The Food and Land Use Coalition
India Country Platform

CRRI
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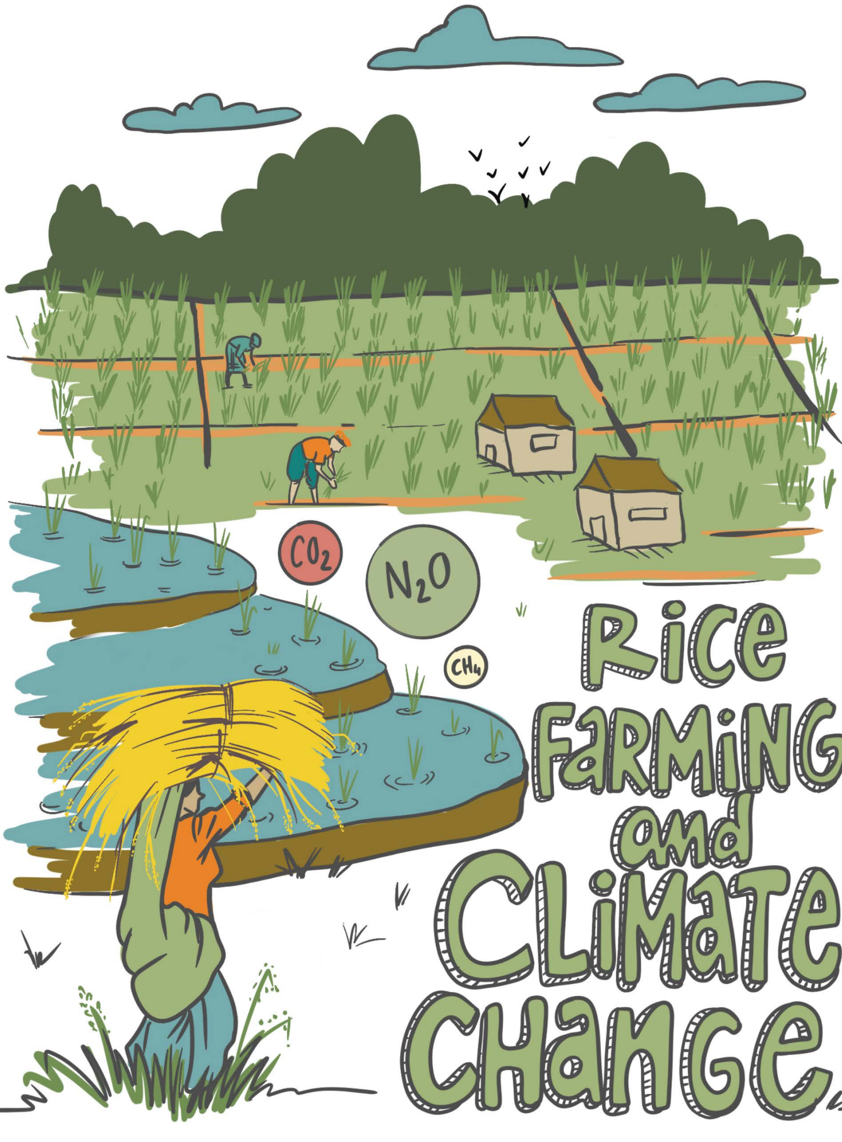

Rice Farming and Climate Change

RICE FARMING AND CLIMATE CHANGE

Making rice agriculture sustainable in India: A guide for agriculture practitioners

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About the book

Rice farming in India has long been both a source and a sink of greenhouse gases. With over 44 million hectares of agriculture land under rice cultivation, millions of livelihoods depend on it. We are facing a two-fold challenge: ensuring food security while reducing agriculture's climate footprint. Further, the understanding of how water, soil, microbes, and crop management interact to influence emissions from rice fields remains fragmented. This book is written to help farmers, Civil Society Organisations (CSOs), and policymakers to understand how rice farming contributes to climate change and more importantly, how it can become part of the solution.

This book was conceived to bridge the gap between science, policy, and practice, translating decades of National Rice Research Institute's (CRRI) research and new scientific insights into accessible knowledge for practitioners, CSOs, and decision-makers. It deconstructs complex biophysical processes and offers actionable strategies for sustainable rice intensification that aligns with India's climate goals.

What this book offers

- **Simplified scientific insights:** Explains how rice fields produce Greenhouse Gases such as methane (CH_4) and nitrous oxide (N_2O), and how these emissions can be mitigated through better soil, water, and fertiliser management.
- **Context-specific solutions:** Offers guidance for rainfed and irrigated systems from uplands to lowlands, detailing how each landscape can be managed for optimal climate and livelihood outcomes.
- **Farmer-centric focus:** Addresses farmers' practical concerns around feasibility, cost, yield, and risk, suggesting pathways for policy incentives such as carbon funds and climate financing to make sustainable choices viable.
- **Vision for the future:** Advocates for a national approach that combines scientific soil testing, zone-specific advisories, and incentive mechanisms to help India move toward climate-smart, low-emission rice systems.

In essence, this handbook empowers practitioners to reimagine rice farming as a powerful instrument for climate action. It calls for collaboration between farmers, scientists, and policymakers to create resilient, low-carbon landscapes that secure India's food and climate future.

Contents

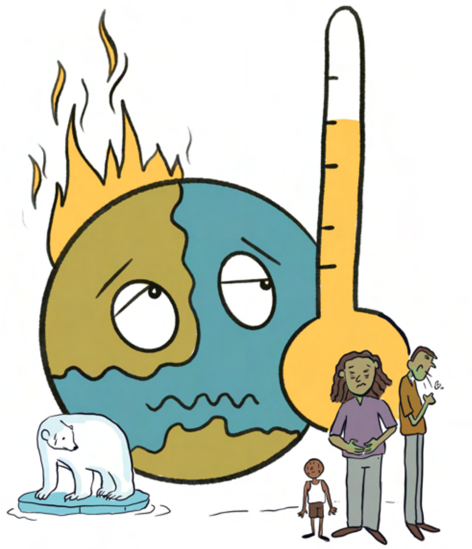
Climate change: Causes and consequences

On 10th January 2025, Nature, a leading scientific journal, ran an article titled *Earth breaches 1.5° C climate limit for the first time*.[1] The authors warned that this is an indication that our species are on the verge of overshooting the 'safe zone' of climate change.

How do we know that the climate is changing?

The 1880s marked the beginning of a new chapter in human history – the second industrial revolution. The rapid advancement in technology during this period led to unprecedented mechanisation in the areas of agriculture and manufacturing, and in scientific discovery. With increased mechanisation came increased dependency on fossil fuel, an unfortunate side-effect of which was its dire impact on climate. The very air we breathe, the water we drink, and the soil we walk on and use to grow our food - changed.

This was also the time when humans started keeping systematic records of various elements of the climate, including fluctuations in average temperatures across the world. Thus, it became possible to quantify the rapid change in the global temperatures that started in the last century and



has continued in this. Multiple governmental and inter-governmental agencies have noted that the last 10 years have been the hottest since 1880, with 2024 being hotter than the rest. [2]

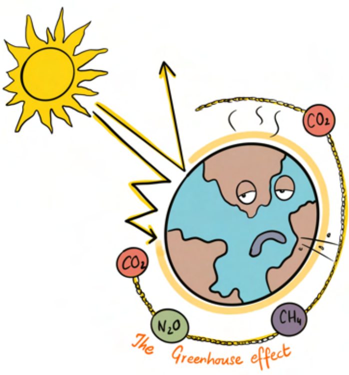
[1] https://www.nature.com/articles/d41586-025-00116-0
[2] https://climate.nasa.gov/vital-signs/global-temperature/?intent=121#:~:text=Key%20Takeaway:,the%20latest%20available%2C%20updated%20annually.

To an average observer it is evident that the monsoons have become more unpredictable with higher number of cyclones. Winters are milder and summers have longer stretches of unbearable heatwaves. There are frequent reports of severe rainstorms, floods, drought, forest fires, and landslides. Extreme weather events and the resulting loss of property and life are now a recurring reality.

There have been drastic changes in the Earth's climate several times since its birth some 4.6 billion years ago. The five major recorded mass extinction events are convincingly linked to climate change, and in some cases the change was almost as rapid as what is happening today. In some of the mass extinctions, climate change was slow enough for life on the Earth to have time to adapt, evolve, and survive. Even though mass extinctions are common to the evolution of the biosphere, this time it might prove calamitous for our species. This time, the survival of all life - including that of humankind - is in peril. What might be the reason for this? There is mounting evidence that human activities, particularly the surge in industrialisation and agriculture, are responsible for this.

Earth's climate system maintains a delicate balance among its various components, enabling the planet to sustain life

The Earth provides the optimum temperature – neither too hot nor too cold- for life to thrive. Its atmosphere, a layered composition of gases, ensures that just the right amount of the sun's heat, needed for survival, is absorbed, rest are radiated back into space. The atmosphere also ensures that the harmful radiations from the outer space do not enter the planet. Because of the increased concentration of Greenhouse Gases (GHGs) in the atmosphere, a part of the heat radiated back is retained as these gases act as blanket in the atmosphere. This process is known as the Greenhouse Effect that is caused by Greenhouse Gases (GHGs). The most common GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapour (H_2O). Each one traps heat to a different extent, and their proportions in the atmosphere affect the average temperature of the planet.



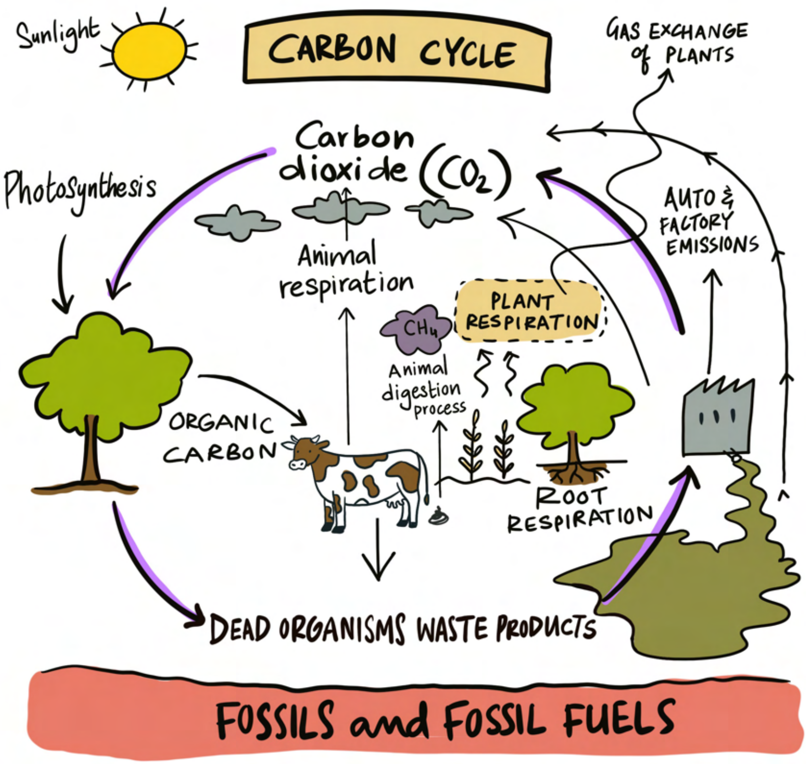
A constant exchange of heat and water takes place between the Earth's atmosphere, land, and oceans, made possible by the dynamic composition of this layer. The gases are continuously moving, sinking down into water and land, rising, being absorbed by life on the Earth, interacting with each other and other chemicals to form complex compounds that are essential for growth and development.

Here is an example of a cycling gas and a major GHG, carbon dioxide (CO_2): Green plants, the primary producers on the Earth, produce carbohydrates, the essential energy source for all life on the planet. They do this by performing photosynthesis, a process that uses water, sunlight and atmospheric CO_2. Carbon from CO_2 is converted to sugars and other carbohydrates, and becomes an integral part of the plant, and oxygen (O_2) from water is released into the atmosphere. Every organism that isn't a primary producer is directly or indirectly dependent on stored plant food sources.

The *Carbon Cycle* continues as herbivores eat plants and acquire carbon from carbohydrates, and carnivores acquire it by consuming herbivores. Through respiration, they release CO_2 into the atmosphere and during digestion, methane gas (CH_4) is produced and emitted. When organisms die and decompose, the carbon in their bodies returns to the environment.

Agriculture is a human-controlled process that cultivates large amounts of biomass in the form of crops. What happens to the carbon in this biomass? Each season, some is consumed by humans and other organisms, while significant portion remains in the soil as dead leaves, roots and stubble. These organic parts left in the soil decompose, and some short-lived by-products of this decomposition release CO_2 into the atmosphere by a process called 'heterotrophic respiration.' This is a natural part of decomposition. The remaining decomposed part of this biomass, however, gets converted to 'humus' or 'humic acid'. This is the nutrient-rich, moist soil we often find on forest-floors, and it is rich in sequestered carbon.

The timeline of 'humification' varies with the composition of soil and climatic conditions. While the process begins on day zero, it may continue for two, three or even up to six months, depending on the type of organic matter and of the microbes present in the soil. Short-chain aromatic carbon compounds are easier for microbes to decompose, while long-chain carbon compounds with aromatic or aliphatic structures are complex and decompose slowly. Soil microbes break these complexes into shorter, more stable polymers that are resistant to further breakdown. This humus, once formed, remains stored in the soil for longer periods, and contributes significantly to overall carbon sequestration.



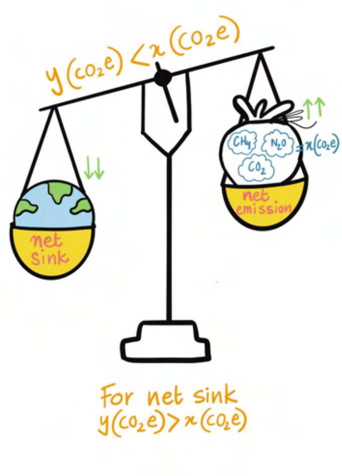
It is important to consider two processes: One is carbon fixing, when C from CO_2 is converted to organic compounds by plants and can be immediately used by life on earth. The second is carbon sequestration, which is a process of integrating C into soils, oceans and also organic matter like fossil fuel, where it can be stored for an extended period, preventing it from easily re-entering the atmosphere. Both these processes are essential for mitigating or lessening global warming.

Why is the planet experiencing unprecedented increase in temperatures in the last few decades?

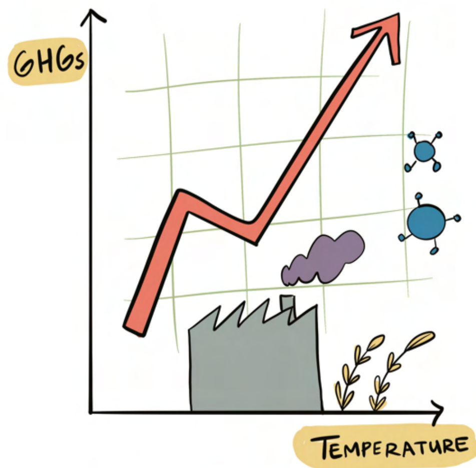
It is because of the altered balance of GHGs in the atmosphere due to increased emissions from land and water bodies.

With industrialisation, many activities that were originally carried out by humans began being taken over by machines. Many machines need energy that comes from fossil fuel or wood which when burnt, releases large quantities of CO_2 into the atmosphere. The growing human population also needs to be fed, which means more land is brought under cultivation and often treated with nitrogenous fertilisers to increase food production. Hence, with the advent of industrialisation and agriculture, more and more CO_2, CH_4 and N_2O are reaching the atmosphere, and less and less carbon seems to be returning to the Earth.

It is easy to see how industrialisation and burning of fuel can increase the levels of GHGs in the atmosphere, thus contributing to increased global temperatures and climate change. However, agriculture has also come under scrutiny as a huge contributor to GHGs and global warming. If photosynthesis helps return CO_2 to the Earth by fixing it, agricultural crops also must carry it out. Then, how is agriculture adversely affecting climate?



In order to meet the growing demand of food for the increasing population, forest land and wetlands were cleared for agriculture, a process in which more Greenhouse Gases (GHGs) were emitted.

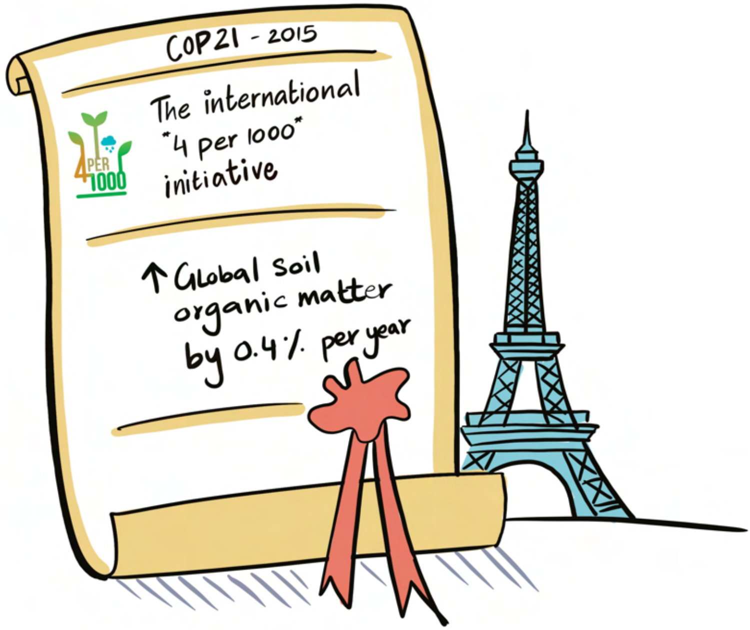


Countries with extensive rice cultivation are also responsible for methane and nitrous oxides emission and countries like China, India and other Southeast Asian nations have received criticism for significant GHG emissions linked to rice farming. This makes it necessary to understand the role of agriculture - particularly rice farming - in climate change and discuss the possible methods to improve our agricultural practices to reduce any adverse impacts.

Can adverse climate change be reversed by increasing carbon sequestration in the soil?

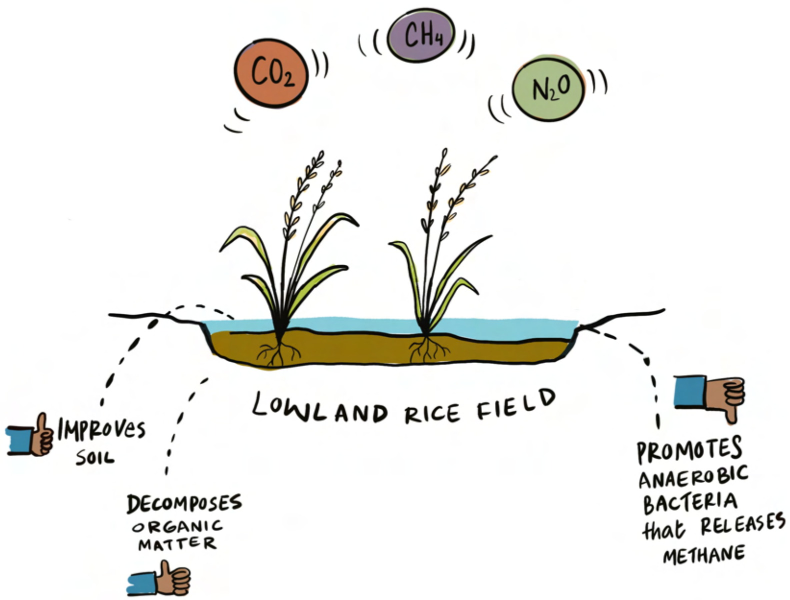
At the time of the 21st Conference of the Parties (COP21) at Paris in 2015, an aspirational proposal of increasing the global soil organic carbon by 0.4% per year to compensate for the GHG emissions due to human activities was put forth. This ‘4 per mille’ or ‘4 per 1000’ proposal hoped to draw enough carbon dioxide from the atmosphere and sequester it into the soil to solve the crises of climate change and global warming.

Increasing soil organic carbon by 0.4% on a global basis is, of course, very difficult. A large portion of soil is simply not available to accommodate organic carbon - for example, the planet has large areas where the soil has already reached its carbon saturation value.



Then, there is soil on the ocean floor, and in deserts, and in degraded lands where soil organic carbon is naturally very low and for good reasons. Agricultural land, however, is different. Since most of the loss of soil organic carbon has resulted from agriculture, if that process can be reversed, there is a chance to mitigate, at least partly, the overall problems of climate change and global warming.

Submerged rice farming: A sink for carbon or a source for GHGs?



The early history of rice cultivation is unclear. Undoubtedly, this crop was instrumental in the transition from hunter-gatherer groups to farming communities that established some of the earliest civilisation centres in Asia. [3] This is quite ancient history, as suggested by the recovery of more than 8000-year-old rice grains from some archaeological sites in China. Farming, including rice, was a great historic alteration of land, and became one of the reasons for global warming. However, our focus here is not on the historical aspect but on present practices and possible mechanisms to mitigate GHG emissions from rice farming.

Rice is a primary food source for about half of the world's population, and over 700 million people in India. Approximately 44 million hectares of land is under rice cultivation. While several rice cultivation practices

[3] https://journals.uclpress.co.uk/ai/article/id/594/

exist, the predominant practice in tropical monsoon climate is flooded rice cultivated in low-land ecology. This practice involves maintaining standing water in the fields, creating a semi-aquatic environment in which the rice plants grow. This practice offers numerous benefits like suppressed weed growth, ensures good crop establishment, enhances nutrient availability, and reduces vulnerability to droughts, and often leads to higher yields. .

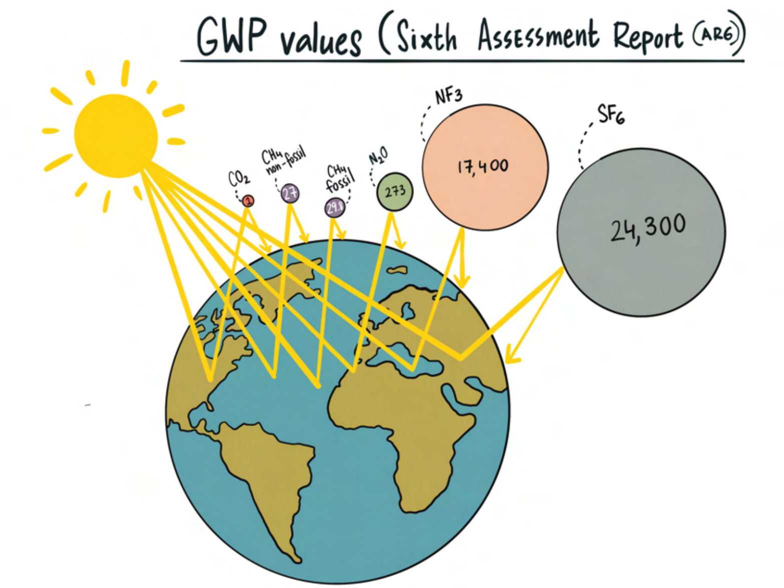
Be that as it may, its effect on climate is more complex.

On one hand, submergence enhances carbon sequestration. Because of continuous waterlogging in rice fields, a lot of organic matter such as leaves, stems, and roots, accumulates at the soil surface and enhances soil organic carbon. Underwater conditions limit oxygen, so this organic matter decomposes slowly, allowing carbon to settle and become sequestered in the soil. As a result, submerged rice farming soils retain substantially more long-lasting carbon compared to fields under non-flooded methods.

On the other hand, submergence cuts off air, depleting oxygen in the soil, and creating anaerobic conditions. The dominant organism that can survive in such environments are anaerobic bacteria that use carbon dioxide (CO_2) and nitrate instead of oxygen for their metabolic reactions. These bacteria feed on submerged organic matter and as a by-product of metabolism, they release methane (CH_4), earning them the name methanogenic bacteria or methanogens. In lowland and irrigated rice fields, where rice is cultivated under continuous flooding, it is one of the biggest 'anthropogenic' or human-driven contributors to methane gas. Rice agriculture produces about 5-20% of global methane emissions each year [4] and unsurprisingly, this will continue to go up as the world population increases, and so does their food requirement.

Thus, in a nutshell, while submerged farming improves soil by sequestering the carbon that is released by slowly decomposing organic matter, at the same time, it promotes anaerobic bacteria that releases methane.

When considering the impact of different gases on our climate, it is important to keep in mind the Global Warming Potential of the different GHGs (Note: more on this in later paragraphs). If a system can absorb the atmospheric carbon - then the system is called a 'sink'. If carbon sequestration in a system exceeds total GHG emissions from it, then one has created a 'net sink'. Consequently, a rice field can also be a sink and net sink, not just a source, for GHGs.



[4] https://www.ipcc-nggip.iges.or.jp/public/gl/guidelin/ch4ref5.pdf

Searching for strategies to tilt the balance towards more carbon sequestration in the rice field and making it a net sink

The average soil organic carbon in Indian farmlands is only about 0.5%. In many parts in the eastern states of India, rice is cultivated in two seasons each year, which has resulted in depleting soil organic carbon even further in these regions. Interestingly, the 'carbon saturation value' of these soils is about 0.8 to 1.2% under managed system. This value indicates that the soil has a substantial reserve capacity - sink capacity - for accommodating carbon. If we manage to sequester that much amount of carbon into rest of the Indian soil, we can nullify the emission impact of rice farming in the country.

Since it is practically impossible to completely avoid the use of standing water and chemical fertilisers, which are the major sources of all GHG emissions, it is reasonable to work towards strategies that would keep the rice field a net sink.

Now, returning to 'balance in nature', here is one example - methane-producing bacteria or methanogens, thrive in anaerobic conditions under-water. But there is another group of specialised bacteria that oxidise some part of this CH_4. These bacteria are called 'methanotrophs', and the process of methane-oxidation, which is a coupled reaction to methane production, is called 'methanotrophy'. The catch here is that for oxidation of methane some oxygen needs to be present in the surrounding. And the requirement of oxygen is not just limited to this chemical reaction. It is important to understand that methanotrophs themselves are 'obligate aerobes', that is - oxygen is essential for their survival!
Incidentally, methane is not the only GHG being produced in the rice fields. Carbon dioxide is a major GHG, though it isn't as potent as either methane or nitrous oxide (N_2O). All three of these - CO_2, CH_4 and N_2O - must be considered when thinking about the impact of agriculture on climate. We will discuss it more in upcoming paragraphs.

Given this scenario, agricultural scientists are trying to develop ways to tilt the balance away from production/emission of GHGs like CH_4 and N_2O, and towards carbon sequestration. To implement any sustainable agricultural management practices, it is crucial to understand how soil responds to changing availability of water, how soil and water impact the activity of soil microbes, how different rice cultivars interact with soil, and what role the composition and quantity of soil itself plays in the production and release of GHGs. To this effect, there is a constant search for more sustainable and affordable farming technologies and environmentally friendly rice cultivation systems to mitigate global warming impacts.

Thus, there is a close interplay among the physical, chemical and biological components of the system - i.e. water, soil, and the diverse compounds present in the soil, participate in chemical reactions driven by the presence or absence of oxygen. Added to this are biological actors like soil microbes, whose metabolic activities have their own unique effect on the environment at the base of the rice plants.

Understanding GHG emissions in a rice system

Methane

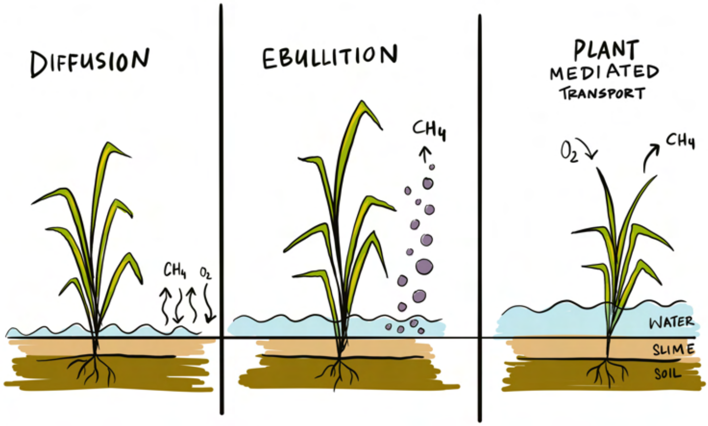
The CH_4 gas produced in the submerged soil needs to escape into the atmosphere, and interestingly, the rice plant helps

There are three ways in which the methane from a rice field reaches the atmosphere:

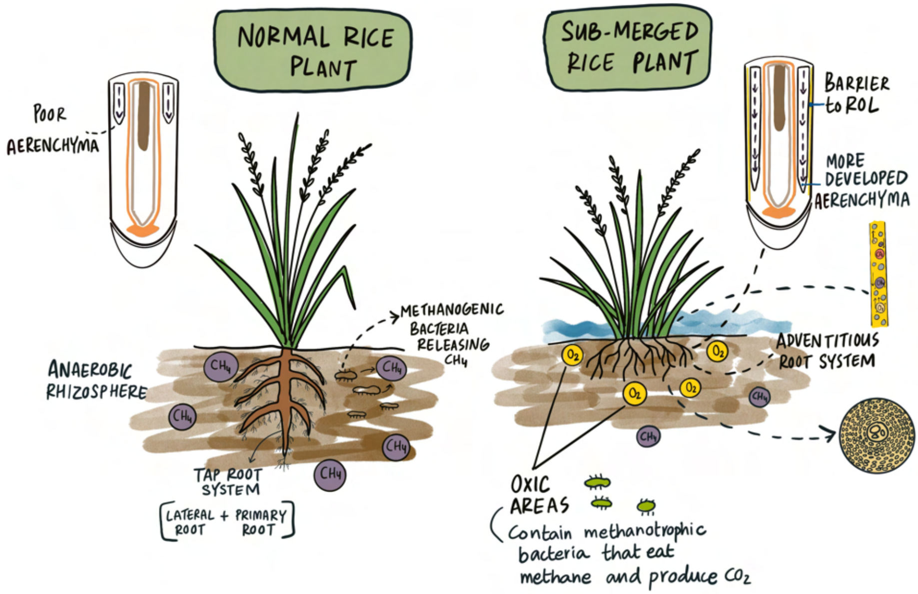
1. By diffusion, when the gas simply disperses from where it is produced to the surrounding areas, and eventually into the atmosphere. This process is drastically slowed down by the presence of water.

2. By ebullition, which is the release of the gas through bubbles that rise from the soil into the surrounding water and then into the atmosphere. This is most commonly observed in rice farms. Interestingly, such bubbling also increases when organic fertilisers are used.

3. Via 'Plant Mediated Transport', which is the most common pathways of methane transport from rice fields to atmosphere in cooler temperate climates, where 90% of the gas is emitted using this method. This is possible due to some curious adaptations seen in rice.



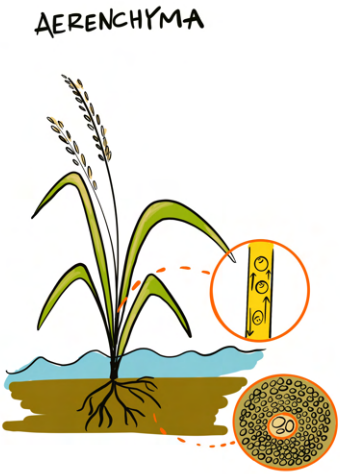
Rice plants have evolved strategies to sustain in semi-aquatic conditions



Submerged conditions are generally unsuitable for any movement of gases - either from the atmosphere to the plant roots, or in the opposite direction - from the water-logged soil around the root system to the atmosphere. The rice plant has evolved certain morphological adaptations that make it possible for them to overcome these challenges.

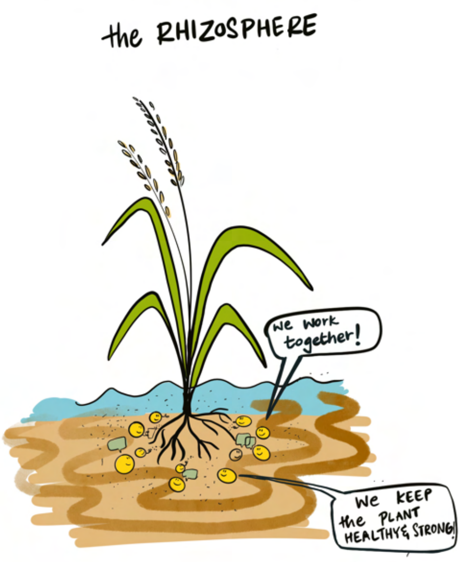
One major feature that the plant has evolved is the development of **'aerenchyma'**, a specialised tissue that is found in many aquatic and semi-aquatic plants. It is an elaborate network of airy spaces in between cells that continues to grow as long as the plant stands in water. The channels formed by aerenchyma extend along the lengths of roots and extend all the way up to stems and leaves, creating avenues for exchange of gases even when the surrounding is waterlogged.

Plants in flooded soils, such as rice, have also evolved an elaborate adventitious root system that contains more aerenchyma than the simpler taproot system. Adventitious root



systems are also more porous. Their morphology, including the large surface area, depth, thickness, and number of lateral roots, adds to the efficiency of gas transport. The aerenchyma usually terminates just before the root tip.

Another important term to

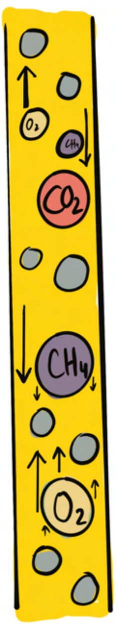


remember here is **'rhizosphere'**, the environment surrounding the root system of a plant. The rhizosphere is where the plant tissue comes in direct contact with soil, water, and soil microbes, and where an elaborate interplay between physical, chemical, and biological components occurs.

Although the rhizosphere may become anaerobic in waterlogged conditions, it also comprises areas that are 'oxic' because of the oxygen that leaks from the roots. The anaerobic areas have a concentration of methanogenic bacteria that generate CH_4, which temporarily accumulates in the rhizosphere, and the oxic areas may contain methanotrophic bacteria that act upon at least some of it.

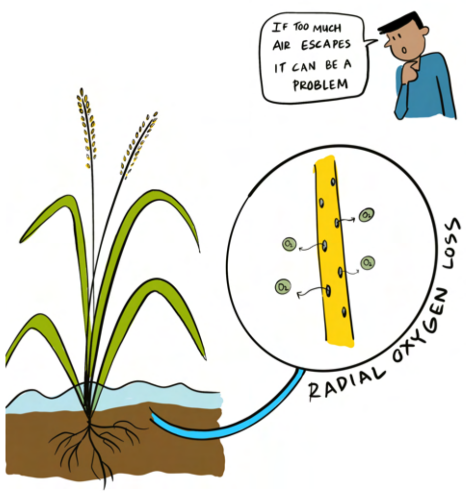
The complex nature of gas transport through the 'straw' that is the plant

A simplistic way to explain how the rice plant with its elaborate aerenchyma helps mediate gas transport, is to imagine each plant as a tube or a straw stuck in the soil. The gases present in the rhizosphere that surrounds this straw can move through it in either direction - upward or downward - depending on their concentrations. This is one pathway that the accumulated methane uses to escape to the atmosphere. Such a 'direct transport system' allows CH_4 to bypass oxic areas of soil where methanotrophic bacteria could oxidise it using the small amount of dissolved oxygen, giving rise to CO_2.



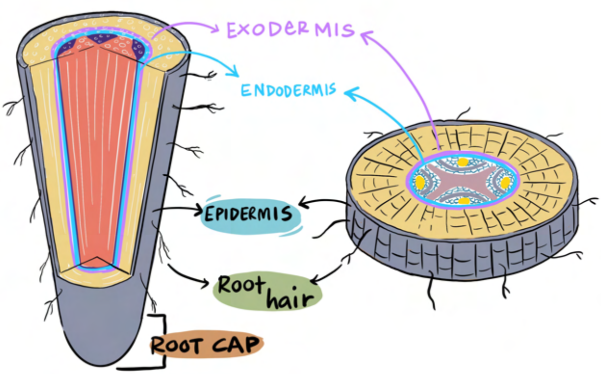
Oxygen is a major gas moving in the opposite direction to that of methane. Root systems in waterlogged conditions require it to grow deeper and stronger. It is transported from the atmosphere down the aerenchyma of a submerged rice plant, till it reaches the root apex. Now, the plant cells are not completely impermeable, but have cell walls that are porous, with pore sizes of 3.5 to 5.2 nm. These pores allow exchange of water, salts and gases between the plant and its surrounding environment, the rhizosphere. Thus, as oxygen from the atmosphere moves downward through the root, some of it leaks out through these pores by a process described as **'radial oxygen loss' (ROL)**.

ROL is necessary to achieve aeration and oxidation of underwater environs of the rice plant. One obvious consequence of ROL is that it stimulates the activity of methanotrophic bacteria in the vicinity, and they start to oxidise CH_4 to generate CO_2, a GHG with a lesser GWP. Plus, increase in oxygen in the rhizosphere helps the general aerobic microbial population in the soil to thrive. Too much ROL before reaching the tips is damaging, because oxygen is necessary for them to grow deeper into the soil. There are several strategies that plants have evolved to overcome this drawback.



Creating a barrier to reduce radial oxygen loss (ROL) from roots

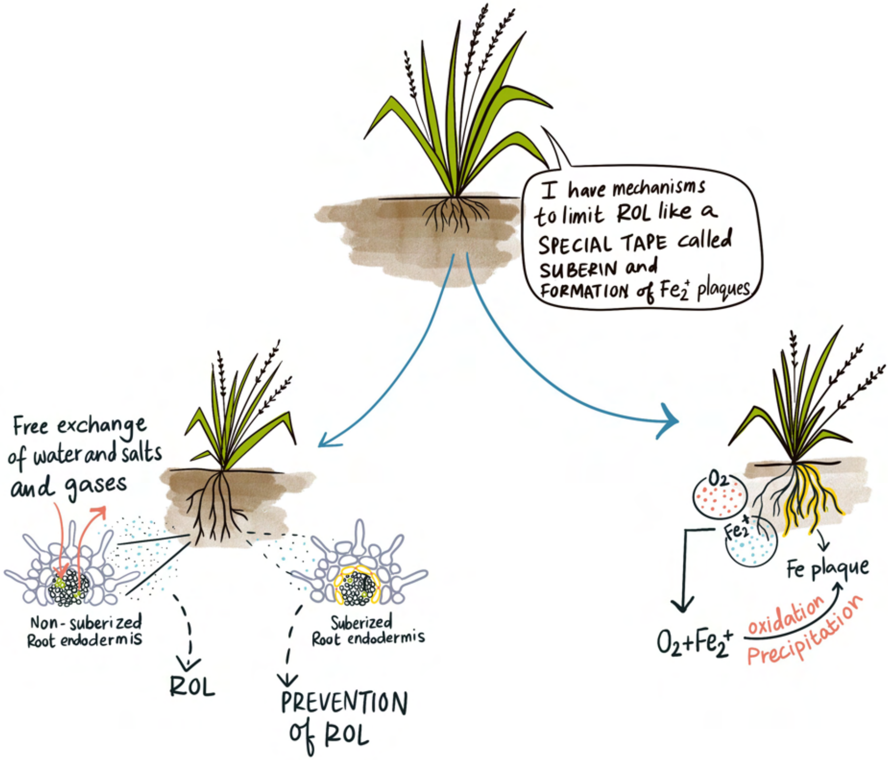
Let's continue with the straw metaphor. As a strategy to reduce ROL, imagine that the whole length of the straw is sealed with a tape, leaving open only the segment before the lower tip. In such a straw, the oxygen going from the top to the bottom will not leak out until it reaches the tip. Root systems develop a barrier in their 'exodermis', the protective outer layer of the plant root system, which limits ROL only to the root tips.



The tape-like barrier in the exodermis is in fact a layer of densely packed cells, covered with a layer of strong, waxy polymers such as 'lignin' and 'suberin'. This polymer deposition reduces the pore sizes in the cell wall. Some studies have also shown that when there are toxic substances in the soil, many layers of suberin are deposited on the roots. Such 'suberisation' is also seen in stress situations like too much salt, or cadmium or ammonium in the environment, or also when there is drought. This makes it clear that the role of suberin is to protect plant cells in the root from any harm from the surroundings.

Plants have developed some other mechanisms that create ROL barriers. When oxygen leaks out into the soil, it oxidises iron ions (Fe^{2+}) dissolved in water, which then precipitate and form iron plaques creating an ROL barrier.

There is a flip side to having protective physical barriers like suberin or iron plaques which must be considered. They do not just prevent



leakage of oxygen but also prevent entry of CH_4. They do not just prevent the entry of toxins, but also the entry of water and nutrients. Depending on the oxygen requirement of the root systems, ROL in the roots of a plant changes during its life cycle as it develops from the sprout stage to tillering, panicle and so on, to the fully matured stage. Also, different rice cultivars have different root porosities, different adaptations to prevent ROL, and thus different oxidation rates. Because of this, some cultivars show higher rates of CH_4 oxidation than others and are better suited to reduce CH_4 emissions from rice fields.

Ways to manage methane production and its release to the atmosphere

Methane can be prevented from reaching the atmosphere by either reducing its production in the soil, or by preventing it from escaping the soil.

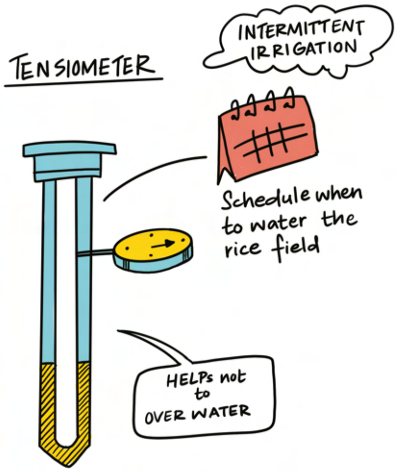
1. **Hydrological measures or management of moisture to manage methane production**

a. **Alternate wetting and drying the field (AWD):** Methane production requires anaerobic conditions for a long period of time. Such conditions become available when the field is submerged for a long time. It has been demonstrated that instead of the conventional method of continuous flooding of rice fields, choosing the practice of alternating between wet and dry conditions reduces methane emissions drastically. In this method, irrigation is withheld until the water level in the soil falls to about 15 cm below the surface, after which the field is reflooded to a depth of about 5 cm. A perforated PVC tube (commonly called pani pipe) is installed in the field to monitor water depth and guide irrigation scheduling. This method saves about 30% irrigation water and reduces 40-50% methane emission without any yield penalty.

b. **Direct seeding of rice (DSR):** Instead of growing rice seedlings in nurseries first and then transplanting them in water-logged fields, seeds are planted directly in dry or moist land and then it is grown under non-flooded conditions. While it has certain drawbacks such as

more weed infestation– if these risks are managed, it reduces water consumption, labour costs, and methane production and leads to increase in net income of the farmers.

c. **Intermittent irrigation using tensiometer:** The rice field is watered or irrigated according to a set schedule based on its water requirement as detected using a tensiometer. Again,

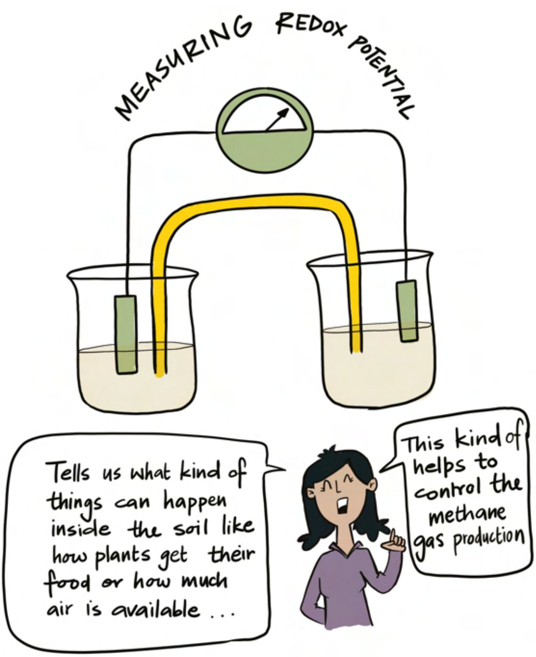


since there is no long-standing water, there is little opportunity for methane production.

d. **Mid-season drainage:** In this method, field is dried during mid-season when rice crop is less sensitive to water stress from mid-tillering to panicle initiation. This results in reduction in methane emissions without affecting rice yields. In this method field is drained completely for 7-15 days and then reflooded.

2. **Chemical measures to manage methane production**

a. **Balancing the redox potential in the rhizosphere:** Scientists use a measurement called 'redox potential' to assess what kind of biochemical reactions are going on inside soil, or even water,



in a certain area. These reactions depend on the available electrons in the system which help in carrying out oxidation or reduction of the compounds in that environment. These reactions are also responsible for regulating nutrient availability in that system. As can be expected, the presence or absence of oxygen in the system has a tremendous effect on the 'redox potential' and thus, on the possible biochemical reactions in that system. Long-term waterlogging causes the redox potential of rice soils to decrease (anywhere from +100 to -300 mV). In well-aerated, aerobic soil, the redox potential is positive (anywhere from +400 to +600 mV).

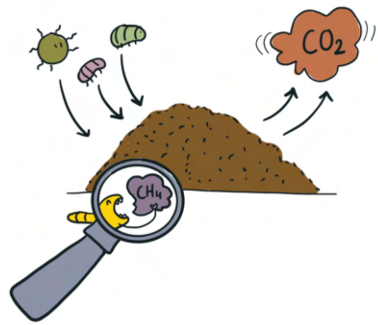
b. **Managing methane production by soil amendment:** Farmers always prepare the soil at the start of a season. Apart from removing rubble, and clearing up debris left by the earlier harvest, the soil is also turned over and rejuvenated by mixing it with substances that improve its nutrient value. Here are some amendments that specifically address the question of GHG emissions.

I. **Mixing sulphate-containing fertilisers such as ammonium sulphate and phosphor-gypsum:** Methanogenic bacteria in the soil compete with sulphate-reducing bacteria for the substrates that these fertilisers provide. It is observed that this eventually leads to reduced methane production.

II. **Adding oxidants such as iron-containing slag:** These increase the pH (alkalinity) and Eh (redox potential) of the soil, which slows down methane production.

3. **Microbiological measures to manage methane production**

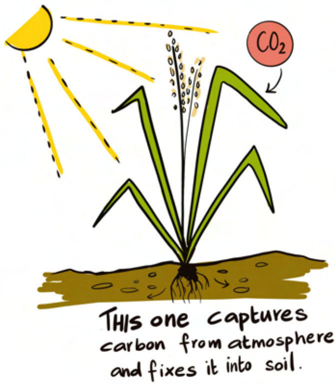
Mixing cultures of soil microbes such as methanotrophs, the bacteria that digest methane, with soil can control methane production. Methanotrophs metabolise methane produced by methanogenic bacteria to produce carbon dioxide, a much milder GHG. This reduces emission of methane from rice fields.



4. **Choosing specific cultivars to manage methane production and transport**

a. **Choosing cultivars according to their water requirement:** Some cultivars of rice require to be submerged for close to 180 days. These are considered 'long duration' rice plants. Planting of such cultivars allows longer periods in which methane can be produced and transported to the atmosphere. A variety that requires 100 days submersion could drastically reduce methane production and transmission.

b. **Choosing cultivars according to their morphology:** Plant morphology contributes to the transport of methane. The density of stomata on leaves, stems nodes and internodes, root architecture, root exudates, internal anatomy of the stem - the size of the aerenchyma, stele and the cortex - all these determine how quickly methane that is formed in the soil can escape to the atmosphere. Also, there are varieties with root anatomies with specific rates of ROL that increase methane oxidation in the rhizosphere and reduce methane transport from soil to the atmosphere. Choosing these cultivars can make a tremendous difference to how much methane reaches the atmosphere.



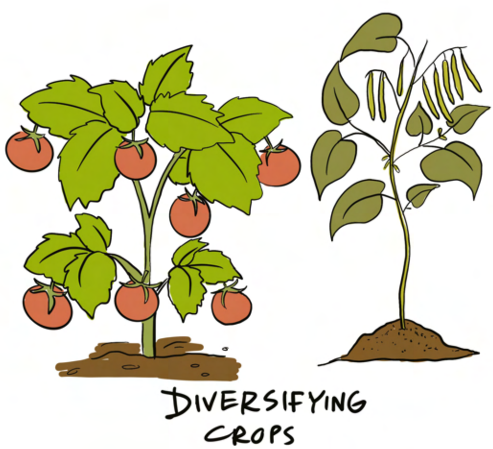
c. **Choosing cultivars that have a high harvest index (HI):** This index gives the proportion of grain to dry biomass. Higher HI suggests more productivity. Since usually all the dry biomass is added back to the soil, higher HI varieties have reduced input of organic matter, which is the substrate for methanogenic bacteria, and thus reduced methane production.

5. **Managing rice straw/residue sustainably can also reduce methane emission**

   Farmers typically burn, remove, or incorporate straw into the soil after harvest. Burning contributes to severe air pollution and Greenhouse Gas emissions, while incorporating straw under flooded conditions accelerates methane generation. Therefore, promoting circular models of straw management such as collecting and repurposing straw for composting, mushroom cultivation, biochar, biofuels or livestock feed, can transform this waste into valuable resources, reducing emissions while creating new livelihood opportunities.

6. **Diversifying away from rice cultivation, to crops that do not require standing water**

   Moving from rice to pulses and oil seeds or vegetables results in changed irrigation practices. Without any standing water soils become aerobic, thus preventing methane production by methanogenic bacteria.



Drivers and barriers to managing methane emissions

Sl. No	Category	Measure	Key drivers	Key barriers
1	Hydrological measures	Alternate wetting and drying the field (AWD)	Saving water, electricity and reduced GHGs emission	Lack of assured irrigation in canal command, lack of opportunity for drainage in low land
		Direct seeding of rice (DSR)	Saving labour, water, reduced cost of cultivation, reduced GHGs emission reduction	Lack of adequate mechanisation, control of weed
		Mid-season drainage	Reduced GHGs emission	Lack of assured irrigation in canal command, lack of opportunity for drainage in low land
2	Chemical measures	Using sulphate containing fertilisers such as ammonium sulphate and soil amendment such as phosphor-gypsum	Reduced GHGs emission	Lack of awareness and additional cost
		Soil amendment by adding oxidants such as iron-containing slag	Reduced GHGs emission	Lack of awareness and additional cost
3	Microbi-ological measures	Mixing cultures of soil microbes such as methanotrophs	Reduced GHGs emission	Technical challenges in production and field application
4	Specific rice cultivars	Low nitrogen requiring and low methane emitting rice cultivar	Reduced cost of cultivation and reduced GHGs emission	Lack of adequate research on low N requiring and methane emitting rice varieties
5	Crop Diver-sification	Diversifying rice with other aerable crop	Improved productivity and reduced GHGs emission	Lack of market linkage and value chain,

When the focus is on all GHGs with a net sink approach, and not on methane alone

We considered the story of methane, but that is not the only Greenhouse Gas emitted from agricultural soil. Carbon dioxide (CO_2) and nitrous oxide (N_2O) are the two other GHGs to which we must also give attention . Also, not all GHGs have the same effect on the environment. The way to think about the potency of GHGs is to measure how much heat they trap in the atmosphere, but 'Global Warming Potential' (GWP) is not an absolute term. To make the measurement simple, the GWP of carbon dioxide is taken as 1, and that of every other gas is measured in terms of 'carbon dioxide equivalent'. Then, the GWP of CH_4 comes to about 27, and that of N_2O, to 273. Thus, N_2O is the most potent GHG among the three.

Since N_2O has a much higher global warming potential, should our focus be more on preventing emissions of N_2O than on CH_4?

To answer this question, it is important to understand the conditions in which each of these GHGs is produced. Also, the quantities produced of each are very different. While N_2O is more potent, it is produced in much smaller quantities than **CH_4**. The conditions in soil that favour the production of each are also not the same.

What kind of soil environments produce CH_4 and N_2O?

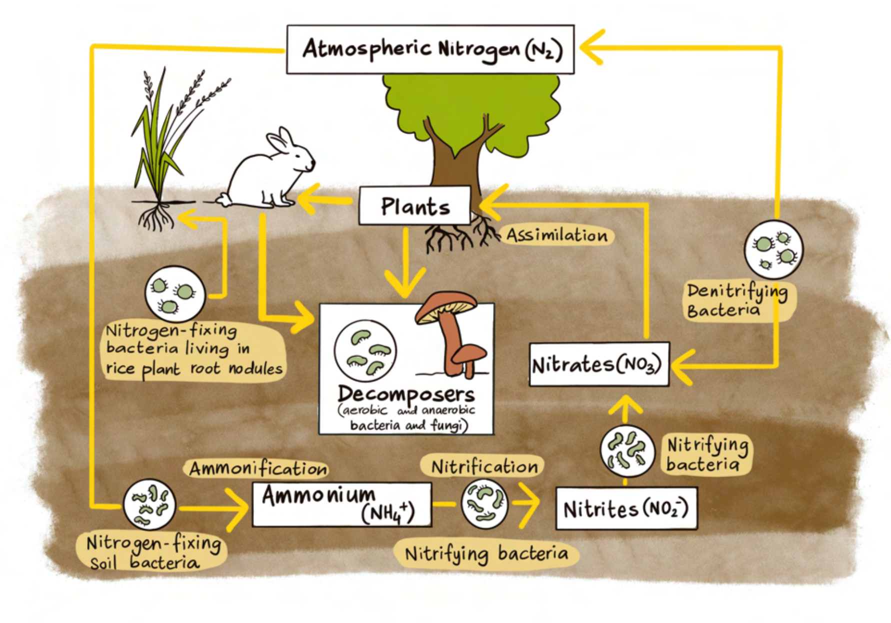
CH_4 production is a reductive process, so the ideal conditions for it are when the system is anaerobic, as in the case of water-logged or submerged farming. The lower the redox levels, higher is the chance of methane formation (-150 mV or below). On the other hand, N_2O production is both an oxidative as well as reductive process. Its emission has a wide range and is most prevalent when the soil is aerated (0 mV and above). Thus, alternative wetting and drying methods of rice farming favour N_2O formation, while prolonged standing water creates reducing conditions, primarily favouring methane production.

Consequently, there must be a trade-off, that is a balance between the two must be maintained when developing strategies to manage GHG emissions from rice soils, so that we don't end up promoting N_2O emission while trying to control CH_4 emission. Using management strategies that focus primarily on creating an oxidising environment is relatively more effective in controlling the production of both, N_2O and CH_4.

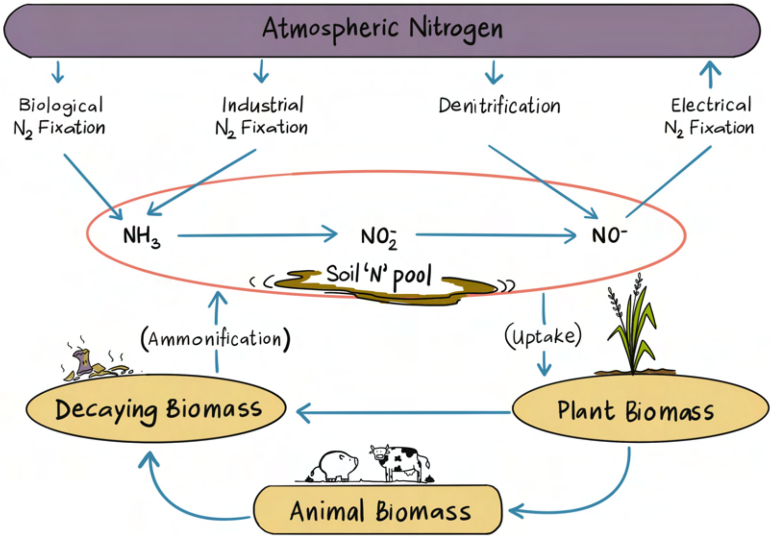
Nitrous oxide

Ways to manage nitrous oxide

Nitrogen is an essential component of any living system, and it is continually cycling between several chemical forms. Plants cannot absorb nitrogen directly from the air in its gaseous form like they do oxygen or carbon dioxide. They can, however, absorb nitrogen-containing compounds, such as ammonium and nitrate. Nitrogen-fixing bacteria convert atmospheric nitrogen (N_2) into usable ammonia (NH_3). Ammonia reacts with water in soil to form ammonium (NH_4^+), and upon oxidation nitrate (NO_3^-) is formed. Ammonium (NH_4^+) is the preferred form for rice plant.

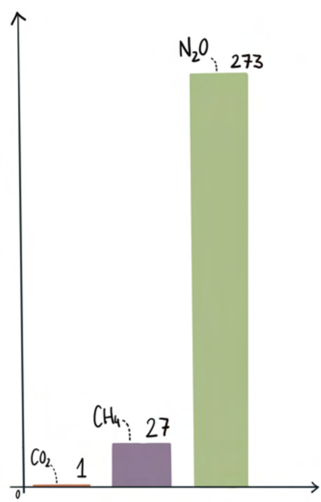


There are two major processes that take place in soil, both carried out by specialised bacteria. Nitrification is a process by which ammonia (NH_3) is sequentially oxidised to form nitrate (NO_3^-). This requires the presence of oxygen. Though not clearly understood, this sequence of reactions produces nitrous oxide (N_2O) as a by-product. The second process, denitrification is how nitrate (NO_3^-) is sequentially reduced to form nitrogen gas (N_2). This happens

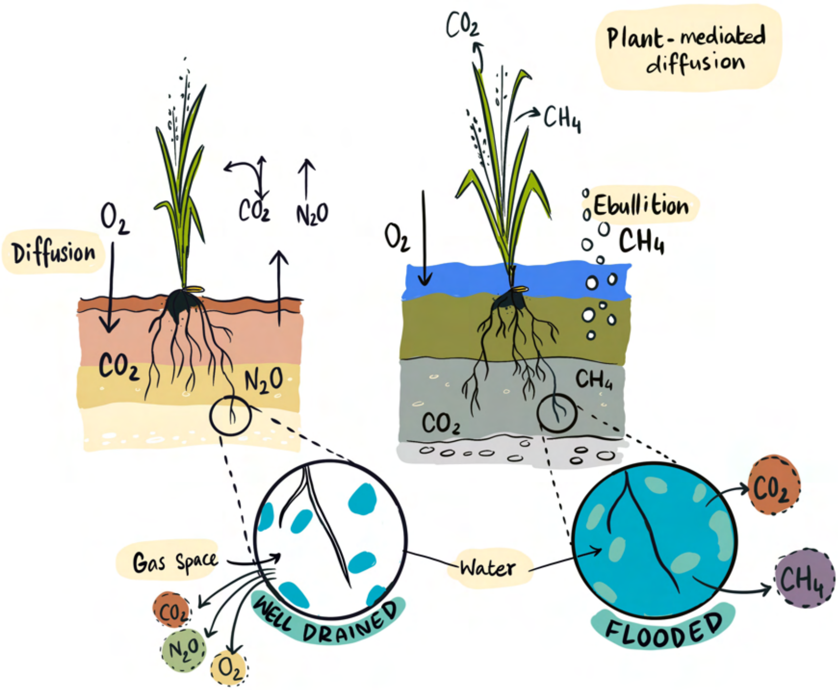


primarily when oxygen levels in soil are low, that is when the conditions are anaerobic / anoxic. Denitrification is not particularly useful for agriculture, because it results in the loss of nitrogen. Also, one of its by-products is N_2O.

Nitrous oxide is a GHG responsible for about 20% of the global warming effect. It has 298 times more global warming potential than carbon dioxide, and its average atmospheric concentration has been rising rapidly in the last two decades. Oceans and estuaries are major producers of N_2O via nitrification. Human activities like the use of fertilisers in agricultural soil, burning of fossil fuel, human sewage and refuse contribute to no less than 30% of N_2O emissions.



Because of the wide variety of biological, chemical and physical factors that affect N_2O emission, it is not easy to regulate it. Once produced in the soil, N_2O is emitted directly from the soil by bubbling. Unlike methane, it does not require the rice plant to come out of the soil and reach the atmosphere. N_2O emissions from the rice field are the same as from any other field, such as the fields of wheat or pulses or other crops. And yet, rice fields contribute substantially to N_2O because they are the biggest consumers of nitrogenous fertilisers [5] (close to 9 million tons annually, according to some reports). The reason for this is the inefficient recovery of nitrogen from the fertiliser by the plants (30-40% or even lower).



Regulating nitrogen fertilisers helps reduce N_2O production and emissions

Nitrogen is incorporated into the soil by several nitrogen fixing organisms, but still it invariably needs to be supplemented in agricultural soils. This is done through application of nitrogen-based fertilisers such as urea, sulphate and nitrate of ammonium, and so on. Excess nitrogen gained through these fertilisers is lost from

[5] https://www.sciencedirect.com/science/article/abs/pii/S0167880922002389

the system in three major pathways: First, by denitrification, which releases nitrogen gas; second, emissions of ammonia; and third, via loss of nitrates through leaching.

We are mainly interested in nitrogen loss via denitrification since that results in the production of nitrous oxide.

A method that has been proved reliable is that of balanced fertilisation or synchronisation of demand and supply. This is the practice of applying the correct combination of fertilisers to the crop at a specific time in its development depending on the plant's need, using the correct method of application. By supplying fertilisers only when there is demand, it is possible to reduce waste of nutrients and also reduce N_2O release into the atmosphere.

Balanced application of a fertiliser: This requires knowledge of the soil, knowledge of the type of crop to understand the requirement of various minerals and salts and understanding of the growth rate of the crop to know when to apply a fertiliser. Fertilisers also come in different forms - soluble fertilisers often require frequent application, while granular fertilisers are often slow-release, and are applied once every few weeks. The process of application also decides the efficacy of the fertiliser. Here are a few methods:

- Broadcasting is a method most commonly used, where fertiliser is uniformly spread across a field either manually or using some form of machinery. However, since it is not a localised application, this method often ends up applying fertiliser without taking into consideration the variability of soil nutrient and even adds to GHG emissions. Also, it may promote the growth of weeds.

- Foliar method of application is when liquid form of fertiliser is directly sprayed on leaves. This is an efficient way of providing nutrients uniformly to plants and when soil application is not possible because of moisture stress (excess/deficit) or plants suffering from root rot. This method may prove ineffective if the leaves do not absorb it efficiently and not meeting the demand of plant. If the concentration is not correctly adjusted, this may even damage the leaves.

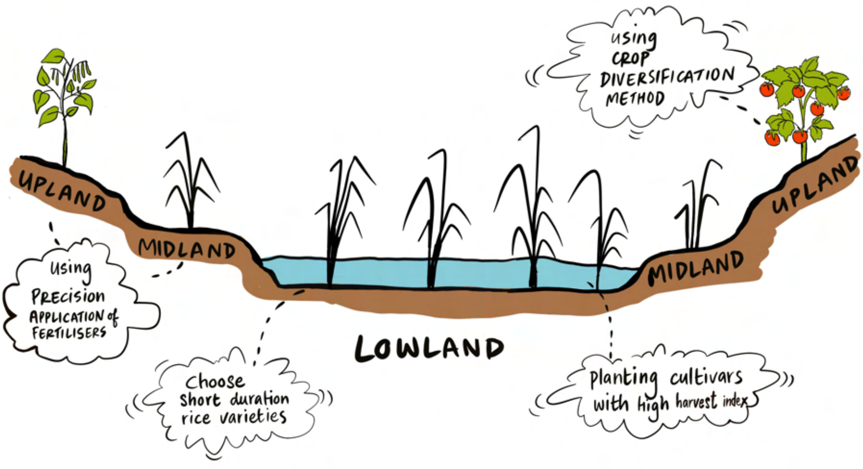
- Placement of fertilisers is when a small amount of fertiliser is placed at a specific location. This is effective when the soil is dry. Fertiliser material can be applied deep into the soil, closer to the rhizosphere where it can be used directly by roots. This method reduces nutrient loss and weed growth.

- Fertigation is a way of applying fertilisers through irrigation. This can be done via drip irrigation, sprinklers or by watering through furrows between the rows of crop. This method requires the fertiliser to be water soluble. Sometimes the deposits may block the whole system, so it needs regular maintenance of the irrigation system. Also, water used for irrigation needs to be managed carefully to prevent over fertilisation.

Rainfed rice cultivation in lands with low, mid and upland farming: The case of the three levels

As far as water management is concerned, the irrigated rice fields can easily adopt AWD, because the water, in both irrigation and drainage, can be easily controlled. However, nearly 50% of Indian agricultural land is rainfed - that is it depends purely on water brought in by the rains. Like all natural stretches of land, most agricultural land in India is made up of flat stretches, combined with undulating terrains, with mounds, slopes and valleys.

For ease of management, rainfed farmlands can be divided into three levels - high or upland, midland, and lowland. It is important to remember that this categorisation is purely based on relative heights/topography of various field, and not on the absolute altitude of the region. All three levels are often found in the same terrain, and rice cultivation in each requires separate planning or management strategies for irrigation, depending on the amount of seasonal rainfall (such as heavy monsoons or hot and dry summers) and general water availability. Because of the different ways the three levels in a farmland interact with water and soil, their potentials for the production and emission of GHGs also differ.
Water management strategy to reduce the climate impacts of rice cultivation also differs between rainfed and irrigated agriculture in India. Indian monsoons are unreliable, and wet spells are interrupted



with dry spells of different lengths. In most rainfed areas that are upland or midland, this results in unintentional AWD. The lowland regions, however, may become waterlogged during the height of monsoons and continue to be so for many days after, making them amenable for management strategies connected to submerged farming.

Lowland management: Because lowlands are often surrounded by slopes, they tend to accumulate water, be it rainwater or from other sources of irrigation. Submerged rice farming becomes the norm in such areas since the land is under water for prolonged periods. In such cases it is more practical to find ways to encourage carbon sequestration by putting more biomass to the soil, than try to control methane and N_2O emissions. This can be achieved by a) choosing short-duration rice varieties, and b) by planting cultivars with high harvest index (HI). In both these cases the soil organic carbon (SOC) increases, since the majority of plant biomass is returned to the soil after harvest. Anaerobes are inefficient decomposer, hence the biomass carbon added to soil remain there for longer period (increased sequestration).

Up and midland management: Methane production in these areas is naturally controlled because of alternating rains and dry spells during the growing season. Production of other GHG such as N_2O can be controlled by keeping rhizospheres at an oxidative level by using 'precision application of fertilisers. Modern techniques of soil testing are used to determine the required quality and quantity of fertilisers. This helps to balance the redox potential of the soil and prevents unintentional increase in N_2O emission in the effort to reduce CH_4 emission.

Upland management: 'Crop diversification' is the ideal measure used to prevent GHG production and emission during rice cultivation in upland regions. The farmers are recommended to stop growing rice and instead switch to crops like vegetables or oil seeds that do not require waterlogging. Here is an example: farmers traditionally grow rice in the upland regions of Jharkhand, Chhattisgarh and some parts of Odisha. In recent years, they have successfully diversified to pulses and horticultural crops. This doesn't just prevent GHG production but also gives the farmers two harvests, in rabi (winter) as well as in kharif (monsoon and autumn) seasons.

Concerns of farmers and possible solutions - FAQs

1. **Do the farmers lack education and knowledge about the technologies to make rice farming more sustainable? If yes, how can this be remedied?**

   Farmers may not be aware of the detailed science behind how GHGs are produced. They may not grasp why preventing GHGs production will benefit the whole of humanity. But they can appreciate practical matters that have an immediate impact on their everyday lives. For example, they are aware that if there is an assured and sufficient supply of water through the growing season, they could reduce their annual water consumption. Or, if they are assured a market for farm-products other than rice, they could grow a wider variety of crops.

   Moving ahead, generating farmer awareness towards climate impacts of rice cultivation, and simultaneously providing options that will have a positive counter-impact on their farming business is certainly a good solution.

2. **What other steps can be taken to onboard farmers to fight negative impacts of climate change?**

   Along with awareness creation, farmers need to be incentivised for effective climate action. Investing in their capacity-building, improving their understanding and awareness of new knowledge and technologies is absolutely essential. Additionally, several social and economic reforms are necessary before bringing radical changes in Indian agriculture.

3. **Is it economically feasible for them to implement these technologies?**

   It is feasible to a large extent, but more than the cost of technology and equipment, the concerns are lack of accessibility to information, and assurance of a market for any new farm-product.

4. **What is the difference in the yield produced using different methods?**

   The yields from submerged cultivation, AWD, and direct seeded rice (DSR) method are not discernibly different. However, the work input required for each might be vastly dissimilar. For example, some of them may require a combination of many small 'component technologies', which can become cumbersome for the farmers.

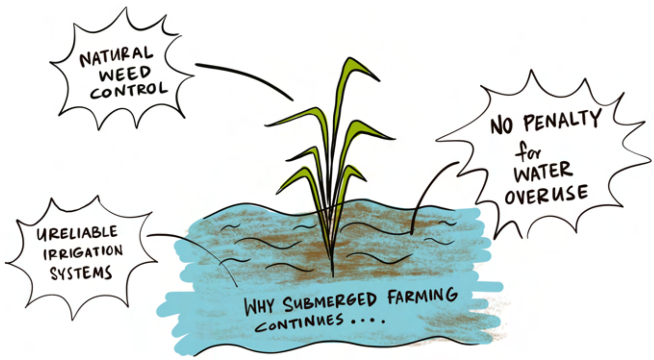
5. **Why are farmers reluctant to move away from submerged farming to practice AWD during rice cultivation? Afterall, AWD has a demonstrably positive impact on GHG emissions and climate change.**

   The reason for this is multifaceted. It has roots in the social-economic attitudes of farmers. Based on years of experience of working in the agricultural sector they have learnt to be overcautious when asking for government support. Added to that are the distrust and aversion to new and unfamiliar technologies and farm-management strategies. Thus, it is dubious whether knowing about global impacts of GHG emissions would change their attitudes.

   - **Weed control:** The first and a very valid reason why farmers prefer submerged farming is that water standing in a field for long periods of time prevents other grasses from growing. This is an effective method of weed control. AWD, on the other hand, allows germination of all kinds of seeds during the dry phase, thus allowing weed infestation. Also, AWD requires more careful decision-making regarding timing and application of fertilisers, which becomes an expensive proposition.

   - **Unreliable water availability:** The second reason is that the irrigation systems available to Indian farmers are unreliable. Water is limited in many parts of India. Since the farmers cannot depend on water availability at all times, they prefer to submerge their fields with water when they can, and hope for the best. Limited water also means that it has to be divided among many farmlands, and the farmers may have to tussle with each other for it. Therefore, when it becomes available, it is used to the fullest extent.

- **Limited but free resources:** The third reason is that in India, even though water supply is unreliable, it is free to farmers. Not only are water and electricity free, there is also no penalty for their overuse. Since there is no monetary cost associated with overuse, there is an unfortunate tendency to abuse these resources. Farmers often apply more water than is necessary, imagining that it will make up for a future lack.

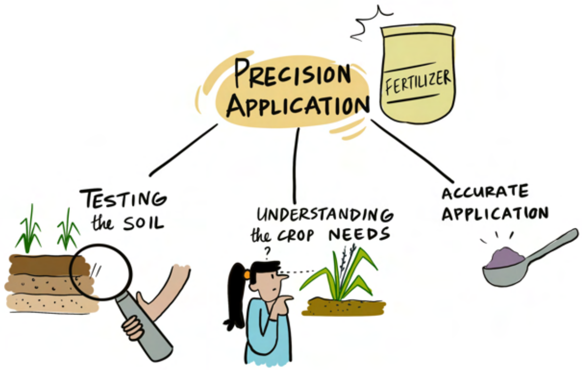


6. What is 'precision application' of fertilisers? How complicated is it to use?

   Most farmers in India depend on recommendations from the Department of Agriculture to determine the kind of fertilisers they should use for a certain crop, the quantity they should apply, and exact time of application during the growth of the crop. This 'precision application' of fertilisers requires soil-testing, assessment of quantity based on the crop developmental stages, and accurate application using appropriate methods and equipment. This not just helps improve yields but also reduces N_2O emissions drastically.

   Ideally, the Department of Agriculture makes these recommendations based on soil quality. However, the quality of soil is not uniform across even a small area of land, and samples from many different points on the land need to be tested, making soil testing a massive undertaking. The infrastructure required for this is currently inadequate in India. Hence, recommendations are given based on the average quality of soil of a whole district, or even a state. Since blanket recommendations are given to all farmers, irrespective of the soil quality and fertility in their individual farmlands, the results are often not optimal.

When it becomes feasible to conduct detailed assessment on such a vast scale, it will also be possible to give suitable recommendations to each farmer.



7. **Why are farmers reluctant to give up rice farming and diversify to other crops?**

Farmers keep a portion of the crop they grow for their personal consumption, a portion as a currency for barter, and the remaining is sold in open markets. There is always some part that remains as surplus, and does not get sold. In India, surplus of some crops like paddy and wheat is bought by the government. Government agencies like Food Corporation of India make a detailed estimate of production of certain crops at the beginning of each marketing season, and purchase excess produce from the farmer at a minimum support price based on a fair average quality of the crop. There are only a few crops that have this 'procurement assurance' from the government.

Recently the government included a few more crops into the procurement assurance programme, but the incentives are not adequate enough for the farmers to want to diversify away from rice farming. Hence, even when the government gives other incentives, this uncertainty about having an assured market for their produce is what makes the farmers reluctant to dabble into cultivating other crops.

Assured procurement from the government makes farmers feel secure. Here is an example: In Haryana, farmers were given incentives for diversifying from rice to non-rice crop. Under the 'Mera Pani Meri Virasat' scheme, the state government promised Rs. 7000 per acre to a farmer who was willing to switch over to alternate crops like maize, cotton, kharif pulses (tur, moong, moth, urad, soybean and guar), kharif oilseeds (groundnut, castor and sesame), fodder crops, and horticultured vegetables (including kharif onion). And yet, very few farmers were willing to switch over because there was no guarantee that these crops would get sold. On the other hand, since water is available for free, they could cultivate rice, for which procurement was absolutely assured. It was an easy choice for the farmers.

The farmers understand that switching over from rice may be good to reduce water usage, because parts of Punjab and Haryana are dealing with water shortage; and yet, this is not a problem that has a science and technology solution. It needs a social and economic solution, and a policy solution.

8. Can the farmers' concerns be soothed? What can help cross these hurdles to adopting more sustainable practices?

Admittedly some, if not all, of these concerns can be addressed. Here are some steps that can be taken:

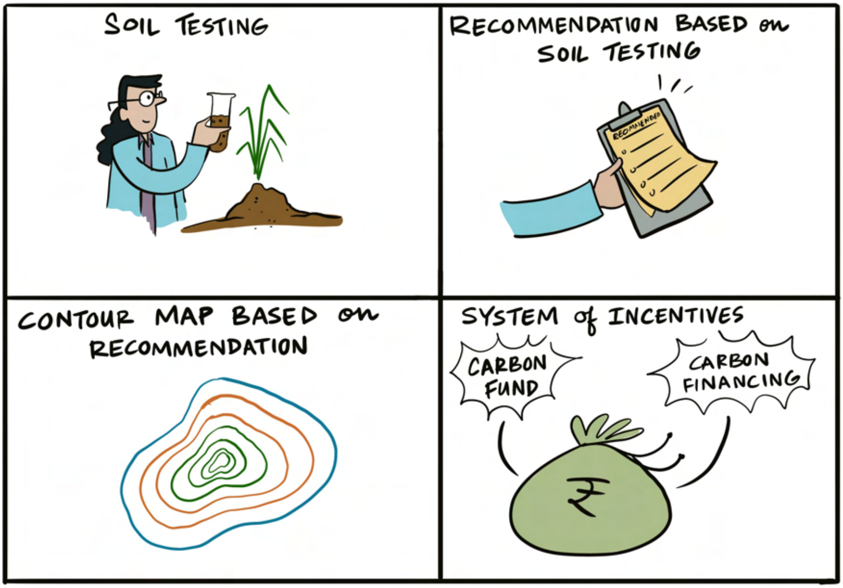
- Offering better weed-management practices, so that some farmers would choose not to use standing water for prolonged periods.

- Assuring reliable and timely water supply, so that farmers may feel secure in not choosing submerged farming.

- Charging for water, which would compel rice farmers to use precise amounts of this valuable resource. This will favour resource-use efficiency of water, and also substantially reduce GHG production.

- Making modern precision management technologies more affordable. This will percolate to all levels of the farming community, creating a willingness among them to move from submerged farming to AWD.

Future of rice agriculture in India



Create a system of soil testing-based recommendations

The quality of any soil depends upon the kind of minerals, organic matter and water content in it. When a piece of land is being prepared for cultivation, it needs to be enriched in a nourishing matrix, aerated by tilling, cleared of weeds, and fertilised according to the quality of soil and the requirements of the crop that would be planted in it. Each piece of land is different. The soil that has remained fallow for long periods will have different requirements than that which has been farmed regularly.

All these qualities of the soil must be taken into consideration before recommending what kind of treatment it needs. Soil-testing before suggesting a fertiliser regimen is the most effective way to help a farmer. Either making soil-testing laboratories available and affordable, or developing soil-testing kits, and training farmers to use them accurately are some of the ways to empower them to make their own decisions about their farmlands.

Providing geography-based recommendation for reducing the climate impacts of rice cultivation

Contour map can be used to classify rainfed and irrigated areas into upland, midland and lowland regions. This is known as 'zonation'. Such a map would help to give effective guidelines to farmers about zone-wise management of their land. As an example, farmers in low lying areas could be advised to apply techniques that promote carbon sequestration rather than trying to control GHG emission; or farmers in midlands would be recommended methods that allow for careful implementation of AWD; and upland farmers would be advised to consider diversification of crops.

Create a system of incentives (carbon fund, carbon financing) and fines to drive action that would lead to globally advantageous results

Is it enough to just offer recommendations to farmers? It may be too expensive for them to make changes in their traditional practices just because a scientist or the government says so. But how can we convince a farmer about the dire realities of Greenhouse Gas emissions, global warming and climate change? How do we make them believe that this is going to affect not just the world, but also them?

Increasingly, as the accumulation of the Greenhouse Gases in our atmosphere are becoming threatening to life on Earth, most countries in the world have begun to sit up and take notice. Several industrialised nations have vowed to make active efforts to reduce their carbon footprint. In countries like India, agriculture is a state matter, with state governments taking steps towards sustainable agriculture interventions and rainfed area management. A major focus in this context is economic benefit to the farmers.

Many Indian states encourage mutually beneficial collaborations between public and private sectors by using innovative ideas to incentivise clean energy projects to reduce GHG emissions. Some such 'carbon projects' are being established by the Madhya Pradesh Government, where a collaboration is formed between businesses that work in the forest, land and agriculture sector (FLAG), particularly the ones that use the state's natural commodities, and farmers or land owners who are willing to commit parts of their land to sustainable and regenerative agriculture. The government has set aside a so-called 'carbon fund' for such projects.

One such project by the Madhya Pradesh Government hopes to revive close to 10,000 hectares of its forest that is degraded by overuse or uncontrolled growth of invasive, non-native vegetation. The fund adheres to the domestic carbon market and Green Credit system. The Government, in collaboration with the private sector, has promised monetary compensation to land owners who are willing to procure these degraded landscapes and revive them. If a farmer is able to mitigate further effects of climate change on land, then they will be able to release substantial funds from this 'carbon finance'.

Similar projects need to be established in other states like Chhattisgarh and Odisha as well. Mapping the upland, midland and lowland areas in the region will help to guide farmers regarding the necessary crop management. For example, the Odisha Government creates a carbon fund, the farmers can easily test their soil for Soil Organic Carbon in their land and establish SOC-improvement programmes. The government can then compensate the farmers by footing the bill. And because this 'domestic carbon market' is created by the locals, it is not bound by international regulations or even methodology. We can craft our own methodology based on local conditions.

Institutions like FOLU India can play an important role in bringing together various stakeholders including government, civil society organisations (CSOs), and research institutions like ICAR to create enabling environment for investments in testing centres. The goal is to make different state governments see the advantage in creating a system that gives broad guidance to farmers to overcome water and climate crises and help individual farmers to make correct decisions. Once the governments recognise this 'climate value', it will be easier to get the industry to invest in it as well.

Overview

1. The way to prevent rice agriculture from being a major source for Greenhouse Gases is to work on balancing carbon sequestration and GHG emission reduction.

2. CRRI studies have shown that it is preferable to focus on carbon sequestration by removing carbon from the atmosphere and fixing it in soil, rather than trying to regulate methane emission. This is because there is a delicate balance between production of methane and that of nitrous oxide, a more potent GHG.

3. The soil subjected to alternate wetting and drying acquires a positive or oxidative redox potential. This reduces or even prevents production of methane, but may continue to promote nitrous oxide production, since N_2O can be produced in both oxidative and reductive soil conditions.

4. The way to achieve the correct balance, or trade-off, so that N_2O production is also regulated in alternate wetting and drying conditions, is to take adequate measures like soil-testing before applying nitrogenous fertilisers. This method, called 'precision application of fertiliser' promotes applying precisely the amount required, at a stage when it is required, and at the location where it has the most effect.

5. Methane emissions can be reduced using chemical inhibition, methanotrophic bacteria, and rice cultivars with appropriate plant physiologies.

6. Draining the rice field even once during a growing season can substantially cut down methane emission. There is no requirement of a strict regimen of wetting and drying the field, rather just the intermittent rainfall and dry spells can help cut off GHG emissions.

7. There is a greater possibility of waterlogging in lowland or low-lying areas, and it may not be always possible to drain the land even once. In these areas, it is always recommended to focus on carbon removal / sequestration rather than trying to reduce GHG emissions.

8. In midland and upland areas, there is a higher potential for alternate wetting and drying. This frequently happens particularly in rainfed regions. In these areas, focus should be given on reducing GHG emissions. However, care must be taken to test the soil , and sue precision application of fertilisers to prevent excessive production of N_2O.

9. In upland regions, crop diversification is the recommended practice. Changing from rice farming to cultivation of any other suitable crop is a more practical solution of managing GHG production and emissions.

10. In all cases - from rainfed to irrigated, and in up, mid and lowland areas - care should be taken when choosing the most suitable cultivar of rice.

11. In all cases, particularly when alternate wetting and drying techniques are used, focus should be given on weed management.

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