake of N and P in intercropping systems featuring PP and cereal grains, a process referred to as "biofertilization" (Saharan et al., 2018). This is accomplished through the formation of a common mycorrhizal network (CMN) which connects neighboring plants with different root systems. By creating bridges between organisms, these biofertilizers can regulate the distribution of water and nutrients throughout the system. For instance, a laboratory study of the finger millet – PP intercrop in drought conditions found that millet samples inoculated with AMF showed no drought effects, while samples which lacked the fungal network experienced drought stress and a 50% reduction in growth (Saharan et al., 2018). The ability of PP to efficiently perform hydraulic lift and transfer water to the cereal grain is therefore highly dependent on the presence of AMF and a CMN in a system, and is further improved through close spatial proximity of the roots of PP and the cereal grain, indicating that appropriate crop spacing is required for the system to function at an optimal level (Singh et al., 2019). It has also been observed in multiple multi-year studies that AMF colonization of cereal grain roots is significantly higher in years following a PP-cereal intercrop or a PP cover crop, indicating that the presence of PP in the system encourages the establishment of a CMN and improves the nutrient use efficiency of the soil (Njira et al., 2017).

While the PP – cereal grain intercrop exhibits multiple mutualistic interactions, both plants have nutrient requirements, and they necessarily compete when grown in proximity in nutrient-poor conditions. Studies which demonstrate the facilitative effects of PP on cereal grains in drought conditions also highlight reductions in biomass of cereal grains in the intercrops versus monoculture, indicating competition for limited resources (Singh et al., 2019). Additionally, while sufficient root colonization by AMF and a CMN to facilitate nutrient transfer led to higher cereal grain survival in drought conditions, those same fungal networks contributed to increased competition for nutrients prior to drought (Singh et al., 2020). To address this on the farm level, PP is often planted two to three weeks after the cereal grain in intercrops in Africa. Initially PP grows slowly, while the cereals expand rapidly to occupy their fundamental niche in the system. As the season progresses the PP roots extend deep into the soil and begin to perform hydraulic lift, stabilizing the cereal crop. The PP plants mature throughout the dry season and into the fall, long after the cereal grains have been harvested, and provide a consistent nutritional reserve for smallholder farmers (Daryanto et al., 2020)(Kimaro et al., 2009). This approach reduces interspecific competition between the two crops; however, it does not address the ongoing nutrient deficiencies in the soil.

It has been demonstrated that the sole addition of PP to cereal grain monocultures in nutrient poor systems increases the availability of N and stabilizes grain yields. The rate that PP converts atmospheric N into bioavailable inorganic compounds in the soil is relative to the size of the existing inorganic N pools, so N-based fertilizer regimens are largely unnecessary. PP biomass has a low C:N ratio, and intercrops that incorporate leguminous residues are associated with increased N mineralization rates and higher levels of N uptake by cereal grains (Njira et al., 2020). The presence of adequate N in the soil also facilitates the mobilization limiting micronutrients, particularly P, by microbes through the process of mineralization (Daryanto et al., 2020). Because both crops require high available nutrient pools in the soil to produce optimal yields and farm fields are depleted annually by the removal of organic materials at harvest, it is necessary to fertilize on a yearly basis. However, by incorporating improved fallow methods and intercropping with PP and other legumes, it is possible to reduce fertilizer inputs by 50% relative to equivalent monocultures, while still optimizing yields.

Conclusion

Intercropping PP with cereal grains has many benefits over equivalent monocultures including improvements in soil fertility, increased nutrient use efficiency amongst crops, and the stabilization of crop yields in drought-prone areas (Kiwia et al., 2019). The deep-rooted PP plant irrigates the shallow-rooted cereal grain crop in drought conditions through hydraulic lift facilitated by biofertilization of both crop’s roots by AMF and the development of the CMN. Thus, AMF act as a “nutrient highway”, elevating water and nutrients into the upper horizons of arid soils, while the CMN distributes them to other plants and soil microbes (Saharan et al., 2018). Additionally, benefits to smallholder farmers include increased monetary returns on investments, improved household nutrition and dietary diversification, and increased food security because PP matures much later in the season than do cereal grains (Kiwia et al., 2019). Leaves of the PP can be used as fodder for livestock, and its dry biomass is an excellent source of firewood. Often it is women who are tasked with retrieving firewood for household energy needs, so this ecosystem service is labor-saving and potentially reduces pressure on local woodlands, allowing them to regenerate. Furthermore, PP can be planted along ridges and contour lines, reducing erosion (Morton et al., 1998). Established PP crops and residues also increase soil cover and decrease weed pressure. To maximize crop yields it is also necessary to apply modest amounts of fertilizer to this intercrop, otherwise interspecific competition results in decreased yields. This can be accomplished either by applying half of the inorganic fertilizer traditionally applied to monocrops, or through a combination of the application of a small amount of manure along with PP crop residues and improved fallows which feature PP and other legumes (Kiwia et al., 2019). If implemented properly this system can be of great value to those who practice subsistence agriculture in sub-Saharan Africa by helping to intensify small farms in a sustainable manner, breaking the cycle of land degradation and ensuing poverty, and improving the livelihoods of those who rely on the land for their sustenance.

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