Mitigating climate change through managing constructed-microbial communities in agriculture

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Abstract

The importance of increasing crop production while reducing resource inputs and land-use change cannot be overstated especially in light of climate change and a human population growth projected to reach nine billion this century. Mutualistic plant-microbe interactions offer a novel approach to enhance agricultural productivity while reducing environmental costs. In concert with other novel agronomic technologies and management, plant-microbial mutualisms could help increase crop production and reduce yield losses by improving resistance and/or resilience to edaphic, biologic, and climatic variability from both bottom-up and top-down perspectives.

Keywords

Symbiosis, plant-microbe interactions, mitigation, agroecology, climate change, synthetic communities, GHGe

1. Crop production, feeding 9 billion people, climate change, and system feedbacks

Food security is an important issue globally (IFPRI 2012; OECD 2012 a and b) according to the International Panel on Climate Change report (IPCC, 2013) climate in the next 25 years will disrupt agricultural production with many regions experiencing production losses due to a variety of stresses resulting from climate change (CC) and climate variation (IPCC, 2013; OXFAM, 2013). Although, cereal production yields have stabilized worldwide in the past decade this stabilization is at levels 25% less than what is needed to meet projected population demands by 2050 (Mwongera et al., 2014; UNEP, 2009). Reductions in crop yields are predicted to be greater than or equal to 10% less current average annual yields (Schlenker and Roberts, 2009; OECD, 2012b; Elbehri et al., 2011; FAO, 2012; IPCC, 2013). Thus, future challenges due to extreme droughts and rainfall events will result in

losses and degradation of critical agricultural soil and water resources (IPCC 2013, Mwongera et al., 2014) and exacerbate current food safety and security challenges.

Globally, agricultural practices generate 30% of greenhouse gas emissions, particularly when land-use change is included in the estimate (FAO 2012). Under the status quo, current agricultural practices lead to increased agrochemical usage as a means of achieving pest and disease resistance, which concomitantly reduces or retards microbial mutualisms (Bever 2015) and negatively impacts long-term host resistance to some crop pests (Kennedy and Smith, 1995; Bale et al., 2002; Logan et al., 2003; Elbehri et al., 2011). Compounding this, global warming is predicted to increase both pest and disease occurrence by favoring their relatively rapid reproductive cycles through higher temperatures and increased larval survival (as reviewed in Logan et al., 2003). This potentially leads to a positive feedback cycle in which increased warming leads to increased plant production and/or resource requirements leading to increased agrochemical production and utilization, and resulting in higher GHGe from soils indirectly, and directly and through chemical production processes (Smith et al., 2013; OECD, 2013; EPA 2015). Changes in agricultural practices are needed to address these feedbacks in order to positively contribute to mitigation of, and adaptation to CC through advances in crop production and management.

One globally available, adaptive opportunity may be found in the soil and plant microbiomes (see review by Singh et al., 2011). Employing novel technologies based on well described biological, ecological and evolutionarily phenomena, in concert with classic breeding technologies enhanced by transgenic tools, (as reviewed in Dangl et al., 2013). This robust approach, addresses complexities inherent in cropping systems (e.g., heterogeneous soil properties, variable pest exposure). This approach recognizes a role for breeding of plant, microbe, and symbiotum (Box 1) traits contributing to, and optimizing host performance. For example, microbial symbionts known to increase host defenses can be used as a means of producing a plant phenotype more resistant and/or readily responsive to pest/pathogen adaptation (see review by Berendsen et al., 2012; Lambrecht et al., 2015; Box 1).

2. All of the above approach

We propose expanding management approaches such Climate Smart Agriculture (CSA) to include the microbial components of crops and soils. Combining breeding strategies and biotechnology with utilization of co-adapted, mutualistic plant-microbial associations (endophytic and rhizosphere) could result in an agricultural approach utilizing *constructed microbial communities*. A *constructed microbial community* approach (Box 1) is a microbial mixture designed to utilize evolutionary and ecological phenomena to inform and develop mutualistic microbial communities. The result is increased production of crops with the ability to adapt to climate change while simultaneously reducing the economic and ecological costs of production e.g., reductions of agrochemical applications.

3. Brief introduction to mutualistic symbionts: Wheels within wheels

Positive or mutualistic symbioses are ubiquitous and gaining increasing interest as we learn more about the prevalence and consequences of plant microbiomes (Supplementary Table 1; as reviewed Berendsen et al., 2012) and their impacts on host response to abiotic and biotic stress (as reviewed by Rodriguez et al., 2009; see also Mei and Flinn, 2010; and Hamilton et al., 2012). Although hidden from the naked eye, microbial mutualists are globally important classes of organisms due in part to their role in ecosystem functioning (as reviewed by Rodriguez et al. 2009) and their impacts on host plant performance (see Supplementary Table 1).

Mechanisms for why mutualists increase biomass production or maintain yields in response to abiotic and biotic stress (Bouton et al., 2002; Govindarajan et al., 2006 and 2008) have extensive documentation (Supplementary Table 1; Assuero et al., 2006; Kevei et al., 2008; Rasmussen et al., 2009; Newcombe et al., 2010; Mei and Flinn 2010; Tian et al., 2010; Redman et al., 2011; Bücking et al., 2012; Fellbaum et al., 2012; Hamilton et al., 2012; Hamilton and Bauerle, 2012; Pellegrino et al., 2012; Tschaplinski et al., 2014; Singh, 2015). For example, enhancement of nutrient acquisition pathways, production of plant growth regulators, alterations in physiological and biochemical properties of the host plant and defending plant roots against soil-borne pathogens are examples of multiple favorable phenotypes resulting from beneficial plant-microbial associations (as reviewed by Mei and Flinn, 2010 and Hamilton et al., 2012; see also Molitor and Kogel, 2009; Weston et al., 2012; Supplementary Table 2).

To create contextually effective, temporally stable *constructed microbial communities*, collaborations between breeders and microbial ecologists will be necessary to develop plant-microbial systems maximizing crop yields and contributing to stable mutualistic symbioses (Fig. 1) while presuming unpredictable and/or unstable resource availability (e.g., water and nutrients). The resulting *constructed microbial community* (Box 1) could contribute to GHGe mitigation and agricultural adaptation to CC by decreasing resource requirements (i.e., fertilizers and pesticides).

4. Reduced inputs, increased profits

Mutualistic microbes can contribute to plant health via increases in:

1. the efficiency of plant resource uptake (e.g., N, water),
2. plant tolerance of abiotic (e.g., salt) stress,
3. plant tolerance of biotic stresses (e.g., pathogens).

For example, it has been reported, reducing utilization of agrochemicals through more effective use of mutualistic microbes could result in reduction of N emissions and leaching as well as carbon (C) emissions directly from the soil (Dobermann and Cassman 2002; De Graaff et al., 2006; Bakarr 2012) or indirectly through agrochemical production (OECD 2012b and 2013). The mitigation potential of decreased N use for agriculture in the European Union (Domingo et al., 2014) is projected to result in a reduction of 44% GHGe from 2009 levels, corresponding to a reduction of 41.3 million metric tons CO₂ equivalent

annually with large-scale, ecosystems and human health benefits (Maumbe and Swinton, 2003; OECD 2013).

5. Increased host stress tolerance from the ground-up

Maintenance of beneficial, soil microbial communities (Duhamel and Vandenkoornhuyse 2013; Govers et al., 2013) is recommended for soil management (Bakarr 2012; Govers et al., 2013) through, in part, fostering of mutualistic soil microbial communities (Shrestha et al., 2014). Increased microbial community complexity can lead to increased biotic heterogeneity, soil quality, decreased soil erosion (Pimentel et al., 1993; Gianinazzi et al., 2010; Bever et al., 2012; Govers et al., 2013) increased water retention (Kennedy and Smith 1995), and increased nutrient turnover and retention (Tilman et al., 2002; Thiele-Bruhn et al., 2012), and improvement of soil aggregate stability (Duchicela et al., 2012).

Many microbial mutualists increase the efficiency of nutrient uptake (Newcombe et al., 2010; Bücking et al., 2012) and therefore have the potential to significantly reduce fertilizer applications (Tilman, et al., 2002). Reduced GHGe through healthier soils and plants requiring lower nutrient additions is mitigative (Drury et al., 2014, see also Smith et al., 2013).

6. Adaptation and Mitigation Potential: Constructed Communities and Synthetic Biotechnology

Utilization of emerging techniques in the field of synthetic biotechnology, as applied to both microbes and plants can plausibly result in *constructed microbial communities* with the ability to improve plant performance and environmental quality (Shong et al., 2012; Kusari et al., 2014). In this scenario the microbes may be genetically engineered to modify 1) intracellular metabolic pathways, 2) predictable features of plant-microbe inter-cellular interactions, or 3) the microbial community composition resulting in improved plant performance (Fig. 1). The potential to engineer plants which in turn alter the community composition of mutualistic microbes has been successfully explored (Brelles-Marino and Ané, 2008). Note, some important microbes, such as AM fungi, have multinucleate genetic systems which are not amenable to engineering.

Another approach, create synthetic microbial communities for improving crop production by combining un-engineered microbe species isolated from nature. This approach can be facilitated by an integration of systems biology, ecology, and evolutionary biology. At the population level syntrophic exchange (i.e. metabolic cross-feeding) between different microbial species (Mee et al., 2014) and synergistic effects on plant growth (Larimer et al., 2014) are operational. Ecological studies can provide information about the impacts of climate change (e.g. elevated ozone, elevated carbon dioxide) on soil microbial community composition and metabolic diversity (Kato et al., 2014; Bao et al., 2015; Singh et al., 2015). Evolutionary studies can predict the stability of synthetic microbial communities and microbial mutualisms over the time (Bever, 2015). Large-scale field trials and controlled experiments can be used to evaluate impact of external factors (e.g. soil physical and chemical properties, drought, elevated CO₂, plant

host genotype) on microbial community composition and synergistic benefits of inoculations.

7. Action now does not Preclude Continued Research, Development, and Refinement

There are numerous, potential challenges to efficacious utilization of mutualistic microbes as a means of increasing crop productivity. Perhaps a legitimate question to ask now, is do we have time to wait for this research to resolve nuanced issues where applications may already be accessible and efficacious? The approach proposed here of *constructed microbial communities*, in conjunction with classic breeding and advanced agricultural management approaches, incorporates biology, ecology, evolution, and economics to produce economic and ecologically sustainable results at local scales. Application now should not restrict on-going research but rather stimulate research and provide important opportunities to improve agricultural systems, while mitigating the impacts of GHGe from current agricultural management regimes. Applied and basic sciences are iterative, mutually dependent processes; to realize their benefits the process needs to begin.

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References Cited

- Assuero, S., Tognetti, J., Colabelli, M., Agnusdei, M., Petroni, E., 2006. Endophyte infection accelerates morpho-physiological responses to water deficit in tall fescue. *New Zealand J. Ag. Res.* 49, 359–370.
- Aguilera, J., Gomes, A., Oлару, I., 2013. Principles for the risk assessment of genetically modified microorganisms and their food products in the European Union. *Intl. J. Food Microbiol.* 162, 2-7.
- Bae, H., Sicher, R., Moon, S., Kim, S-H., Strem, M.D. et al., 2009. The beneficial endophyte *Trichoderma harzianum* isolate DIS 219b promotes growth and delays onset of the drought response in *Theobroma cacao*. *Exp. Bot.* 60, 3279-3295.
- Bakarr, M., 2012. Dirt matters: investing in soil ecosystem services for the global environment and food security. *The Greenline* (December). <http://www.thegef.org/gef/greenline/december-2012/dirt-matters-investing-soil-ecosystem-services-global-environment-and-food-s>.
- Bakker, M., Manter, D., Sheflin, A., Weir, T., Vivanco, J., 2012. Harnessing the rhizosphere microbiome through plant breeding and agricultural management. *Pl. Soil* 360, 1-13.
- Bale, J. S., Masters, G. J., Hodkinson, I., Awmack, C., Bezemer, T., Brown, V., et al., 2002. Herbivory in global climate change research: Direct effects of rising temperature on insect herbivores. *Glob. Change Biol.* 3, 1-6.

- Baltruschat, H., Fodor, J., Harrach, B., Niemczk, E., Barna, B., et al., 2008. Salt tolerance of barley induced by the root endophyte *Piriformospora indica* is associate with a strong increase in antioxidants, N. Phytol. 180, 501-510.
- Bao, X., Yu, J., Liang, W., Lu, C., Zhu, J., Li, Q., 2015. The interactive effects of elevated ozone and wheat cultivars on soil microbial community composition and metabolic diversity. Applied Soil Ecology 87: 11-18.
- Berendsen, R., Pieterse, C., 2012. The rhizosphere microbiome and plant health. Trends Pl. Sci. 17, 478.
- Bever, J., Platt, T., Morton, E., 2012. Microbial Population and Community Dynamics on Plant Roots and Their Feedbacks on Plant Communities. Annu. Rev. Microbiol. 66, 265-283.
- Bever, J., 2015. Preferential allocation, physio-evolutionary feedbacks, and the stability and environmental patterns of mutualism between plants and their root symbionts. N. Phyt 205:1503-1514.
- Bouton, J., Latch, G., Hill, N., Hoveland, C., McCann, M., et al., 2002. Reinfection of tall fescue cultivars with non-ergot alkaloid-producing endophytes. Ag. J. 94, 567-574.
- Bücking, H., Liepold, E., Ambilwade, P., 2012. The Role of the Mycorrhizal Symbiosis in Nutrient Uptake of Plants and the Regulatory Mechanisms Underlying These Transport Processes. In: Plant Science (Eds.) N.K. Dhal, S.C. Sahu, Intech Pub.
- Calderon, A., Zapata, J., Romualdo, M., Pedreño, M., Barceló A., 1993. Resveratrol production as a part of the hypersensitive-like response of grapevine cells to an elicitor from *Trichoderma viride*. N. Phytol. 124, 455-463.
- Cassman, K., 1999. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. PNAS 96, 5952-5959.
- Chacón, M., Rodriguez-Galán, O., Benitez, T., Sousa, S., Rey, M., et al., 2007. Microscopic and transcriptome analyses of early colonization of tomato roots by *Trichoderma harzianum*. Int. Microbio. 10, 19-27.
- Chaparro, J., Dayakar, V., Vivanco, J., 2014. Rhizosphere microbiome assemblage is affected by plant development. ISME J 8, 790-803.
- Cocking, E., 2003. Endophytic colonization of plant roots by nitrogen-fixing bacteria. Pl. Soil 242, 169-175.
- Dakora, F., 2003. Defining new roles for plant and rhizobial molecules in the soil and mixed plant cultures involving symbiotic legumes. N. Phytol. 148, 39-49.
- Dangl, J., Horvath, D., Staskawicz, B., 2013. Pivoting the plant immune system from dissection to deployment. Science 341, 746-751.
- De Graaff, M., Van Groenigen, K., Six, J., Hungate, B., Van Kessel, C., 2006. Interactions between plant growth and soil nutrient cycling under elevated CO₂: A meta-analysis. Global Change Biol., 12, 2077-2091.
- Dobermann, A., Cassman, K., 2002. Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia. Pl. Soil 247, 153-175.
- Domingo, J., De Miguel, E., Hurtado, B., Métayer, N., Bochu, J.-L., et al., 2014. Measures at Farm Level to Reduce Greenhouse Gas Emissions from EU Agriculture. European Parliament, Directorate-General for Internal Policies (<http://www.europarl.europa.eu/studies>).
- Duchicela, J., Vogelsang, K., Schutlz, P., Kaonongbua, W., Middleton, E., et al., 2012. Non-native plants and soil microbes: potential contributors to the consistent reduction in soil aggregate stability caused by the disturbance of North American grasslands. N. Phytol. 186, 212-222.

- Duhamel, M., Vandenkoornhuyse, P., 2013. Sustainable agriculture: possible trajectories from mutualistic symbiosis and plant neodomestication. *Trends Pl. Science* 18, 597–600.
- Drury, C.F., Reynolds, W.D., Tan, C.S., McLaughlin, N.B., Yang, X.M. 2014. Impacts of 49-51 years of fertilization and crop rotation on growing season nitrous oxide emissions, nitrogen uptake and corn yields. *Can J Soil Sci* 94, 4421-433.
- Elbehri, A., Genest, A., Burfisher, M., 2011. Global Action on Climate Change in Agriculture: Linkages to Food Security, Markets and Trade Policies in Developing Countries. Food and Agriculture Organization of the United Nations Rome, Trade and Markets Division. Pgs 96.
- Fellbaum, C., Gachomo, E., Beesetty, Y., Choudhari, S., Strahan, G.D., et al., 2012. Carbon availability triggers fungal nitrogen uptake and transport in the arbuscular mycorrhizal symbiosis. *PNAS* 109, 2666–2671.
- Food and Agriculture Organization of the United Nations., 2012. Proceedings of a Joint FAO/OECD Workshop: Building Resilience for Adaptation to Climate Change in the Agriculture Sector. (Eds.) A. Meybeck, J. Lankoski, S. Redfer, N. Azzu, V. Gitz.
- Gianinazzi, S., Gollotte, A., Binet, M-N., van Tuinen, D., Redecker, D., et al., 2010. Agroecology: the key role of arbuscular mycorrhizas in ecosystem services. *Mycorrhiza* 20, 519-530.
- Govers, G., Merckx, R., Van Oost, K., van Wesemael, B., 2013. Managing Soil Organic Carbon for Global Benefits: A STAP Technical Report. Global Environment Facility, Washington, D.C.
- Govindarajan, M., Balandreau, J., Muthukumarasamy, R., Revathi, G., Lakshminarasimhan, C., 2006. Improved yield of micropropagated sugarcane following inoculation by endophytic *Burkholderia vietnamiensis*. *Pl. Soil* 280, 239–252.
- Govindarajan, M., Balandreau, J., Kwon, S., Weon, H., Lakshminarasimhan, C., 2008. Effects of the inoculation of *Burkholderia vietnamiensis* and related endophytic diazotrophic bacteria on grain yield of rice. *Microb. Ecol.* 55, 21–37.
- Hahn, H.M., McManus, T., Warnstorff, K., Monahan, B., Young, C., et al., 2008. *Neotyphodium* fungal endophytes confer physiological protection to perennial ryegrass (*Lolium perenne* L.) subjected to a water deficit. *Environ. Exp. Bot.* 63, 183-199.
- Hamilton, C., Gundel, P., Helander, M., Saikkonen, K., 2012. Endophytic mediation of reactive oxygen species and antioxidant activity in plants: A review. *Fung. Div.* 54, 1-10.
- Hamilton, C., Bauerle, T., 2012. A new currency for mutualism? Fungal endophytes alter antioxidant activity in hosts responding to drought. *Fung. Div.* 54, 39–49.
- Hanada, R., Pomella, A., Costa, H., Bezerra, J., Loguercio, L., et al., 2010. Endophytic fungal diversity in *Theobroma cacao* and *T. grandiflorum* Cupuacu trees and their potential for growth promotion and biocontrol of black-pod disease. *Fung. Biol.* 114, 901-910.
- Hardoim, P., van Overbeek, L., van Elsas, J., 2008. Properties of bacterial endophytes and their proposed role in plant growth. *Trends in Micrbiol.* 16, 463-471.
- Intergovernmental Panel on Climate Change., 2013. Climate Change 2013: The Physical Science Basis - Working Group I Contribution to the IPCC Fifth Assessment Report. Geneva, Switzerland.
- International Food Policy Research Institute, *Sustainable Food Security Under Land, Water, and Energy Stresses*, 2012 online: www.ifpri.org/ghi/2012/sustainable-food-security-under-land-water-energy-stresses.

- Kato, S., Yoshida, R., Yamaguchi, T., Sato, T., Yumoto, I., Kamagata, Y., 2014. The effects of elevated CO₂ concentration on competitive interaction between acetoclastic and syntrophic methanogenesis in a model microbial consortium. *Frontiers in microbiology* 5.
- Kennedy, A., Smith, K., 1995. Soil microbial diversity and the sustainability of agricultural soils. *Pl. Soil* 170, 75-86.
- Kennedy, I., Choudhury, A., Kcskés, M., 2004. Non-symbiotic bacterial diazotrophs in crop=farming systems: Can their potential for plant growth promotion be better exploited? *Soil Biology Biochem.* 36, 1229-1224.
- Ker, K., Seguin, P., Driscoll, J B.T., Fyles, W., Smith, D.L. 2012. Switchgrass establishment and seeding year production can be improved by inoculation with rhizosphere endophytes. *Biomass Bioenergy* 47, 295–301.
- Kevei, Z., Loughon, G., Mergaert, P., Horváth, G.V., Kereszt, A., et al., 2008. A 3-hydroxy-3- methylglutaryl coenzyme a reductase interacts with NORK in the nodulation signaling pathway. *Pl. Cell* 9, 3974–3989.
- Köhl, L., Oehl, F., van der Heijden, B., 2014. Agricultural practices indirectly influence plant productivity and ecosystem services through effects on soil biota. *Ecol. App.* 24, 1842-1853.
- Kusari, S., Singh, S., Jayabaskaran, C., 2014. Biotechnological potential of plant-associated endophytic fungi: Hope versus hype. *Trends Biotechnol.* 32, 297-303.
- Lambrecht, I., Vanlauwe, B., Maertens, M., 2015. Integrated soil fertility management: From concept to practice in Eastern DR Congo. *IJAS* 10.1080/14735903.2015.1026047
- Larimer, A., Clay, K., Bever, J., 2014. Synergism and context dependency of interactions between arbuscular mycorrhizal fungi and rhizobia with a prairie legume. *Ecology* 95:1045-1054.
- Logan, A., Regniere, J., Powell, J., 2003. Assessing the impacts of global warming on forest pest dynamics. *Frontiers Ecol. Environ.* 1, 130-137.
- Long, H., Schmidt, D., Baldwin, I., 2008. Native bacterial endophytes promote host growth in a species-specific manner; Phytohormone manipulations do not result in common growth responses. *PLOS One* 3, e2702.
- Maumbe, B., Swinton, S., 2003. Hidden health costs of pesticide use in Zimbabwe's smallholder cotton growers. *Soc. Sci. Med.* 47, 1559-1571.
- Mee, M., Collins, J., Church, G., Wang, H., 2014. Syntrophic exchange in synthetic microbial communities. *PNAS* 111: E2149-E2156.
- Mei, C., Flinn, B., 2010. The use of beneficial microbial endophytes for plant biomass and stress tolerance improvement. *Recent Pat. Biotechnol.* 4, 81–95.
- Molitor, A., Kogel, K-H., 2009. Induced resistance triggered by *Piriformospora indica*. *Pl. Signal. Behav.* 4, 214-216.
- Mwongera, C., Boyard-Micheau, J., Baron, C., Leclerc, C., 2014. Social process of adaptation to environmental changes: How Eastern African societies intervene between crops and climate. *Wea. Climate Soc.* 6, 341-353.
- Newcombe, G., Martin, F., Kohler, A., 2010. Defense and Nutrient Mutualisms in *Populus*. In *Plant Genetics and Genomics: Crops and Models* (Ed.) Richard Jorgensen 247-277.
- Organization of Economic Cooperation and Development, 2012a. *OECD Environmental Outlook to 2050: The Consequences of Inaction*. OECD Publishing, Paris, France.
- Organization for Economic Cooperation and Development, 2012b. *Environmental Outlook to 2050*. <http://www.oecd.org/environment/outlookto2050>.

- Organization for Economic Cooperation and Development Compendium of Agri-environmental Indicators, 2013.
http://www.keepeek.com/Digital-Asset-Management/oecd/agriculture-and-food/oecd-compendium-of-agri-environmental-indicators_9789264186217-en#page1, OECD Publishing.
- Owen D., Williams, A., Griffith, G., Withers, P., 2015. Use of commercial bio-inoculants to increase agricultural production through improved phosphorous acquisition. *Appl. Soil Ecol.* 86, 41-54.
- OXFAM, 2013. The Future of Agriculture: Synthesis of an Online Debate, www.oxfam.org/files/dp-future-of-agriculture-synthesis-300713-en.pdf.
- Panaccione, D., Beaulieu, W., Cook, D., 2014, Bioactive alkaloids in vertically transmitted fungal endophytes, *Funct. Ecol.* 28, 299-314.
- Pellegrino, E., Turrini, A., Gamper, H., Cafà, G., Bonari, E., et al., 2012. Establishment, persistence and effectiveness of arbuscular mycorrhizal fungal inoculants in the field revealed using molecular genetic tracing and measurement of yield components. *N. Phyt.* 194, 810–822.
- Pimentel, D., McLaughlin, L., Zepp, A., Lakitan, B., Krau, T. et al., 1993. Environmental and economic effects of reducing pesticide use. *BioScience* 41, 406-409.
- Rasmussen, S., Parsons, A., Newman, J., 2009. Metabolomics analysis of the *Lolium perenne-Neotyphodium lolii* symbiosis: more than just alkaloids? *Phytochemistry Rev.* 8, 535–550.
- Redman, R., Kim, Y., Woodward, C., Greer, C., Espino L., et al., 2011. Increased fitness of rice plants to abiotic stress via habitat adapted symbiosis: a strategy for mitigating impacts of climate change. *PLoS One* 6, e14823.
- Rodriguez, R., White, J., Arnold, A., 2009. Fungal endophytes: diversity and functional roles. *New Phytol.* 182, 314–330.
- Schlenker, W., Roberts, M., 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *PNAS* 106, 15594–15598.
- Shong, J., Diaz, M., Collins, C., 2012. Towards synthetic microbial consortia for bioprocessing. *Cur. Op Biotech.* 23, 798-802.
- Sikora, R., Pocasangre, L., zum Felde, A., Niere, B., Vu, T., Dababat, A., 2008. Mutualistic entophytic fungi and *in planta* suppressiveness to plant parasitic nematodes. *Biol. Control* 46, 15-23.
- Singh, J., Pandey, V., Singh, D., 2011. Efficient soil microorganisms: A new dimension for sustainable agriculture and environmental development. *Ag. Ecosyst. Environ.* 140, 339-353.
- Singh, J. 2015. Microbes: The chief ecological engineers in reinstating equilibrium in degraded ecosystems. *Agric Ecosyst Environ* 203:80-82.
- Singh, S., Reddy, V., Sharma, M., Agnihotri, R., 2015. Dynamics of plant nutrients, utilization and uptake, and soil microbial community in crops under ambient and elevated carbon dioxide. *In Nutrient Use Efficiency: from Basics to Advances*. Springer, pp 381-399.
- Shrestha, K., Stevens, S., Shrestha, P., Adetutu, E., Walsh, K., et al., 2015. Characterization of the soil microbial community of cultivated and uncultivated vertisol in Australia under several management regimes. *Ag. Ecosys. Environ.* 199, 418-427.
- Smith, F., Smith, S., 2011. What is the significance of the arbuscular mycorrhizal colonization of many economically important crop plants? *Pl. Soil* 348, 63-79.
- Smith, W.N., Grant, B.B., Desjardings, R.L., Kröbel, R., Qian, B., worth, D.E., McConkey, B.G., Drury, C.F. 2013.

- Assessing the effects of climate change on crop production and GHG emissions in Canada. *Agri Ecosyst Environ* 179, 139-150.
- Tanaka, A., Christensen, M.J., Takemoto, D., Pyoyun, P., Scott, B., 2006. Reactive oxygen species play a role in regulating a fungus-perennial ryegrass mutualistic interaction. *Pl. Cell* 18, 1052–1066.
- Tanaka, A., Takemoto, D., Hyon, G., Park, P., Scott, B., 2008. NoxA activation by the small GTPase RacA is required to maintain a mutualistic symbiotic association between *Epichloë festucae* and perennial ryegrass. *Molecular Microbiol.* 68, 1165–1178.
- Thiele-Bruhn, S., Bloem, J., de Vries, F., Kalbitz, K., Wagg, C., 2012. Linking soil biodiversity and agricultural soil management. *Curr. Op. Environ. Sustain.* 4, 523–528.
- Tian, C., Kasiborski, B., Koul, R., Lammers, P., Bücking, H., et al., 2010. Regulation of the nitrogen transfer pathway in the arbuscular mycorrhizal symbiosis: gene characterization and the coordination of expression with nitrogen flux. *Pl. Physiol.* 153, 1175–1187.
- Tilman, D., Cassman, K., Matson, P., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. *Nature*, 418, 671–677.
- Tschaplinski, T., Plett, J., Engle, N., Deveau, A., Cushman, K., et al., 2014. *Populus trichocarpa* and *Populus deltoides* exhibit different metabolomic responses to colonization by the symbiotic fungus *Laccaria bicolor*. *Mol. Plant-Microbe Interact.* 27, 546-556.
- United National Environment Programme, 2009. The Environmental Food Crisis – the Environment’s Role in Averting Future Food Crises. www.eldis.org/go/home&id=42309&type=Document.
- Weston D., Pelletier D., Morrell-Falvey J., Tschaplinski T., Jawdy S., et al., 2012. *Pseudomonas fluorescens* induces strain-dependent and strain-independent host plant responses in defense networks, primary metabolism, photosynthesis, and fitness. *Mol. Plant-Microbe Interact.* 25, 765-778.

Box 1. List of definitions

Word	Definition	Example
Constructed Microbial Communities	Manipulation of plant microbiome and or soil microbial community composition designed to increased plant yields and/or resilience/resistance to perturbation; context cognizant design	Selection of mutualistic mycorrhizal and bacterial rhizosphere community membership with broad host taxonomic range with positive impacts on host phenotype, e.g., increased drought tolerance, increased host resistance., also increasing soil quality
Mutualisms	An interaction between a symbiotic organism mutually beneficial to both organisms	Pollinators and plants; gut microbes and mammals
Plant Microbiome	Community of microbial organisms residing within host tissues/organs likely spanning a continuum of interactions	Rhizobia, mycorrhizae, dark septate endophytes, foliar endophytes – simultaneous colonization
Precision Agriculture	Spatially explicit evaluation of soil and landscape conditions including and resulting from soil characteristic determined by topography and geology	Time and degree of till, quantity and quality of chemical applications based on soil heterogeneity at field-scale, utilization of polycultures to increase soil nutrients, changes in seeding and harvesting based on complex climate models, etc.
Climate Smart Agriculture	Sustainably increases productivity, resilience (adaptation), reduces/removes greenhouse gases (mitigation), and enhances achievement of national food security and development goals (FAO, 2012)	Inclusion of multi-cropping systems, low/no-till farming and novel technologies which employ context dependent solutions and include socio-economic limitations /opportunities
Symbiotum	An interaction involving two or more organisms resulting in changes to at least on organisms' phenotype	Pollinators and their plant hosts, fungal pathogens and plant/animal hosts, gut microbes

Table 1. List of literature citing mutualistic endophytic associations between microbes and multiple plant hosts. For exploration of the stability and complexity of these interactions see the following reviews, Kaldorf et al. 2005 and Hamilton and Bauerle 2012.

Plant	Endophyte	Root, Shoot, Whole Plant	Stress	Plant Age; Experimental Context	Reference
Cacao Tree	<i>Trichoderma hamatum</i>	Root	Drought	seedlings; growth chamber	Bae et al. 2009
Wheat	<i>Piriformaspora indica</i>	Root	Salt	Seedlings, plants; growth chamber	Baltruschat et al. 2008
<i>Vitis vinifera</i>	<i>T. viride</i>	Root	None	Cell culture	Calderon et al. 1993
<i>Nicotiana benthamiana</i> ; Tomato	<i>T. harzianum</i>	Root	None	Seedlings, plants; growth chamber, hydroponics	Chacón et al. 2007
<i>Festuca spp.</i>	<i>Neotyphodium spp</i>	shoot	drought	seedlings; growth chamber plants; greenhouse	Hamilton & Bauerle 2012
<i>Lolium perenne</i>	<i>N. lolii</i>	shoot	drought	seedlings; growth chamber plants; greenhouse	Hahn et al. 2008
Cacao Tree	Multiple	Shoot	Biotic resistance	<i>In vitro</i>	Hanada et al. 2010
Various vegetable crops	<i>Trichoderma spp.</i>	Root	Stress resistance	plants; greenbous; field	Harman et al. 2004
Various	Various Bacteria	root	Abiotic stress	Plants, greenhouse	Review by Hardoim et al. 2008
<i>Brachypodium sylvaticum</i> , <i>L. perenne</i>	<i>Epichloë spp</i> , <i>arbuscular myorrhizae (AMF)</i>	Shoot, root	None	Greenhouse	Larimer et al. 2012
Potato, <i>Nicotiana attenuata</i>	Various Bacteria	root	None	<i>In vitro</i>	Long et al. 2008

Convolvulaceae	<i>Periglandula spp.</i>	Root	Biotic resistance	seedlings; greenhouse, growth chamber	Review – Panaccione et al. 2014
Rice	<i>Curvularia protuberate, Fusarium culmorum</i>	Shoot; whole	cold, drought, salt	seedlings; greenhouse, growth chamber	Redman et al. 2011
<i>Dichanthelium lanuginosum, Leymus mollis, Rice, Tomato</i>	<i>Colletotrichum magna, F. culmorum</i>	Shoot, whole	drought, heat, salt	seedlings, plants; growth chamber, field	Rodriquez et al. 2008
Various crops	<i>F. oxysporum, Trichoderma sp. Meloidogyne spp. Radopholus similis</i>	Root shoot	Biotic resistance	Greenhouse, field	Sikora et al. (2008)
<i>Lolium perenne</i>	<i>Epichloë festucae</i>	Root	None	seedlings; greenhouse	Tanaka et al. 2006& 2008

Table 2. Brief list of citations supporting utilization of microbial endophytes to increase plant production (e.g. food crop production). Merged cells indicate bacterial and fungal partners or the soil microbiome, as a whole, was evaluated for plant growth promotion. Plant growth promotion includes increases resistance to pests, abiotic tolerance, and plant biomass yields. For contrasting opinions see Verbruggen *et al.* 2012.

Bacterial	Fungal
Dakora 2003	Redman <i>et al.</i> 2011
As reviewed by Richardson <i>et al.</i> 2011	
Cocking 2003	Smith and Smith 2011
As reviewed by Chaparro <i>et al.</i> 2012	
Ker <i>et al.</i> 2012	
	Duhamel and Vandenkoornhuyse 2013
Köhl <i>et al.</i> 2014	
Owen <i>et al.</i> 2014	
Kennedy <i>et al.</i> 2004	

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