



Rice Methane Innovation Accelerator

STATE OF SCIENCE

Plant Genetics

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Plant genetics and breeding are important components of integrated strategies to reduce methane emissions from rice cultivation. Numerous studies have reported significant variation in methane fluxes among rice varieties associated with differences in above- and below-ground morphology, plant phenology, and physiological processes^{1,2}. However, results are inconsistent and most studies have evaluated only a small number of genotypes and in a few environments because measuring methane emissions is labor-intensive and costly. Furthermore, methane emissions are strongly influenced by rice genotypic interactions with agronomic practices, soil characteristics and soil microbial communities, making genetic selection particularly challenging. Developing a new variety is generally considered a long-term project, taking 5-10 years even with newer approaches like speed breeding and genomic technologies. Using unadapted or wild species of rice lengthens this process further. The development of high-throughput phenotyping methods and reliable genetic-and/or other bio-markers for methane-related traits would represent a major advance for rice breeding.

There have been a few reports of low-methane experimental rice lines developed through transgenic modifications (GMO)³. However, genetically modified (GMO) plants face market acceptance issues in many countries which limits cultivar development to traditional breeding methods and other accepted genetic approaches, like gene editing and marker-assisted selection. In general, two complementary genetic approaches to mitigating methane production in rice fields include reducing methane production associated with the plant and developing rice varieties that are adapted to methane reducing cropping systems.

BREEDING RICE WITH REDUCED METHANE EMISSIONS

Several physiological, morphological, and phenological traits are reported to be promising breeding targets for directly reducing methane emissions from rice but incorporating these in new varieties must be done in a manner that does not impair other critical agronomic, productivity, and grain quality traits that will negatively impact adoption by growers and marketing to consumers.

CHANGING CARBON PARTITIONING BETWEEN ABOVE-GROUND AND ROOT STRUCTURES

During the vegetative phase of plant growth, photosynthates from leaves and tillers support the expanding root system. During the reproductive phase, carbon resources are remobilized from these structures to the developing grain. The distribution of photosynthates between shoots, roots, and grains plays a central role in determining carbon resources available to soil organisms that produce methane. Khatibi et al.¹ reported that hybrid rice, as compared with inbred varieties, is characterized by high yield, high harvest index (HI), early maturity, and high root biomass and rooting depth. These hybrid traits change carbon allocation to roots and contribute to changes in the rhizosphere that increase methanotrophs and lower methane emissions. Kwon et al.⁴ showed that incorporation of *gs3*, an allele that increases grain size, resulted in changes in carbon transport to the roots, affecting root development genes, and enriching the methanotroph population. These results indicate that using genetics to redirect the

distribution of carbohydrates in the plant may be a means to reduce methane emissions and increase productivity.

MODIFYING THE ROOT SYSTEM ARCHITECTURE TO REDUCE SOIL METHANE PRODUCTION

Root system architecture (RSA) - the depth, density, and branching of roots - is an indirect driver of radial oxygen loss and organic acid contents that influence the presence of methanotrophs and methanogens⁵. Peak methane emissions generally occur during the tillering–booting phase prior to carbohydrates being redirected to the developing grain during reproduction. Recently, Jin et al.⁶ reported that low fumarate-high ethanol root exudates decreased methane production and were a selectable trait. Varietal differences for RSA traits that result in greater oxygenation of flooded soils have been associated with reducing methane while other traits have been proposed that reduce methane penetration from the soil into the plant⁷. However, a machine learning approach used to analyze RSA traits among 25 varieties divergent in methane emissions found that root traits that are associated with greater oxygenation of the soil were more important than those related to diffusion of methane through the plant to the atmosphere⁸. A genetic analysis of 250 genotypes identified seven genes linked with root porosity and root diameter that may be promising candidates for marker-assisted selection of low methane producing varieties⁹. A better understanding of the interaction between the RSA, the production of organic acids, and the proliferation of soil microbes under different soil types and cropping systems may be crucial to developing more effective methane mitigation strategies.

OPTIMIZING GAS EXCHANGE CHANNELS IN THE PLANT TO REDUCE METHANE

Ninety percent of the methane produced in flooded rice fields is released to the atmosphere through aerenchyma cells that occur in the leaf sheaths, roots and stems¹⁰. Aerenchyma cells develop in response to flooded soils, triggered by ethylene, hypoxia, and sulfide stress. They also transport oxygen below ground, allowing roots to survive in flooded soils and result in an oxygenated rhizosphere more favorable for proliferation of methanotrophs¹¹. Jimenez and Pedersen⁷ suggest that developing rice cultivars having high aerenchyma formation but cellular barriers to radial oxygen loss will promote growth of the root system and oxygenation of the rhizosphere particularly in flooded systems. In addition, developing cultivars that have fewer unproductive (non-seed bearing) tillers may reduce gas-conducting pathways for methane transfer to the atmosphere with no loss in grain yield.

BREEDING FOR ADAPTATION TO LOW METHANE CROPPING SYSTEMS

Rice cropping practices aimed at reducing or eliminating the flood period significantly reduce methane emissions from paddies due to aerobic conditions in the soil and the proliferation of methanotrophs. However, most of the currently available rice varieties have been developed for production under conventional flooded systems. New rice varieties adapted to cropping systems that do not use season long flooding could be important contributors to integrated solutions for methane emissions.

RICE VARIETIES DEVELOPED FOR PRODUCTION USING INTERMITTENT IRRIGATION

Research has shown that rice production practices that use intermittent irrigation to reduce methane emissions generally show no or only small yield reductions compared to a conventional flooded system. Perry et al.¹² showed that a single field draining during the tillering–panicle initiation stage was sufficient to significantly reduce methane emissions without loss of yield. However, these studies assume that conditions allow close control of water resources to prevent severe water stress on the crop, which may not be the case at a farm level. Accordingly, growing varieties that have improved water-use efficiency may be well suited to cultural practices which use less water and reduce methane emissions¹³. Development of rice varieties that are resilient to fluctuations in soil moisture content will facilitate greater adoption of water-conserving rice cultivation practices such as Alternate Wetting and Drying (AWD).

DEVELOPING VARIETIES SUITED FOR DIRECT SOWING AND AEROBIC RICE PRODUCTION

The predominant method for planting rice is transplanting seedlings into flooded fields. Direct-seeded rice (DSR) is an alternative method that reduces the time a field is under flooded, anaerobic conditions, thereby reducing methane emissions¹³. The method includes dry DSR, wet DSR, and broadcast seeding. These methods have been used in many South and Southeast Asian countries, as well as in those regions where farmers have access to mechanized seeding. Compared to transplanted rice, the main constraints to adoption include variable plant stand establishment, weed competition, and plant nutrient management. Varieties that have rapid growth under early, cool-season conditions, rapid mesocotyl elongation, a root system architecture that enhances nutrient uptake, and lodging resistance are needed for DSR¹⁴. Development of

genetic markers associated with these traits that have complex inheritance, provides a means to select progeny of breeding crosses that are well adapted to DSR.

Aerobic rice is a system that includes using direct seeding in fields that are well watered but not flooded for an extended period of time. This unique rice cropping system is suited for irrigated lowlands and has the potential to reduce methane emissions by up to 88% while lowering irrigation demand¹⁵. Despite these potential benefits, adoption has been limited due to lower yields and there have been limited breeding and research efforts to develop varieties for this production system. In the review by Rebolledo et al.¹⁵, they propose to increase adoption, high-yielding germplasm needs to be improved for traits that are necessary for aerobic culture such as reduced stomatal density, increased leaf area index, decreased short lateral roots, and increased root diameter.

DEVELOPING VARIETIES WITH STRONG RATOON CROP POTENTIAL AS AN ALTERNATIVE TO DOUBLE CROPPING

Using cultivars with a short growth cycle reduces the time irrigation is needed in flooded systems, thereby decreasing the duration of anoxic soil conditions that result in methane generation. Short-season varieties generally have lower yields than longer season varieties and they require close management to optimize yields. However, where double cropping is possible due to a long growing season, using short-season varieties that can be ratoon-cropped is another means of achieving high yields. Ren et al.¹⁶ found that ratoon-cropped rice produced comparable yields to double-cropped rice but had significantly lower methane emissions and total GWP. Zou et al.¹⁷ showed that this is due to abscisic acid (ABA) signaling in the ratoon crop that allocates more carbon to the grain than to root exudates. Moreover, Zhang et al.¹⁸ found that when strong ratoon crop varieties were grown using AWD, as compared to production under conventional flood, they produced higher yield but lower methane emissions and total GWP. Using machine learning methods, Ding et al.¹⁹ determined that 70% of China's rice-growing area was suitable for ratoon cropping, suggesting that cultivars with strong ratoon potential may be able to replace some double crop areas and reduce methane emissions while sustaining yields. Breeding goals to improve ratoon crop potential focus on early main crop harvest, stem and bud regeneration rates, assimilate transport, stem weight, and late season cool temperature tolerance.

RESEARCH GAPS AND FUTURE DIRECTIONS

Combining plant genetic improvement with climate-smart agronomic practices offers a promising pathway towards large-scale methane mitigation. The flooded rice cropping systems commonly found throughout South and Southeast Asia are a major source of rice methane emissions and a primary target for mitigation. Developing high-yielding indica rice cultivars with low methane emissions that are adapted to these growing environments and local cropping practices as well as meet consumer preferences, is a crucial step. Research goals in plant genetics that can be part of an integrated approach to reducing methane generation in rice production systems include:

- Developing effective high throughput phenotyping methods for traits that result in reduced methane emissions in rice production and can be used to reduce development time of new cultivars.
- Identifying existing elite indica cultivars (inbreds or hybrids) that contribute to low methane emissions and are adapted to flooded, intermittent irrigation, aerobic production, direct seeding or ratoon cropping systems that can be used directly and/or as breeding parents.
- Identifying plant traits that affect soil microbial communities through root exudates or rhizosphere oxidation that result in reduced methane generation.
- Identifying high yielding cultivars that are resilient to fluctuations in soil moisture levels that can be used in low methane generating production systems in regions where growers have limited control over water resources.

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