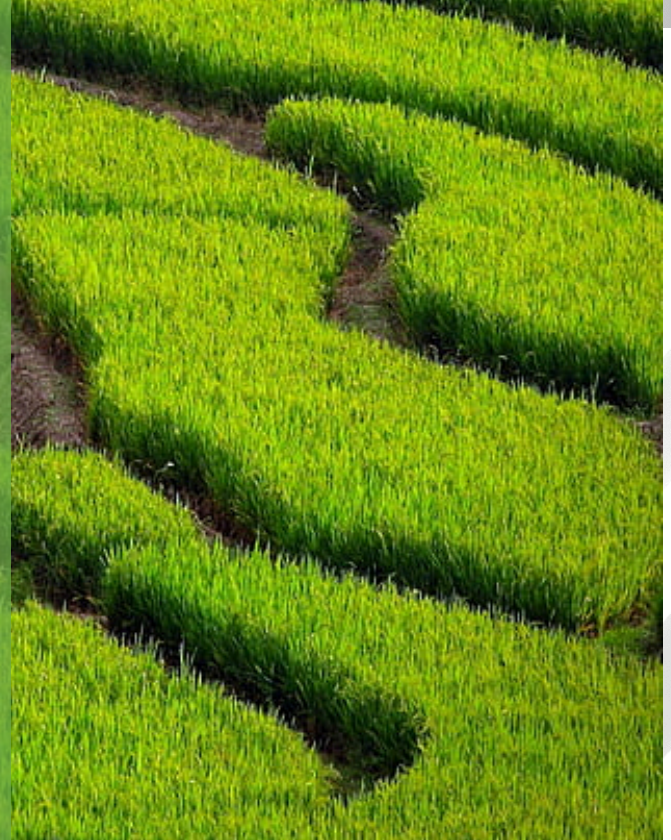


# APN

ASIA-PACIFIC NETWORK FOR  
GLOBAL CHANGE RESEARCH

## FINAL REPORT

Greenhouse gas emissions  
from paddy ecosystems  
(GREPEC): critical  
windows of water and gas  
diffusivity



CRRP2020-07MY-Deepagoda



# 2023



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## 1. Summary

Rice is consumed by more than three billion people on earth and has long been the staple food for largest number global communities. In fact, more than 45 million rice consumers are annually added to the Asian population, despite increasing challenges in rice productivity including water scarcity, alternate and competing uses of water, and other environmental consequences. Since rice is an extremely water-sensitive plant, Asian paddy ecosystems essentially exhibit a strong hydrological coexistence. In Asia, rice occupies 64-83% of irrigated area, and broadly accounts for 24-30% of world's developed freshwater resources. With increasing demand for rice productivity under intense pressure on water availability, novel strategies emerge to optimal use of available water. Alternate wetting and draining (AWD) method, for instance, has recently received marked scientific attention as a promising water management practice in many aspects. Irrigated paddy ecosystems, however, constitute a predominant source of greenhouse gases, ( $\text{CH}_4$ ) and nitrous oxide ( $\text{N}_2\text{O}$ ), two high potent gases responsible for global warming and regional climate shifts. The characteristically submerged paddy landscapes in Asia provide favorable anaerobic conditions for methanogen-originated  $\text{CH}_4$  and denitrification-driven  $\text{N}_2\text{O}$  production. In addition, soil properties and water management practices such as irrigation frequency and drainage also affect the amount of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  production. The produced gases should migrate through soil and emit to the atmosphere by diffusion, which can be explained by soil-gas diffusivity. Soil-gas diffusivity, in essence, is a function soil air content, and tortuosity of functional soil-air phase. The presence of water, therefore, provide a two-fold effect on soil-gas diffusivity due to the decrease in soil-air and increase in moisture- induced tortuosity. Under submerged conditions, gas migration occurs as ebullition, an important but poorly understood mechanism of methane emission in paddy ecosystems.

This project forms a regional research initiative to understand the impact of soil and environmental factors and water management strategies on paddy ecosystems and emissions related to soil-gas diffusivity. The study proposes the best management practices the region can adopt to minimize GHG emissions while maintaining the crop productivity and develops gas diffusivity fingerprints in paddy soil under different saturations using predictive diffusivity models for future predictions.

## 2. Objectives

- To characterize soil-gas diffusivity in relation to the soil and atmospheric properties and country-specific water management practices of the region.
- To assess  $\text{N}_2\text{O}$  and  $\text{CH}_4$  fluxes throughout the growing season and investigate its functional relationship to soil-gas diffusivity.
- To investigate the critical gas diffusivity and water windows which trigger emission peaks.

- To develop predictive models to estimate soil- gas diffusivity.
- To propose best water management strategies to avoid excessive emissions and recommendations for policy decisions.

### 3. Outputs, Outcomes and Impacts

Outputs	Outcomes	Impacts
<p>GHG (Greenhouse gas) emission from paddy ecosystems outlook of 3 Asian countries (Sri Lanka, India, and Japan)</p> <p>A policy meeting at Ministry of Environment Sri Lanka, 2023.</p> <p>Online seminar related to seasonal dynamics of Methane and Nitrous Oxide emissions in Sri Lankan paddy soils under controlled water management.</p> <p>Conduct physical seminar on the effect of mid-season drainage on greenhouse gas emissions from paddy ecosystem for the Dept. of Civil Engineering, Indian Institute of Science by Sri Lankan team.</p> <p>A leaflet regarding GHG emission from paddy ecosystems according to conventional practices in 3 countries.</p>	<p>CH<sub>4</sub> and N<sub>2</sub>O emission from rice paddies and atmospheric, subsurface emission controlling parameters documented.</p> <p>24-hour measurement camp conducted for diurnal emissions at Sri Lankan rice fields.</p> <p>Detailed research on CH<sub>4</sub> emission pathways through ebullition and paddy plants</p> <p>Seasonal and diurnal variation of CH<sub>4</sub> and N<sub>2</sub>O from rice fields and the feasibility of AWD in Sri Lanka and India published and under review.</p> <p>Studies related to soil gas diffusivity emission from agricultural soils published in high quality journals.</p> <p>A novel soil gas diffusivity model (called ASEX model) developed to predict GHG emission from paddy soils and has been published in high quality journal.</p>	<p>A useful regional insight on the behaviour of GHG emission, mainly CH<sub>4</sub> and N<sub>2</sub>O from paddy ecosystems under various country specific treatments (i.e., AWD and water management, fertilizer application, straw management).</p> <p>Alternate wetting and draining (AWD) method recommended as an emerging solution for water conservation and mitigation of greenhouse gases, while maintaining the crop yield for Asian region with ever-expanding population and depleting resources.</p> <p>Emphasis on straw recycling in paddy systems as a practice which require considerable attention as it potentially enhances methane emissions.</p>

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#### 4. Key facts/figures

- AWD reduced water usage by 27-35% compared to CF in Sri Lankan paddy sites.
- Reduction in CH<sub>4</sub> emission under AWD is 32-43% in Sri Lanka and 31-311% in India.
- AWD triggered N<sub>2</sub>O emission.
- Ebullition accounted for 60% of the total emission at heading stage according to Japanese experiments.
- 1 Book chapter, 2 Journal articles, 12 Conference papers, Abstracts were published, and 5 Journal articles are under review.
- Seven presentations on conference were done.
- Policy meeting was held at Ministry of Environment in Sri Lanka by addressing all outputs with leaflets.
- Physical and online seminars were conducted at Faculty of Engineering, University of Peradeniya and Dept. of Civil Engineering, Indian Institute of Science.
- One MPhil thesis has been published.

#### 5. Publications

1. Lakshani, M. M. T., Deepagoda, T. C., Clough, T. J., Jayarathne, J., Thomas, S., Balaine, N., . . . Smits, K. M. (2022). Effects of soil moisture on simulated methane flow under varying levels of soil compaction. In R. Dissanayake, P. Mendis, K. Weerasekera, S. De Silva, S. Fernando, & C. Konthesingha (Eds.), 12<sup>th</sup> International Conference on Structural Engineering and Construction Management (Vol. 266, pp. 271–282). Springer Nature Singapore. [https://doi.org/10.1007/978-981-19-2886-4\\_20](https://doi.org/10.1007/978-981-19-2886-4_20).
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6. Lakshani, M. M. T., & Chamindu Deepagoda, T. K. K. (2021, October 9). Density effects on soil gas diffusivity in agricultural soils. *Proceedings of the IESL Young Member's Technical Conference*, 162-167. <https://app.box.com/s/gtqlwepd5wcn3mvh5e8iurzpz428haz1>.
  7. Lakshani, M. M. T., Deepagoda, T. K. K. C., Clough, T. J., Jayarathne, J. R. R. N., Thomas, S., Balaine, N., Elberling, B., & Smits, K. (2021, December 17-19). Effects of soil moisture on simulated methane flow under varying levels of soil compaction. *Proceedings of 12<sup>th</sup> International Conference on Structural Engineering and Construction Management ICSECM*. <https://link.springer.com/book/10.1007/978-981-19-2886-4>.
  8. Abeysinghe, A. M. S. N., Amarasinghe, U. D. H. N., Lakshani, M. M. T., & Chamindu Deepagoda, T. K. K. (2021, December 17-19). Soil-gas diffusivity in pasture topsoil. *Proceedings of 12<sup>th</sup> International Conference on Structural Engineering and Construction Management ICSECM*, <https://link.springer.com/book/10.1007/978-981-19-2886-4>.
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  12. Lakshani, M. M. T., & Chamindu Deepagoda, T. K. K. (2022). *A New Predictive Model for Saturation-Dependent Soil-gas Diffusivity*. IESL Young Member's Technical Conference, Sri Lanka. (Accepted)

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16. Arunakumar, G. P., Chanakya, H. N., Deepak, C. A., Sheshashayee, M. S., Sivakumar Babu, G. L., & Chamindu, D. (2023) Greenhouse gas emissions from Paddy ecosystem: impact of water regime, crop management, and nutrient management strategies. *Applied Biological Chemistry* (Under review).
17. Arunakumar, G. P., Chanakya, H. N., Chamindu, D., Sivakumar Babu, G. L. & Lakshani, M. M. T. (2023) Assessing Greenhouse Gas Emission Levels in India and Global Perspectives: Insights and Mitigation Strategies. *Current Science* (Under review).
18. Arunakumar, G. P., Chanakya, H. N., Deepak, C. A., Sheshashayee, M. S., Sivakumar Babu, G. L. & Chamindu, D. (2023) Greenhouse Gas Emission Dynamics in Contrasting Paddy Cultivation: Assessing Varied Nutrient Supplementation Effects in Summer Paddy. (Under internal review).
19. Arunakumar, G. P., Chanakya, H. N., Chamindu, D., Sivakumar Babu, G. L., & Lakshani, M. M. T. (2023) Predicting soil gas diffusivity with varying degree of saturation. (Under internal review).
20. Kobayakawa, T., Hamamoto, S., Cui, D., Xuping, M., Kajira, M., Tokida, T., & Nishimura, T. (2022, November 17-18). *Seasonal and diurnal variations in methane emissions via plant and ebullition from a rice paddy*. [Paper presentation]. PAWEES2022 International Conference, Fukuoka, Japan.

Redear is referred to following link for papers:  
<https://drive.google.com/drive/folders/1TyTv10eWPrDp97QvysvFpqO-vq-S2Q91?usp=sharing>.

## 6. Media reports, videos, and other digital content

Featured on Twitter regarding the newly developed soil-gas diffusivity model, "ASEX model: A new exponential model for predicting soil gas diffusivity with varying degree of saturation" published on December 28, 2022.

<https://twitter.com/vadosezonej/status/1608115686986874880?s=20>

Featured on Insight magazine (Bi-annual digital research footprint, Volume 1 Issue 1) Dept. of Civil Engineering, University of Peradeniya. Published on March 2022

<https://eng.pdn.ac.lk/civil/resources/insight/v1i1/index.html#page/12>

Featured on CSA (Crop Science, Soil Science, Agronomy of America) news magazine regarding the newly developed soil -gas diffusivity model. Published on March 2023.

[https://drive.google.com/drive/u/1/folders/1Tkkqozn\\_xNdmgdczaziaFA9irVnJ27tk](https://drive.google.com/drive/u/1/folders/1Tkkqozn_xNdmgdczaziaFA9irVnJ27tk)

Featured on American Geophysical Union (AGU) Tumblr about GREPEC research project. Published on January 04, 2022.

<https://americangeophysicalunion.tumblr.com/post/672485335958159360/greetings-from-sri-lanka-emission-of-greenhouse>

Featured on Eos science newsletter by AGU about the research project. (Volume 103 No. 3) Published on March 2022. (Page 51)

[https://drive.google.com/drive/u/1/folders/1Tkkqozn\\_xNdmgdczaziaFA9irVnJ27tk](https://drive.google.com/drive/u/1/folders/1Tkkqozn_xNdmgdczaziaFA9irVnJ27tk)

## 7. Pull quotes

"This project brought many local, regional, and international scientists to a common platform to investigate a pressing issue of maintaining a climate-healthy paddy cultivation while preserving water and securing crop productivity. The project outcomes are strongly aligned with the desperate paradigm shift the Asian farmers need from traditional submerged cultivation to drained paddy systems for the future of their nations".

*Dr. Deepagoda T.K.K.C, Lincoln University, New Zealand*

"This project opens new physical, chemical and microbiological insights into single and double cropped paddies in sandy and sandy loams of peninsular India where natural and agronomic

situations are conducive to raise paddy crops with no significant different GHG footprint over uncropped wet soils and can provide future ways for low GHG footprint cropping options”.

*Dr. Chanakya, H. N., IISc, India.*

“The judicious application of fertilizers, the implementation of effective water management strategies, and the adoption of cultivation practices tailored to the specific characteristics of the soil type play pivotal roles in the management and mitigation of greenhouse gas (GHG) emissions originating from paddy fields”.

*Dr. Sivakumar Babu, G. L., IISc, India.*

"Coming from a rice growing family of south India and rice being my staple food, I ascertain that agriculture is irreplaceable and the environmental concerns on agricultural GHG emissions can only be addressed through deeper understanding of GHG sources, which helps in precisely quantifying the roles of water management, organic amendments and soil-gas interactions to develop sustainable mitigation strategies."

*Dr. Madhavi Latha Gali, The Chair, Centre for Sustainable Technologies, IISc.*

"The project gave deep understanding of greenhouse gas emissions from paddy fields. The favourable physicochemical soil conditions, combined with sustainable agronomic practices for single or double paddy cropping, enables paddy cultivation as an eco-friendly endeavour in this agroecological region of peninsular India."

*Dr. Arunakumar, G. Pandit, IISc, India.*

## **8. Acknowledgment**

We would like to express our sincere gratitude to the Asia-Pacific Network for Global Change Research (APN) for funding the project. We would also like to express our sincere thanks to Dr. Senanayake D.M.J.B from Rice Research Development Institute, Sri Lanka, Prof. Nissanka S.P from Dept. of Crop Science, University of Peradeniya, Dr. Chanakya H.N., Sivakumar Babu G.L., and Dr. Parameswaran T.G. from Indian Institute of Science, India, and Prof. Soichiro Hamamoto from university of Tokyo. Also, special thanks are extended to Prof. Bo Elberling from University of Copenhagen, Denmark, Prof. Timothy J. Clough from Lincoln University, New Zealand, and Prof. Kathleen M. Smits from Southern Methodist University, USA.

Our special thanks to several researchers, government officials, and nongovernmental organizations who participated in this project directly and indirectly by providing valuable time, experiences, and expertise, including being part of the policy workshop, and seminars conducted under this project.

## 9. Appendices

### Appendix 1: Policy Meeting at Ministry of Environment Sri Lanka (2023.04.21)



### Appendix 2: Physical and online seminars which conducted at Faculty of Engineering (11.07.2022), University of Peradeniya and Dept. of Civil Engineering, Indian Institute of Science (24.05.2022).

Civil Engineering Research Club (CERC) in Collaboration with Civil Engineering Research Promotion Sub-Committee of the Department of Civil Engineering, University of Peradeniya

Presents 9<sup>th</sup> Research Seminar of Full-Time Postgraduate Student  
[https://eng.pdn.ac.lk/civil/research/cerc\\_seminar\\_11\\_07\\_2022.php](https://eng.pdn.ac.lk/civil/research/cerc_seminar_11_07_2022.php)



Some glimpse of meeting the staff of IISc, Bangalore and the seminar conducted on effect of mid-season drainage on greenhouse gas emissions from paddy ecosystem.

### Appendix 3: Journal Article

#### 1. A new exponential model for predicting soil gas diffusivity with varying degree of saturation. (Published in Vadose zone journal)

##### Abstract

Soil gas diffusivity ( $D_p/D_o$ , gas diffusion coefficients in soil and in free air, respectively) and its relation to soil moisture is of great importance for describing and quantifying essential provisional and regulatory functions associated with terrestrial ecosystems such as soil aeration and greenhouse gas (GHG) emissions. Because gas migration in terrestrial soil systems is predominantly diffusion controlled, soil gas diffusivity becomes a fundamental prerequisite to quantify diffusive gas fluxes. Descriptive–predictive models are often used to estimate  $D_p/D_o$  from easily measurable soil physical properties. Most of the available models take the form of power-law functions and often tend to mischaracterize soil moisture effects at high moisture regimes. Based on a wide range  $D_p/D_o$  data available in literature representing both intact and repacked soils, this study developed a novel air-saturation-dependent exponential (ASEX) gas diffusivity model to model  $D_p/D_o$  in relation to soil air saturation. The model variable  $\alpha$ , which represents the diffusivity at half air saturation normalized by the same in complete soil air saturation, could potentially differentiate moisture effects on different soil structural states. For specific applications in intact soils, we propose corresponding  $\alpha$  values for upper-limit ( $\alpha = .6$ ) and lower-limit ( $\alpha = .05$ ) estimates of diffusivity, while an average value ( $\alpha = .3$ ) for general applications in both intact and repacked soils. As expected, our model based on a few a prior measured supportive data showed a better performance over the classical predictive models

that do not use such measurements. The new model was further used to derive useful implications to showcase soil density effects on  $D_p/D_o$ .

## **2. Impact of Water Management on Methane Emission Dynamics in Sri Lankan Paddy Ecosystems (in Press, *Water* journal)**

### Abstract

Paddy ecosystems constitute a dominant source of greenhouse gases, particularly of methane (CH<sub>4</sub>), due to the continuous flooding (CF) practiced under conventional paddy cultivation. A new management method, alternative wetting and draining (AWD) (i.e., flooding whenever surface water level declines to 15 cm below the soil surface) is an emerging practice developed to mitigate CH<sub>4</sub> emissions while providing an optimal solution for freshwater scarcity. Despite extensive paddy cultivation in Sri Lanka, no systematic research study has been conducted to investigate CH<sub>4</sub> emissions under different water management practices. Thus, field experiments were conducted in Sri Lanka to investigate the feedback of controlled water management on seasonal and diel variation of CH<sub>4</sub> emission, water consumption, and crop productivity. Adopting the same rice variety, two water management methods, continuous flooding (CF) and alternative wetting and draining (AWD), were compared under with plants (W/P) and without plants (N/P) present. Emission of CH<sub>4</sub> was measured using the static closed chamber method. Results show a 32% reduction of cumulative CH<sub>4</sub> emission, on average, under AWD when compared to CF. Yield under the AWD was slightly higher than that of CF. Although it was not statistically significant ( $p > 0.05$ ) there was not any reduction in yield than CF. The total water saving under AWD ranged between 27-35% when compared to CF. Thus, the results support (without considering nitrous oxide) AWD as a promising method for mitigating CH<sub>4</sub> emissions while preserving freshwater and maintaining grain yield in paddy systems.

Key words: Methane, Continuous flooding, Alternative wetting and draining, water consumption, crop yield

## **3. Soil-Gas Diffusivity-Based Characterization of Variably Saturated Agricultural Topsoils (Published in *Water* journal)**

### Abstract

Soil-gas diffusivity and its variation with soil moisture plays a fundamental role in diffusion-controlled migration of climate-impact gases from different terrestrial agroecosystems including cultivated soils and managed pasture systems. The wide contrast in soil texture and structure (e.g., density, soil aggregation) in agriculture topsoils (0–10 cm) makes it challenging for soil-gas diffusivity predictive models to make accurate predictions across different moisture conditions. This study characterized gas diffusivity and gas-phase tortuosity in soils sampled from managed pasture and cultivated sites in Sri Lanka at 0–10 cm depth, together with selected soil-gas diffusivity data from the literature. Soil-gas diffusivity

was measured using a one-chamber diffusion apparatus using N<sub>2</sub> and O<sub>2</sub> as experimental gases. The measured diffusivity, together with literature data representing both intact and repacked soils, were tested against five existing widely known gas diffusivity predictive models. The tested models tended to mischaracterize the two-region behavior in some of the aggregated soils, suggesting the need of soil-specific diffusivity models to better describe gas diffusivity in agricultural soils. We suggested a new parametric two-region model, developed in line with literature-based models, to represent both unimodal and bimodal/two-region behaviour of selected soils. The new model statistically outperformed the existing predictive models for both intact and repacked soils and, hence, demonstrated its applicability to better characterize site-specific greenhouse gas emissions under different soil water regimes.

Key words: agricultural topsoils, soil-gas diffusivity, gas phase tortuosity, soil-moisture effects, predictive–descriptive models

#### **4. Greenhouse gas emissions from Paddy ecosystem: impact of water regime, crop management, and nutrient management strategies. (Under review in Applied Biological Chemistry Journal)**

##### Abstract

Flooded paddy fields are implicated to be significant anthropogenic GHG source while they assume great importance due to the indispensability of rice as a staple food for over half of the global population. To address GHG emissions, specifically CH<sub>4</sub> and N<sub>2</sub>O during paddy cultivation, modifications in agronomic practices and their influencing factors are key and vary across the World. A comprehensive field experiment was conducted, encompassing diverse agronomic practices like continuous flooding and mid-season drainage, varying nutrient sources such as recommended dose of fertilizer (RDF) and organic matter (vermicompost), and identifying the role of exudates in appropriately laid out experimental plots with plots with and without plants. Meticulous monitoring of methane and nitrous oxide emissions throughout the crop season, coupled with detailed assessment of soil redox potential were undertaken to firstly show that continuously flooded plots without plants exhibited higher and consistent methane emissions compared to plots with plants. Mid-season drainage showed around ~30% reduction in methane emissions in all plots. An increase in N<sub>2</sub>O emissions was found in presence of plants suggesting a potential trade-off between these two GHGs. The complex interplay between diffusivity, tortuosity, and moisture levels was examined to gain deeper insights into their influence on GHG emissions, aiming to minimize the GHG released. This study unequivocally established that in the current single/double cropped puddled sandy-loams of South India, methane emission is an inherent characteristic of paddy soil, for which neither the added soil organic matter nor root exudates appear to form the key source for methane emissions. Midseason drainage, while adversely raising redox potential of paddy soils and reversing methane emissions, acts as a trigger for nitrous oxide emissions. Identifying methane substrates from such paddy fields can yield valuable scientific insights and can aid in GHG emission reducing agronomic options.

Key words: GHG, soil organic matter, root exudates, mid-season drainage, diffusivity, tortuosity

## **5. Assessing Greenhouse Gas Emission Levels in India and Global Perspectives: Insights and Mitigation Strategies (Under review in Current Science Journal)**

### Abstract

Implementing policies based solely on empirical data from emission factors can harm a nation's global reputation. This review highlights the importance of a comprehensive bottom-up data collection program for accurate evaluation of methane emissions. Despite India's GHG emissions being below IPCC values, reducing methane is crucial. Understanding the influencing factors is key to informed strategies and precise conclusions. Rigorous research considering local conditions is necessary to effectively mitigate methane emissions. Recognizing regional, production, and agricultural differences helps develop targeted policies. Analysing soil type, agronomic practices, land use, and climate provides insights to implement accurate mitigation strategies. In conclusion, relying on generic emission factors is inadequate for policy formulation. A comprehensive approach, backed by a well-designed data collection program, is needed for accurate assessments and informed decision-making. By adopting this approach, tailored strategies can effectively reduce GHG emissions, including methane, and enhance the nation's global standing.

Key words: Redox potential, anaerobic decomposition, submerged soil, base line emissions

## **6. Greenhouse Gas Emission Dynamics in Contrasting Paddy Cultivation: Assessing Varied Nutrient Supplementation Effects in Summer Paddy (Under internal review)**

### Abstract

The escalating concern over increasing greenhouse gas (GHG) emissions has globally prompted a meticulous examination of various sectors, with agriculture, particularly paddy cultivation, coming under scrutiny as a substantial anthropogenic source of these emissions. However, to thoroughly assess the validity of projected emission levels, empirical on-site reports are essential. The intricacies of GHG emissions are primarily shaped by the interplay between substrate availability and soil redox potential, a dynamic that exhibits both spatial and temporal fluctuations. Consequently, a comprehensive experiment was conducted, designed to contrast the outcomes of two distinct paddy cultivation methodologies: continuous flooding and aerobic cultivation. These practices were further supplemented with inputs in the form of synthetic fertilizers and combination of organic amendments, specifically vermicompost and synthetic fertilizers. The study's outcomes underscore that exclusively methane (CH<sub>4</sub>) emissions were promoted within the context of continuously flooded paddy soils, while solely nitrous oxide (N<sub>2</sub>O) emissions were detected in aerobic paddy cultivation. These discernible patterns can be largely attributed to the distinctive soil redox potential exhibited by each cultivation practice. Remarkably, the introduction of vermicompost, anticipated to exert a discernible influence on GHG emissions, yielded no statistically significant impact. The emission profiles of

both CH<sub>4</sub> and N<sub>2</sub>O remained within moderate ranges, substantiated by the interplay between soil redox potential and substrate availability that inherently governs the release of these GHGs. Crucially, the cumulative emissions as well as the associated global warming potential amplify the importance of CH<sub>4</sub> over N<sub>2</sub>O emissions in the context of paddy cultivation practices. These findings emphasize the critical role of environmental factors in mediating GHG dynamics and elucidate the necessity for precise and localized assessments when formulating mitigation strategies for the agricultural sector, particularly in paddy cultivation scenarios.

**Key words:** Redox potential, labile organic matter, continuously flooding, aerobic paddy.

## **7. Predicting soil gas diffusivity with varying degree of saturation. (Under internal review)**

### Abstract

The substantial volume of methane generated within the paddy soils through anaerobic methanogenic processes is subject to mitigation through oxidation by aerobic methanotrophic microorganisms. This methane oxidation phenomenon predominantly occurs within the oxic zones, at the interface of soil and water, and on root surfaces, all in the presence of oxygen. Methane oxidation is hindered by limited oxygen, making oxygen diffusion into paddy soils crucial for maximizing methane oxidation, serving as a natural CH<sub>4</sub> mitigation strategy. Soil porosity aids aeration through macro pores. When soil is waterlogged, it hinders gas exchange, acting as a barrier due to reduced air-filled spaces and increased tortuosity. Estimating the diffusivity ( $D_p/D_o$ ) becomes a practical challenge under high-moisture regimes. This variability arises from random moisture bridge formation in the soil matrix. To address this challenge, an experimental study was conducted to assess the soil gas diffusivity of soils with different textures under varying levels of saturation. The diffusivity was determined utilizing the Taylor and Currie method. The results of this investigation revealed that sandy loam soil exhibited the highest diffusivity, followed by sandy clay loam, loam, and clay loam soils. Achieving a balance between diffusivity values ranging from 0.005 to 0.01 and tortuosity values ranging from 5 to 7 can substantially increase gas retention time within the soil matrix. This extended retention time not only enhances methane oxidation but also reduces emissions of nitrous oxide, contributing to more sustainable agricultural practices.

**Key words:** Methane oxidation, soil porosity, diffusivity, tortuosity.

## **Appendix 4: Book Chapter (Published in Lecture Notes in Civil Engineering, Springer)**

### Abstract

Soil density plays an important role in regulating the migration of greenhouse gases from terrestrial soils to the atmosphere. Soil moisture is one of the main soil physical control determining the fate and transport of gases in soils. This study investigated the transport of methane (CH<sub>4</sub>) originating from a simulated CH<sub>4</sub> source within a variably compacted pasture soil. Simulations were carried out for dry and variably saturated soils. Steady-state methane

flow was simulated as a density-dependant, multiphase flow considering a multicomponent mixture of CH<sub>4</sub>, water vapour and air, under different soil moisture conditions. We used measured soil-water characteristic (SWC) and gas diffusivity data at five density levels (1.1, 1.2, 1.3, 1.4, and 1.5 Mg m<sup>-3</sup>) to parameterize predictive models. Permeability was estimated using an existing SWC-based saturated hydraulic conductivity function. Results show a distinct effect of soil density on CH<sub>4</sub> concentration profiles within the soil. Clear effects of soil moisture on CH<sub>4</sub> transport could also be seen in differentially compacted soils. Relatively smaller CH<sub>4</sub> concentrations were observed in dry soils where permeability, gas diffusivity and air-filled porosity were higher. With increasing density, the profile-accumulated concentrations > 0.3% increased up to 200 times under the dry condition. In moist soils, on the other hand, smaller air-filled porosity and higher moisture-controlled tortuosity resulted in reduced permeability and gas diffusivity, yielding high CH<sub>4</sub> concentrations in the soil profile with only a maximum five-fold increase in the accumulated concentration with increasing density.

Key words: soil-gas diffusivity, soil compaction, soil moisture, methane transport, numerical modelling

## Appendix 5: Thesis Article

### 1. Experimental and numerical investigation of greenhouse gas emissions from paddy ecosystems.

#### Abstract

Paddy ecosystems constitute a major source of greenhouse gases (GHG) dominated by methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). Typical water-logged conditions practiced in Sri Lanka favor simultaneous production of CH<sub>4</sub> and N<sub>2</sub>O in paddy fields. A wide range of atmospheric (e.g., temperature, soil moisture changes) and subsurface (e.g., soil type, soil organic carbon, soil redox status) variables play a vital role in production and diffusive transport of the gases. Net subsurface emission of GHGs across soil-plant-atmosphere continuum is controlled mainly by diffusion, expressed by soil-gas diffusivity ( $D_p/D_o$ ) which evaluates the ability of the porous media to facilitate diffusion-controlled gas movements. Typically,  $D_p/D_o$  is a function of air-filled porosity ( $\epsilon$ ), and gaseous phase tortuosity ( $\tau$ ). The presence of “critical windows of water and gas diffusivity” in paddy soils enables excessive emission of CH<sub>4</sub> and N<sub>2</sub>O from rice fields. Atmospheric emission of gases is regulated by soil and atmospheric controls and country-specific water management practices. This study investigated seasonal and diurnal variation of CH<sub>4</sub> and N<sub>2</sub>O emissions from paddy ecosystems under the emerging alternative wetting and drying (AWD) water management method as compared to the conventional continuously flooded water management. The local feasibility of AWD was studied in the light of water consumption and yield productivity. For diffusivity-based soil characterization, soils from Sri Lankan paddy sites, literature data on eight different agricultural locations in Denmark and pasture soil data at Duncan Block, New Zealand have been considered. Further, N<sub>2</sub>O flux measurements were carried out for paddy soils at Kurunegala, Sri Lanka and grazed pasture belongs to Lincoln University, New Zealand as laboratory based repacked samples. Measuring

$D_p/D_o$ , however, is instrumentally challenging due to the need of specific apparatus and careful control of initial and boundary conditions. Predictive models offer a convenient alternative to estimate  $D_p/D_o$  from easily-measurable properties such as airfilled porosity ( $\epsilon$ ,  $\text{cm}^3 \text{cm}^{-3}$ ) and total porosity ( $\Phi$ ,  $\text{cm}^3 \text{cm}^{-3}$ ). Modelling studies on  $D_p/D_o$  in literature are extensive and generally describe  $D_p/D_o$ - $\epsilon$  relation by means of power-law functions. Hence, a new gas diffusivity model, referred to as air-saturation-dependent exponential (ASEX) model which takes the effect of air saturation by a variable model parameter and thus accounts for moisture effects in structurally disturbed and undisturbed soils was developed. An ensemble of competing predictive models was compared statistically with the ASEX model to demonstrate the performance of the new model.

#### Appendix 6: List of young researchers

Name of young scientists	Institute	Country	Contact details
Ms. M M T Lakshani	University of Peradeniya	Sri Lanka	mmtharindilakshani@gmail.com
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#### Appendix 7: Conference Presentations

Topic	Author	Conference/Symposium/Seminar Name	Year
$\text{N}_2\text{O}$ emission dynamics in differently sized aggregates in agricultural soils	Ms. M M T Lakshani	8 <sup>th</sup> International Symposium on Advances in Civil and Environmental Engineering Practices for Sustainable Development ACEPS	2021
Density effects on soil gas diffusivity in agricultural soils	Ms. M M T Lakshani	IESL Young Member's Technical Conference	2021
Effects of soil moisture on simulated methane flow under varying levels of soil compaction	Ms. M M T Lakshani	12 <sup>th</sup> International Conference on Structural Engineering and Construction Management ICSECM	2021

Soil-gas diffusivity in pasture topsoil	Mr. A M S N Abeyasinghe and M.M.T Lakshani			12 <sup>th</sup> International Conference on Structural Engineering and Construction Management ICSECM	2021
Modeling soil gas diffusivity in undisturbed soils: A literature study.	Ms. M M T Lakshani			International Conference on Environmental Governance ICEG	2021
Comparison of Classical and Recent Predictive Models for Soil-Gas Diffusivity	Ms. M M T Lakshani			Jaffna University International Research Conference	2022
Nitrous Oxide Emission Dynamics in Sri Lankan Paddy soils under controlled water management	Ms. M M T Lakshani			XXI International N Workshop	2022
Seasonal Dynamics of Methane and Nitrous Oxide Emissions in Sri Lankan Paddy Soils Under Controlled Water Management	Ms. M M T Lakshani			AGU Fall Meeting	2022
Effect of mid-season drainage on greenhouse gas emissions from paddy ecosystems	Ms. M M T Lakshani			iLEAPS - OzFlux Joint Conference, Auckland	2023
Gas diffusivity-based characterization of paddy topsoils	Ms. M M T Lakshani			9 <sup>th</sup> International Symposium on Advances in Civil and Environmental Engineering Practices for Sustainable Development ACEPS	2023