Declining soil fertility and farm productivity is a major global concern in order to achieve food security for a burgeoning world population. It is reported that improving soil health alone can increase productivity by 10–15% and in combination with efficient plant traits, farm productivity can be increased up to 50–60%. In this article we explore the emerging microbial and bioengineering technologies, which can be employed to achieve the transformational increase in farm productivity and can simultaneously enhance environmental outcomes i.e., low green house gas (GHG) emissions. We argue that metagenomics, meta-transcriptomics and metabolomics have potential to provide fundamental knowledge on plant-microbes interactions necessary for new innovations to increase farm productivity. Further, these approaches provide tools to identify and select novel microbial/gene resources which can be harnessed in transgenic and designer plant technologies for enhanced resource use efficiencies.

Introduction: Food Security, Soil Health, and Resource Use Efficiency

Securing food security for an increasing world population is a major challenge. It is estimated that by 2050, food production needs to increase between 50–70%.1,2 The challenge for policy makers, farmers, scientists and agronomists is that this increase in food production needs to be achieved from available arable lands. However, soil fertility has been in decline globally due to intensification of farming, soil erosion and inappropriate use of agrochemicals and heavy machinery. The pressure on arable land differs between developed and developing countries.3 In developed countries for example, national food security is not a major concern but pressure on arable land for production of biofuels, mining and other industrial activities is prevalent. Additionally, there has been significant declines in the structure and fertility of much arable land in developed countries. As a result, further resource inputs do not results in yield gains across many farming regions.4 A recently observed phenomenon called multiple nutrient limitation has been identified as a major limiting factor on resource use efficiency in farms. For example, a lack of phosphorus (P) or potassium availability (resulting from chemical fixation into the top soil layers), can limit farm productivity due to its negative impact on N use efficiency.5 Additional major challenges in developing countries, lie in substantially increasing yield quality and quantity without further increase in farming cost and detrimental environmental impacts.

Soil security is a critical component for food security but also for sustaining living terrestrial ecosystems. Soil quality and/or health has been defined as the capacity of a specific kind of soil to perform functions within natural or managed ecosystem boundaries to sustain biological productivity, promote environmental quality and maintain plant and animal health.6 Low input or organic farming in some areas are critical and necessary for economic and social reasons. In such systems, the role of microbes in nutrient availability for plant growth and resistance against disease and pests is of vital importance.

Conventional farming practice remains one of the major approaches to increase crop productivity. However recent
evidence suggest declining or stagnating yields in many areas, and the sustainability of such practices has been questioned. Undoubtedly the situation is likely to become exacerbated due to limited availability of P fertilizers and increasing costs associated with mining less productive sites for commercial P acquisition. Further uncertainty is due to inevitable changes in weather patterns and the intensity and frequency of extreme weather events. Soil physico-chemical and biological environments are key factors for primary productivity, and through their interactions, these factors modulate farm profitability. Key components of productive soils vary greatly depending on soil type, regional climate conditions, types of crops grown and agronomic practices employed. None the less common attributes necessary to maintain productive soils include increasing soil C contents, enhancing water and/or nutrient holding capacities, increasing water filtration rates, minimizing erosions and providing healthy habitats for beneficial organisms. Improved resource (water and nutrient) use efficiency is key for productive and profitable farming. Current resource use efficiency is very low in farming systems. For example, nitrogen (N) and P use efficiency is considered below 50% and 30% of total inputs respectively. Global annual consumption of P fertilizer is 50 million tonnes and world resources of good quality P is estimated to be exhausted in 80 y. It is obvious that increasing resource use efficiency will save cost and improve environmental benefits by reducing GHG emissions and leaching losses, thus improving soil and water quality. One of the major key constraints in resource use efficiency is ability of soils to hold resources (water and nutrients) in the form that is available for plant uptake. It is postulated that use of appropriate technologies and management practices can substantially increase the productivity. For example, it is believed that increasing soil health alone can increase productivity by 10–15% which, in combination with better plant traits, can increase farm productivity up to 60%. In this article, we explore emerging biotechnological approaches which increase soil productivity and can contribute to food security by improving availability of resources and resource use efficiency for plants.

One of the major constraints of resource use efficiency includes availability of nutrients for plant uptake. Nutrients applied to crops undergoes biotic and abiotic transformation and become less available for plant uptake. For example, applied N fertilizers (urea and/or ammonium based) are utilized by microbes as a substrate for nitrification and denitrification. This can result in a significant amount of applied-N being immobilized, leached or nitrate into water bodies (causing eutrophication) or released into the atmosphere as N2O, a potent GHG. Similarly applied P fertilizers are distributed into different pools and the majority of this becomes unavailable for plant uptake. Unlike N, there is no biological fixation of phosphorus or losses to the atmosphere, but it gets chemically fixed in clay and organic particles within soil and becomes unavailable for plant uptake.

Harnessing Plant-Microbes Interactions for Transgenic Technologies

In natural ecosystem, plant-microbe interactions are key for primary productivity. Plants release carbon (C) in the form of rhizodeposits which are utilized by microbial communities for growth and activity. Microbes, in turn, provide other essential nutrients (primarily N and P) through atmospheric fixation of N2 or mineralization of organic matter. There are number of symbiotic and free-living microbes which are known to enhance nutrient availability to plants. A few common example for symbiotic interactions include, rhizobia-legume nodule symbiosis associated with N2-fixation and plant-arbuscular mycorrhizal (AM) fungi interaction associated with phosphorus acquisitions. There are numerous free-living microbes inhabiting the rhizosphere which fix atmospheric N2 and solubilize P for plant uptake. Some bacteria and fungi (mainly mycorrhiza) enhance availability of P to plant from organic and fixed P by mineralization and solubilization. Additionally, microbes can enhance P acquisition and availability by promoting root growth. Previous studies have demonstrated incorporation of P acquisition by inoculating P-solubilizing microbes. Additionally, arbuscular mycorrhizal fungi are known to enhance plant P use efficiency by foraging soil P over greater volume of soil due to vast hyphal networks. Previous works have highlighted approaches to harness microbe-rhizosphere are utilized by microbes as a substrate for nitrification and denitrification. but how these interactions could be exploited for biotechnological applications is not fully known. Rhizosphere-microbial interactions are modulated by a number of chemicals produced by plant roots to communicate with soil microbes. Identifying these signal molecules and harnessing them to improve interaction between beneficial microbes and plant roots can improve resource availability and use efficiency. One such mechanism is to genetically modify plants to enhance plant-microbial signalling which can serve this purpose. Transgenic plants which encourage colonization and persistence of beneficial microbes through altered root exudation has been suggested as an effective approach.

Nitrogen fertilizers remain the major limiting resource in crop productivity and the main cost to farming. Transgenic technologies can be used to reduce N inputs by two potential approaches: (1) Genetic engineering of non-legume crops to form N2-fixing nodules with Rhizobia, resulting in N acquisition through N2 fixation. However, nodule formation in legumes involves a complex signaling dialog between plant and rhizobia to initiate colonization, nodule formation and N2 fixation. Each step is mediated by multiple genes and therefore successful transfer of nodule forming ability in non-legume crops requires a complete understanding of interactions between multiple (several dozen) plant and bacterial genes. Rapidly growing omics technologies will help greatly in understanding this complex series of interactions in the future. However, our current technological ability to successfully engineer such complex traits is limited. (2) Another potential approach to increase N availability to plants includes engineering crops with N-fixing (nif) genes. Nif genes encode nitrogenase enzyme, a key
enzyme in the fixation of $N_2$, and are distributed in a number of free-living and symbiotic bacteria. However, successful engineering of nif genes in crops will require a fuller understanding of the interactions between different genes and $N_2$ fixing biochemistry. For example, the nitrogenase enzyme needs protection against oxygen for its activity. It has been used for inserting and expressing in cell organelles such as chloroplast and mitochondria due to their similarity with bacterial cells. However, there are still huge technical challenges to overcome before this can be successfully achieved. For example, at least 10 different genes need to be transferred into plants in order to achieve $N_2$ fixation. Before the effectiveness of these approaches can be realized, a fuller understanding of the complexity of different gene interactions is needed.

Similarly, conceptually plants can be engineered with some P mineralizing and/or solubilizing genes from soil bacteria. Several plants already contain acid phosphatase enzymes for P-solubilization, but it can be envisaged that alkaline phosphatase and phytase genes can be harnessed through transgenic technologies so that crops can directly access organic and/or fixed phosphorus and thus improve access to P. Some success in transferring phy- tase and phosphatase genes in transgenic plants have been reported. Currently, however, no evidence is available to evaluate the success and effectiveness of such an approach at commercial scale and the challenges remain similar as those for transfer of $N_2$ fixing genes.

Although the use of transgenic expression of bacterial genes in plants to improve N and P efficiencies has yet to be fully realized, promise can be taken from other examples where soil bacteria have been the major source of genes for transgenic technologies. Perhaps the two most successful examples of transgenic plants have been reported. Currently, however, no evidence is available to evaluate the success and effectiveness of such an approach at commercial scale and the challenges remain similar as those for transfer of $N_2$ fixing genes.

There is a need of knowledge and technology to make sure that seed applied products can produce seeds and/or seedlings needed for farm application, this technology can have direct positive impacts on farm productivity. These associations are well documented for their positive impact on plant growth and yield. However, if soil productivity was compromised due to multiple-nutrient limitation, soil pH management can be used to identify the type of intervention required to restore soil health. For example, if soil productivity is compromised due to loss of organic matter, supplementa- tion with compost, green waste, cover crop, etc., can be implemented. Similarly, if the soil productivity was compromised due to multiple-nutrient limitation, introduction of bioinoculants such as P-solubilizing microbes, free living and/or symbiotic N-fixing microbes, transgenic and/or designer plants along with other agronomic measures, i.e., precision tech- nology, soil pH management can be used to restore land productivity.

Harnessing Plant-Microbes Interactions for Designer Plants

Potentially it is possible to manipu- late microbial activity in the rhizosphere to maximize the availability of nutrients for plant uptake. One such approach is development of better root traits in crops which can access different zones in soils for nutrient and/or water uptake. More importantly, systems which can promote and/or attract beneficial microbes such as mycorrhiza, P-solubilizing, N2-fixing and plant growth promoting bacteria can have direct positive impacts on farm productivity. These associations are well documented for their positive impact on plant growth and yield. However, if soil productivity was compromised due to multiple-nutrient limitation, soil pH management can be used to identify the type of intervention required to restore soil health. For example, if soil productivity is compromised due to loss of organic matter, supplementa- tion with compost, green waste, cover crop, etc., can be implemented. Similarly, if the soil productivity was compromised due to multiple-nutrient limitation, introduction of bioinoculants such as P-solubilizing microbes, free living and/or symbiotic N-fixing microbes, transgenic and/or designer plants along with other agronomic measures, i.e., precision tech- nology, soil pH management can be used to restore land productivity.

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against indigenous microbes and form strong association with growing plants.

Conclusion

Achieving food security for the growing world population requires scientific breakthroughs and technology developments at many fronts. Enhancing soil productivity through better resource availability and use efficiency in arable soils is one of those key challenges. Transgenic technologies have already served well in several farming regions but focus of this technology has been mainly for pest management. Developing transgenic plants to improve resource-use efficiency is scientifically more challenging because these traits seems to be multigenic and post translation products needs bacterial cell environment for activity. However, there is a strong concept available (transfer of N₂-fixing genes) and efforts are being made in this direction. However, it may take several years, and even decades, before such technologies could be implemented for field application. It can be argued that the designer plant approach may have better applicability in the shorter term. Technologies for seed dressing with beneficial microbial spores are well-established. If a successful technology for introducing endophytic bacteria in seeds at a commercial scale can be achieved, this technology may serve well in the effort to secure improved resource use efficiency. To achieve this, concerted effort is needed between plant and microbial scientists, agronomists and engineers. Social and economic constraints also need to be addressed. Success in this direction will not only improve farm productivity and profitability but improve soil, air, and water quality, relying less on external inputs so that proportionally more will be utilized by plants, reducing environmental burden and stress on soil and ecosystems health.

Disclosure of Potential Conflicts of Interest

No potential conflict of interest was disclosed.

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van der Heijden MGA, Wagg C. Soil microbial diversity and nitrogen-assimilation functioning. Plant Soil 2007; 297:395-407.

Oss C, Dolfus C, Camin-Spitler MP, Cooper JM. Impacts of organic and conventional crop management on diversity and activity of free-living nitrogen-fixing bacteria and total bacteria are subsidiary to temporal effects. PLoS One 2012; 7:e23881; PMID:23123518; http://dx.doi.org/10.1371/journal.pone.023881.

Vermolen A, Dimon M, Regula P, Karipidis I, Chardon M, Kamin P, Jonkers I, Klett I. The genetic diversity of cultivable nitrogen-fixing bacteria in the rhizosphere. Microb Ecol 2011; 62:277-96; PMID:22897896; http://dx.doi.org/10.1007/s00248-010-9787-4.

Jakobek, Chaudhry, Mallik, Lamborg, Zhu, YG. Culturing phosphorus acquisition of microorganisms with that of root hairs using the root hairless barley mutant. Plant Cell Environ 2011; 28:928-38; PMID:21887369; http://dx.doi.org/10.1111/j.1365-3040.2011.02149.x.

Kurniad HC, Potential of PGPR in Agricultural Intenations. In: Mokhtar AD, ed. Plant growth and health promoting bacteria, 2010:45-79.

Abhijit M, Trivedi I, Beneficial soil microorganisms, an ecologically available for soil fertility management. In: Lichtfouse E, eds. Genetics, Biofuels and the Environment. Madison: American Society of Agronomy, 2005:437-94.

Barbara C, Bardgett RD, Smith P, Reay DS. Unravelling rhizosphere-microbial interactions: novel applications for exploitation. Trends Microbiol 2012; 20:10-17; PMID:22203415; http://dx.doi.org/10.1016/j.tibtech.2012.04.004.

Tian J, Wang X, Tong Y, Chen X, Liu H. Bioengineering and management for efficient phosphorus utilization in crops and pastures. Eur J Plant Biochem 2012; 23:666-77; PMID:2244791; http://dx.doi.org/10.1186/1475-2891-11-6.

Wang Y, Xu D, Ding, G, Xue. Characterization of Phi6 and alpha gene improves soil phosphorus utilization and nodulation ability in Sinorhizobium 2013; 8:86001; e; PMID:23753385; http://dx.doi.org/10.1371/journal.pone.0086001.

Kouwen J, Moulin M, Bjoel Point of view: crops expressing Alcali phosphate transport and biological control. Nat Biotechnol 2006; 24:453-5; PMID:17047895; http://dx.doi.org/10.1038/nbt1080.

Liu KS. Biocrop's: products, production and prospects. Food Technology 1999; 53:42.