# 2023作物永續栽培體系國際研討會論文輯

# Proceedings of International Conference on Cropping System for Sustainability

蘇致柔、林延諭、唐愷良、陳裕星、楊宏瑛 主編

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# 序

鑒於氣候變遷對環境及人類生存的威脅加劇，全球已有 130 多國宣示在 2050 年達成「淨零排放（Net Zero）」目標，這顯然需要政府的積極參與，更需要業界的創新思維和實踐。農業部自 2021 年 11 月起深入全國各縣市，邀請在地農民、農企業、農村社區、法人團體與官方機構進行交流討論，綜整歸納出減量、增匯、循環、綠趨勢等 4 大具體策略並據以實行。

基此，如何兼顧產業發展與環境維護，是我們必須要思考及執行的重點。在推動低碳生產技術時，亦需以自然生態為本，關注及改進各種生產管理，由生產到廢棄，以更高更廣角度，包括作物科學知識、水資源、土壤微生物、耕作制度、碳排監測等，達到淨零、永續、生產，三者不漏失的目標。淨零碳排不是農業的阻礙，是推動農業轉型與永續發展的契機。

「2023 作物永續栽培體系國際研討會」是以作物永續栽培為核心，本場邀請國內外專家學者進行交流討論，共同探討農業生產過程中的碳監測與減排技術、土壤及水資源之永續管理策略，同時也藉由展示各種耕作系統的成功案例，為提升農業生產韌性，實現永續發展目標提供有力的支持。本專刊集結本次研討會相關報告與現場討論資料，期能協助農業界因應淨零趨勢，並提升減排技術與資源管理知能。值此專刊出版之際，先進們能毫無藏私地提供寶貴的經驗與技術傳承，在此致上由衷謝忱。

臺中區農業改良場

場長 楊宏瑛 謹誌

中華民國 112 年 9 月

# 2023作物永續栽培體系國際研討會
## International Conference on Cropping System for Sustainability

時間 Date　2023 年 9 月 21 日 (21 September 2023)

地點 Venue　國立臺灣大學圖書館國際會議廳
International Conference Hall of National Taiwan University Library

| 議程 Agenda | | |
|---|---|---|
| 09:00~09:30 | 報到 Registration | |
| 09:30~10:00 | 開幕式及長官致詞 Opening and Welcome Remarks / 合照 Group Photo | |
| 主持人：農業部農業科技司 李紅曦司長<br>Chair: Director General Hung-Hsi Lee, Department of Agricultural Science and Technology, MOA | | |
| 10:00~10:30 | 利用區塊鏈技術監測水稻生產和認證中的溫室氣體排放<br>Monitoring Greenhouse Gas Emissions in Rice Production and Accreditation with Block-Chain Technology | 國立臺灣大學生物資源暨農學院林裕彬院長<br>Prof. Yu-Pin Lin. Dean, College of Bioresources and Agriculture, National Taiwan University |
| 10:30~11:00 | 氣候變遷下亞洲作物生產永續發展與資源管理<br>Sustainable Development of Crop Production and Resource Management under the Climate Changes in Asia | 日本京都大學縄田栄治教授<br>Prof. Eiji NAWATA. International Strategy Office, Kyoto Univ. ASEAN Center, Kyoto Univ., Japan |
| 11:00~11:30 | 作物低碳永續栽培的微生物解方 - 芽孢桿菌益生菌之多元應用<br>Microbial Based Solutions to Low Carbon Sustainable Crop Management - Multifunctional Bacillus-based Probiotics | 國立中興大學植病系黃姿碧教授<br>Prof. Tzu-Pi Huang. Dept. of Plant Pathology, National Chung Hsing University |
| 11:30~12:00 | 作物輪作：提高作物生產效率並最小化碳足跡的有效系統<br>Crop Rotation: An Effective System to Improve Crop Production Efficiency and Minimize C footprints. | 加拿大農部渥太華研究中心馬保羅博士<br>Dr. Bao-Luo Ma. Research Scientist, Ottawa Research and Development Centre, Agriculture and Agri-Food Canada, Canada |
| 12:00~13:30 | 綜合座談與午餐 Plenary Discussions & Lunch | |

| 節次 A：循環農業與稻作栽培<br>Session A: Circular Agriculture and Rice Cultivation<br><br>主持人：國立臺灣大學生物資源暨農學院 林裕彬院長<br>Chair: Prof. Yu-Pin Lin. Dean, College of Bioresources and Agriculture, National Taiwan University | | |
|---|---|---|
| 13:30~13:50 | 循環農業在臺灣的機會與挑戰<br>Opportunities and Challenges of Circular Agriculture in Taiwan | 國立中興大學土壤環境科學系高培慈助理教授<br>Dr. Pei-Tzu Kao. Dept. of Soil and Environmental Sciences, National Chung Hsing University |
| 13:50~14:10 | 作物模式應用於水稻灌溉策略之研擬<br>Application of Crop Model in Planning Rice Irrigation Strategy | 國立臺灣大學農藝系劉力瑜教授<br>Prof. Li-yu Liu. Dept. of Agronomy, National Taiwan University |
| 14:10~14:30 | 應用 DNDC 模擬作物生育與溫室氣體排放<br>Modeling of Crop Growth and GHG Emission by DNDC | 農業試驗所農業化學組陳柱中副研究員<br>Mr. Chu-Chung Chen. Associate Researcher, Division of Agricultural Chemistry, Taiwan Agricultural Research Institute |
| 14:30~14:50 | 水稻減碳生產技術策略<br>Reducing of Greenhouse Gas Emission in Paddy Rice through Precision Irrigation and Culture Practices | 臺中區農業改良場吳以健博士<br>Dr. Yi-Chian Wu. Taichung District Agricultural Research and Extension Station |
| 14:50-15:10 | 休息 Coffee Break | |

| 節次 B：灌溉管理與耕作模式<br>Session B: Irrigation Management and Cropping Pattern<br><br>主持人：農業部國際事務司 林家榮司長<br>Chair: Director General Vincent Lin, Department of International Affairs, MOA | | |
|---|---|---|
| 15:10~15:30 | 利用共生微生物提高作物的用水效率：耕作系統中水管理的潛在永續方法<br>Improvement of Water-Use Efficiency of Crops using Symbiotic Microorganisms: A Potential Sustainable Approach to Water Management in Cropping Systems | 國立臺灣大學園藝暨景觀學系盧炯敏助理教授<br>Dr. Hyungmia Rho. Dept. of Horticulture and Landscape Architecture, National Taiwan University |
| 15:30~15:50 | 永續設施生產：水養液有效利用零滲漏策略<br>Sustainable Greenhouse Production - Strategy to Efficient Water Utilization with Zero Emission | 臺中區農業改良場陳葦玲博士<br>Dr. Wei-Ling Chen. Taichung District Agricultural Research and Extension Station |
| 15:50~16:10 | 因應氣候變化下西南沿海農業區的耕作模式設計<br>Cropping Pattern Design in Southwestern Coastal Agricultural Areas in Response to Climate Change | 農業試驗所農業化學組江志峯助理研究員<br>Mr. Chih-Feng Chiang. Assistant Researcher, Division of Agricultural Chemistry, Taiwan Agricultural Research |
| 16:10~16:30 | 花蓮地區有機雜糧耕作模式介紹<br>Introduction to Organic Cultivation of Upland Crops in Hualien | 花蓮區農業改良場陳緯宸助理研究員<br>Mr. Wei-Chen Chen. Hualien District Agricultural Research and Extension Station |
| 16:30~16:50 | 綜合討論 Discussions | |

# 目　錄

# 區塊鏈技術應用於稻米生產過程之溫室氣體排放

林裕彬 [1*]

## 摘要

2022 年聯合國氣候變遷專門委員會 (IPCC) 發布第六次評估報告 (AR6) 指出，目前全球升溫已來到 1.07˚ C，唯有全球碳排量減半才能有機會達到《巴黎協定》中設定之 1.5℃目標，因此國際間已有逾 130 國響應 2050 年淨零排放 (Net Zero)，並各自承諾減排目標。根據全球食品排放數據庫 (EDGAR-FOOD) 估算 1990 年至 2015 年間的溫室氣體 (CO2、CH4、N2O、氟化氣體 ) 排放分布，其中糧食系統排放量達到每年 18 億噸二氧化碳當量，佔總溫室氣體排放量的 34%，而貢獻最多為農業活動和土地利用 (71%)。我國之農業淨零策略以減量、增匯、循環及綠趨勢為方向，因此本研究應用區塊鏈具可追蹤 (Traceability)、不可修改 (Unmodifiable)、去中心化 (Decentralization) 等特性，記錄不同農業耕作系統之活動紀錄與相關農業溫室氣體排放、土壤碳匯至農業剩餘資源循環之量測數據，整合建構一具有透明性、完整性、準確性與一致性之綠色知識區塊鏈履歷追蹤系統。

**關鍵詞：**溫室氣體、淨零碳排、產銷履歷、土壤碳匯、區塊鏈

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# Monitoring greenhouse gas emissions in rice production and accreditation with block-chain technology

Yu-Pin Lin [1]*

## Abstract

The Intergovernmental Panel on Climate Change (IPCC) released its Sixth Assessment Report (AR6) in 2022, stating that global warming has reached 1.07 ° C. It emphasized that global carbon emissions need to be halved to have a chance of achieving the 1.5° C target set in the Paris Agreement. As a result, over 130 countries have committed to achieving net-zero emissions by 2050, each setting their own reduction targets.

According to the Emissions Database for Global Atmospheric Research (EDGAR-FOOD), greenhouse gas emissions (GHG, $CO_2$, $CH_4$, $N_2O$, fluorinated gases) from the food system accounted for 1.8 billion tons of CO2 equivalent annually between 1990 and 2015, constituting 34% of total GHG emissions. The agricultural activities and land use contributed the most to these emissions (71%).

In response, our country has formulated an agricultural net-zero strategy focusing on reduction, enhancement, circularity, and green trends. To address this, the present study utilizes blockchain technology with features such as traceability, immutability, and decentralization. It records activity logs of various agricultural cultivation systems, related agricultural GHG emissions, soil carbon sequestration, and measurements of residual resources in the agricultural cycle. This integration aims to establish a green knowledge blockchain ledger tracking system characterized by transparency, completeness, accuracy, and consistency.

**Keyword:** Greenhouse gas, Net-zero, Traceability, Soil carbon sequestration, Blockchain

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# Sustainable development of crop production under the climate changes in Asia

Eiji NAWATA[1]*

## Abstract

For the future food security, the status of world crop production must be carefully monitored. At present, the negative impacts of climate changes are anticipated to give adverse influences on agricultural production. In this study, the present status of the crop production in the world and tropics was studied in comparison to the recent past and the tendencies were analyzed. The tropics have increased the importance in the world agricultural production and special attentions were given to the production in the tropics. Recently, world 3 major cereals production has been high and stable. Annual production in recent several years could feed more than 10 billion people if all the harvested crops were delivered fairly and equally and consumed for food only. This stably large production has been realized by the development of agricultural technologies, farm management improvement, cropping systems optimization, etc. General stability of the society in the world may have contributed too. Based on the agricultural statistics of recent several decades, the causes of the present high crop productivities and future prospect of world food production is discussed.

**Keyword:** Energy consumption, Major cereals, Positive impacts, Sugarcane, Tropics

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# Introduction

The adaptation to the climate change, or global warming is one of the biggest challenges, now we are facing. Global surface temperature at present was 1.09 ºC higher than 1950-1900 period according to IPCC (2023) and this trend may continue unless appropriate measures are taken. Global warming has caused many weather and climatic extremes in every region across the world (IPCC, 2023), and may have given adverse effects on various aspects of our activities, including agriculture. Recently, the occurrences of the climatic events have been reported frequently in many areas in the world, such as drought and heat wave, torrential rain and resulting flood, etc. These climatic events may have negative impacts on agricultural production, and they are frequently reported recently (IPCC, 2023).

On the other hand, overall agricultural production has increased under such circumstances as shown by world agricultural statistics (e.g. FAOSTAT). There are various factors, which contribute to the present stable and high agricultural production of the world under the progress of global warming, such as the development of agricultural technologies and stabilization of the public order in many areas. One of them may be positive impacts of global warming on agricultural production. In this paper, these factors are discussed later in details.

The studies on the impacts of global warming on agricultural production have been tended to focus on the agricultural activities in the temperate areas, because the temperate areas are major crop production sites in the world, even though many crops including rice, maize and sugarcane are tropically originated. This is also because in the tropics air temperatures are originally high and the increase in air temperatures may not have caused direct large influences. Recently, however, the crop productivity in the tropics have been rapidly increased, as shown later in this paper and the importance of crop production in this area is increasing. In addition, the instability of rainfall, frequent occurrence of climatic events, such as drought and flood, has been reported recently in the tropics (IPCC, 2023). It is prerequisite for more studies on the impacts of climate changes on agricultural production in the tropics.

This paper aims to describe the present status of world major crop production, analyze the factors which contribute to the present stable and large crop production, and discuss the future prospect of world crop production and measures to mitigate negative impacts of climate changes. Major concerns are placed on those in the tropics.

## Material and Methods

Statistical data on agricultural production and fertilizer use were collected from FAO websites (FAOSTAT). Production (t), cultivated area (ha) and yield (t/ha) of 4 major crops, i.e. bread wheat, rice, maize and sugarcane, in the world and tropics, were collected during these 30 years. Three major cereals were selected due to its importance as staple food crops in many parts of the world and it is very convenient for discussing world food security. Sugarcane was selected for its importance in tropical areas. Collected data were analyzed for the long-term changes, stability, comparison among areas. The contribution of the tropics to world crop production was analyzed, and especially ASEAN areas were mainly focused on for the analysis.

## Results and Discussion

### 1. 3 major cereals

Recent trends of the production of major 3 cereals (rice, maize and bread wheat) in the world are shown in Fig. 1. In these 3 decades, world 3 major cereals production has increased from ca. 1.5 billion tons to ca. 2.7 tons, although the cultivating area did not show conspicuous changes. The present world cereal production is huge. If the annual consumption of 3 major cereals per capita is assumed to be ca. 200 kg, which is a rough estimate of the consumption of 3 major cereals of Japanese for these 10 years, this amount could have feed more than 12 billion people. In addition, the world 3 major cereals production in recent years has been very stable (Fig. 2), even though recent increase in climatic events, such as drought and flood, probably due partly to the adverse influences of global warming. During the period from 2014 to 2016, large scale El Nino phenomenon occurred and the agricultural damages caused by drought and flood, or other environmental stresses were frequently reported in many areas in the world (IPCC, 2023).

These recent high and stable cereal production may have been realized by the development of agricultural science and technology, such as high yielding varieties, fertilizer application technologies, plant protection technologies, irrigation & drainage technologies, agricultural machineries, etc. Other factors, like economic development and general social stability in many countries and regions may also contribute to these high and stable crop production. In this regard, recent expansion of COVID-19 and its adverse impacts on economic activities may have caused serious influences on world cereal production, although at least the production in 2020 and 2021 was not much reduced. Russian invasion to Ukraine in early 2022 had very serious impacts on the world food supply chain, and it is considered that the production may also have been heavily influenced adversely, but at present, world agricultural statistics is not available and its impacts on the world production of major cereals is not known yet.

Fig. 3 shows the production of maize and rice of the world, tropics and Southeast Asia during these 3 decades. The world maize production increased by 2.4 times during this period, but that of the tropics increased by 4.2 time and that of Southeast Asia by 3.2 time. The world maize production increase was remarkable, but that of the tropics and Southeast Asia is even more remarkable. The increase in the rice production was also observed, but the extent of the increase was less than that in maize. The increase in the rice production in the tropics and Southeast Asia was a little bit more appreciable. Anyway, these data suggested that the tropical areas, including Southeast Asia, recently have increased the contribution to world cereal production.

In Southeast Asian countries, what kind of trends were seen in major cereals production? Table 1 shows the production of maize and rice in major producers in Southeast Asia during these 3 decades. In maize production, all countries except for Thailand showed large increase during these 3 decades. Thailand maintained already high maize production during this period.

Major countries in Southeast Asia also increased rice production, although the extent of the increase is smaller than that of maize. Thailand showed the increase, but the extent of the increase is smaller than that of Vietnam, Myanmar and the Philippines. It is generally accepted that Thailand has more producing potential of rice, and the production of rice in Thailand is seriously affected by price and government policy (Poramacom, 2014).

To these large increases, the improvement of the productivities has contributed in both crops (Table 2). In maize, all the countries showed large increases in the productivity. In rice, the same trend was observed, but the extent of the increase was smaller than that in maize. It is pointed out that rice productivity in Thailand is lower than that of the other countries. It may be due to low rice yield in Northeast Thailand. Because of the lack of irrigation facility and the prevailing sandy soils, which is characterized by their low water holding capacity and poor nutrition, the productivity of rice in that area is generally low and unstable (Kono et al., 2001). In addition, paddy fields in this area occupies 40% of total paddy fields of Thailand, causing the reduction in the rice productivity of Thailand.

Just like the trend of the world production of maize and rice, the production of both crops was stable during the period from 2015 to 2019, in which most countries show low C.V. (the coefficient of variance) (Table 3). Only one exception with a high value of C.V. is the maize production in Indonesia, but the large C.V. value was due to its increase with a large extent and not caused by the fluctuation of the production. It can be concluded that the production of 2 major cereals in Southeast Asia is stably high recently and have contributed to world food production in a relatively large extent. It can be also said that the presence of Southeast Asia in the world maize and rice production is steadily larger and this trend may continue, unless unexpected events occur.

## 2. Sugarcane

Fig. 4 shows the recent trends of the production of sugarcane in the world. In these 3 decades, world sugarcane production has increased from ca. 1 billion tons to ca. 2 billion tons, by twice with the increase in the harvested area. In addition, sugarcane production in recent years has been very stable (Fig. 5), just like 3 major cereals, even though recent increase in climatic events. As stated in the last section, during the period from 2014 to 2016, large scale El Nino phenomenon occurred and the agricultural damages caused by drought and flood, or other environmental stresses were frequently reported in many areas in the world.

These recent high and stable sugarcane production may have been realized by the development of agricultural science and technology, such as breeding high yielding varieties, fertilizer application technologies, plant protection technologies, irrigation & drainage technologies, agricultural machineries, etc., just like 3 major cereals. In addition, sugarcane is known to be very tolerant to various environmental stresses, such as drought, high temperature and waterlogging (Ferreira et al., 2017). These traits may contribute to the stable production of this crop during these several years. Of course, other factors, like economic development and general social stability in many countries and regions may also contribute to these high and stable production just like 3 major cereals shown in the previous section. Recent expansion of COVID-19 and its adverse impacts were also expected to occur, but at least in 2020 and 2021, the conspicuous changes of the production were not known. The influences of the Russian invasion to Ukraine are also anticipated, but most of sugarcane producing countries are located in tropical areas and the direct influences are considered to be limited, although the price increase of fertilizers and fuels (for agricultural machineries and transportations) may have given some adverse effects.

Fig. 6 shows the production of sugarcane of the world, tropics and Southeast Asia during these 3 decades. The world production increased by 1.9 times during this period, and that of the tropics by 2.2 times and that of Southeast Asia by 2.1 times. Considering the fact that most of the sugarcane production is done in the tropics, it is not surprising that the increase rate is not very different between that of world and tropics. Still, the increases in the sugarcane production in these 30 years are large, and the contribution of the development of agricultural technologies must be high.

Fig. 6 shows stable increase in sugarcane production in Southeast Asia, but in each country in this area what kind of trend was observed? Table 4 shows the production of sugarcane in major producers in Southeast Asia during these 3 decades. All countries in mainland Southeast Asia showed large increases in sugarcane production during these 3 decades. Thailand showed 3.6 times increase during this period and in 2019 the production exceeded 130 million t per year. Although Myanmar showed 5.1 times increase, the production was about 12 million t per year. Similarly, Vietnam showed 2.9 times increase, but the total production was rather limited. Table 4 showed that Thailand is the leading producer of sugarcane in this area and occupied more than 80% of the sugarcane production in mainland Southeast Asia. In insular Southeast Asia, Indonesia and Philippines are major producers of sugarcane. Indonesia showed a slight increase in these 30 years, and Philippines showed a decrease. As a result, the sugarcane production in this area, which was similar to that of mainland Southeast Asia 30 years ago, was much less than that in 2019. The causes of the lack of increase in Indonesia and Philippines are not clear, but both countries are rice importers and the demand of rice production is large. It is considered that the farmland allocation and/ or farmers intension to sugarcane cultivation is rather restricted, in comparison to rice. On the contrary, Thailand is a large rice exporter and farmers may have options to select sugarcane instead of rice or upland crops. Sugarcane is tolerant to wetland conditions to some extent, and the conversion from paddy fields to sugarcane fields is not very difficult.

In Mainland Southeast Asia, to large increases of sugarcane production, the improvement of the productivities may have contributed (Table 5). The productivity of sugarcane was 1.3 to 1.6 times larger than those of 30 years ago in this area, although the increases in the production were much larger than that of the productivity, suggesting the production area increased in these 30 years in this area. On the contrary, in Insular Southeast Asia, the productivity was not improved or reduced. The reason is not clear, but agricultural investment to sugarcane production may have been restricted to some extent.

Just like the trend of the world production of sugarcane, the production of sugarcane was stable or stably increased during the period from 2015 to 2019, in which most countries showed low C.V. (the coefficient of variance) (Table 6), with the exceptions of Vietnam and Philippines in 2019. Although a high value of C.V. was shown in the production in Thailand, the large C.V. value was due to its increases of recent 2 years with a large extent and not caused by the big fluctuations of the production during these 5 years. The causes of the abrupt reductions in the production in 2019 in Vietnam and Philippines are not clear, and further investigations are necessary. Recent increase in the production in Thailand may be caused by the changes of the Government policy on sugarcane price, but the details are not known.

## 3. Future prospect

As shown in the former sections, the present world agricultural production is large and stable, even though the influence of global warming is becoming apparent in recent years. During this period, world population has increased by 1.45 times (from 5.24 billion in 1989 to 7.63 billion in 2019), whereas those of southeast Asia 1.52 times (0.432 billion to 0.656 billion). It seems that the improvement of world agricultural productivities satisfies the increase in the world food demand at present. As previously stated, the development of agricultural technologies may have largely contributed to the present high and stable agricultural production. For example, Fig. 7 shows the changes of the world N fertilizer use during these 30 years. The world N fertilizer use has been increased from ca. 79 million t in 1989 to 105 million t in 2019 by 1.33 times. In the tropics and Southeast Asia, the increment was larger than that, 2.49 and 2.34 times, respectively. Other fertilizers showed similar tendencies (data not shown). Recently, crop cultivation management has been developed, with the optimization of the cropping systems, adapting to local environment. The agricultural fields have been well managed with the efforts of farmers, researchers and public or private agricultural extension workers. The irrigation systems have been gradually developed, although in some areas, full irrigation system development is still difficult. The recent developments of agricultural machineries may have promoted the improvement of crop productivities in various areas in the world. Effective plant breeding could have produced many new varieties by not only conventional methods, but also molecular breeding (Lenaerts et al., 2019).

As another factor, the stability of the world society and good public order in general may have contributed to the present status of crop production. To apply the outcomes of the improvement of agricultural research to actual production, the stability of the society are indispensable. During recent 3 decades, the world is generally stable and peaceful, and this is one of the important factors for the world high and stable agricultural production. In this meaning, we need to carefully observe the effects of what happens in Ukraine at present.

In addition to the above factors, we need to consider the positive impacts of climate changes. Although negative impacts of climate changes on agricultural production have been emphasized, we should recognize that there are several positive influences of climate changes. Within a certain range of the temperature, global warming accelerates photosynthetic activities of crops in line with a rise of atmospheric $CO_2$. As the respiration activities of crops also increase, the net productivities reach the maximum at a certain threshold temperature, depending on crop species. When the temperature is lower than this threshold, the higher the temperature, the higher the net photosynthetic activity. Another positive impact is the expansion of cultivated area to higher latitude or altitude. Recent increase in the cultivated area of each crop is partly due to the expansion of cultivated area to higher latitude or altitude areas. Global warming may have induced the extension of cropping season. Air and soil temperature rise enables early planting and late harvest. The extension of cropping period may allow farmers to use more productive late varieties and more flexible cropping systems.

Another important positive impact of global warming is the expansion of cultivation of highly productive tropical crops ($C_4$ plants) to higher latitude and altitude areas. Many domesticated plants originated in tropical areas, such as maize and sugarcane, have $C_4$ photosynthetic pathway and are known to be highly productive, although their advantages are decreasing due to the rise of atmospheric $CO_2$ concentration. Recent increases in the production of maize and sugarcane may be partly due to this factor.

Although we understand that recent crop production is high and stable, does this trend continue? Are there no worries about future food security? Unfortunately, answers to these questions are "No". There are many problems to threaten the present agricultural productivities and production systems.

The first problem is direct negative impact of climate changes. At present, it seems positive impacts exceed negative ones, but soon the negative impacts may overtake the positive ones. Climatic events like drought, extreme heat and flooding are more frequent than the recent past (IPCC, 2023) and this trend will continue. Rainfall is more instable, and the crop season is more unstable together with more frequent climatic events and natural disasters. If the temperature rise cannot be suppressed, the air temperature exceeds the threshold for maximum net photosynthesis for many crops. The temperature rise causes not only the reduction in quantitative productivities, but also adverse influences on crop growth, such as the failure in flower bud initiations in some crops (Craufurd & Wheeler, 2009, Krishna Jagadish, 2020). It is rather difficult to predict when the negative impacts exceed the positive ones, but it is not distant future unless further development of agricultural technologies and appropriate measures to suppress the global warming are taken.

Another big issue is energy consumptions for the agricultural production. The present high and stable productivities are highly dependent on the energy consumption. At actual cultivation in the modern agriculture, it is prerequisite to use agricultural machines, which consume much energy and the use of the machine is quickly extended including the tropics. The production of agricultural chemicals, i.e. chemical fertilizers, pesticides and herbicides, consume a lot of energy. Postharvest treatments essential for commercialized agriculture need large amounts of energy. In some of horticultural production, tremendous energy is consumed for the environmental control. Even, new variety development needs a large amount of energy. Table 7 shows the ratio of input energy to the energy outputs in Japanese agriculture (Yoshimoto & Ogimoto, 1994). This table shows that modern agriculture must consume energy with concrete examples. But energy is not infinite.

Although the above issues are difficult challenges to be solved, we need to make efforts to deal with them and many researchers, farmers and related stakeholders are actually accumulating efforts to do so. In order to adapt the agricultural technologies to the climate changes, new cultivation systems are necessary, which include new variety development, new cultivation management, and new cropping system development. As repeatedly stated, recently the frequency of the climatic events like drought, extreme heat and flooding are increasing. New varieties tolerant to these environmental stresses are necessary. In addition, cultivation management to avoid damages from these stresses must be developed, such as technologies to avoid sensitive stages of crop growth from high frequency period of climatic events. This can be enabled by introducing new cropping systems and/or the adaptive genotypes together with the weather simulation technologies. Smart agriculture can optimize the cultivation of crops under new environment caused by the climate changes (Lipper et al., 2014). Smart agriculture is also effective for the energy saving cultivation (Bandur et al., 2019). The development of energy saving new varieties are also necessary.

Of course, population growth is a big problem for world future food security. Although the world population growth is less worried than the past, due to the economic development of some populated countries and resulting reduction in the rate of population growth, this is still a big issue, especially in rapidly developing countries in the tropics. As described previously, social stability and overall peaceful world is a necessary condition for the stable agricultural production. At present, large-scale conflicts produces an instable world status and the food systems are deeply and seriously damaged. Although the present crop production is stably high, there are always some famines somewhere in the world, indicating the lack of the appropriate distribution systems of food. These issues are also big challenges for future food security, but they are multidisciplinary issues and cannot be solved by efforts of only agricultural researchers and farmers. Dialogues among various stakeholders including policy makers are indispensable.

## Conclusion

In this study, based on the world agricultural statistics, the present status of world important crop production was analyzed, and it was shown that the world crop production at present is high and stable. Various factors may have contributed to the high and stable productivity of crop production including agricultural technology development. There is a possibility that the positive impacts of climate changes may have appeared at this stage of global warming. Although the present 3 major cereal crop production can feed more than 10 billion people, present world food systems failed to feed all the people in the world. In the near future, negative impacts of climate changes may overtake positive ones and we need to prepare for that. The consumption of huge amount of energy for agricultural production is another big issue for the future agricultural production. These issues are so-called grand challenges for all of us, and multidisciplinary and multilateral collaborations are necessary for the future stable agricultural production.

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**Table 1　Crop production of Southeast Asia during these 30 years.**

a) maize (million t, except "2019/1989" rows, whose values are unitless)

| Year | Mainland | | | | Insular | | |
|---|---|---|---|---|---|---|---|
| | Myanmar | Thailand | Vietnam | Total | Indonesia | Philippines | Total |
| 1889 | 0.19 | 4.39 | 0.84 | 5.52 | 6.19 | 4.52 | 10.81 |
| 1999 | 0.34 | 4.29 | 1.75 | 6.57 | 9.20 | 4.58 | 13.92 |
| 2009 | 1.23 | 4.62 | 4.37 | 12.27 | 17.63 | 7.03 | 24.83 |
| 2019 | 1.99 | 4.31 | 4.76 | 13.18 | 30.69 | 7.98 | 38.80 |
| 2019/1989 | 10.25 | 0.98 | 5.68 | 2.39 | 4.96 | 1.76 | 3.59 |

b) rice (million t, except "2019/1989" rows, whose values are unitless)

| Year | Mainland | | | | Insular | | |
|---|---|---|---|---|---|---|---|
| | Myanmar | Thailand | Vietnam | Total | Indonesia | Philippines | Total |
| 1889 | 13.81 | 20.60 | 19.00 | 57.48 | 44.73 | 9.46 | 55.97 |
| 1999 | 20.13 | 24.17 | 31.39 | 81.83 | 50.87 | 11.79 | 64.72 |
| 2009 | 32.17 | 32.40 | 38.95 | 114.24 | 59.01 | 16.27 | 77.91 |
| 2019 | 26.27 | 28.36 | 43.45 | 112.40 | 54.60 | 18.81 | 76.41 |
| 2019/1989 | 1.90 | 1.38 | 2.29 | 1.96 | 1.22 | 1.99 | 1.37 |

**Table 2　Crop yield of Southeast Asia during these 30 years.**

a) maize (t/ha, except "2019/1989" rows, whose values are unitless)

| Year | Mainland | | | | Insular | | |
|---|---|---|---|---|---|---|---|
| | Myanmar | Thailand | Vietnam | Total | Indonesia | Philippines | Total |
| 1889 | 1.58 | 2.57 | 1.64 | 1.67 | 2.10 | 1.23 | 1.60 |
| 1999 | | 3.55 | 2.53 | 2.35 | 2.66 | 1.74 | 1.95 |
| 2009 | 3.38 | 4.18 | 4.01 | 4.24 | 4.24 | 2.62 | 3.45 |
| 2019 | 3.85 | 4.50 | 4.80 | 4.64 | 5.44 | 3.17 | 4.81 |
| 2019/1989 | 2.44 | 1.75 | 2.92 | 2.78 | 2.59 | 2.59 | 3.01 |

b) rice (t/ha, except "2019/1989" rows, whose values are unitless)

| Year | Mainland | | | | Insular | | |
|---|---|---|---|---|---|---|---|
| | Myanmar | Thailand | Vietnam | Total | Indonesia | Philippines | Total |
| 1889 | 2.92 | 2.09 | 3.21 | 2.40 | 4.25 | 2.70 | 2.88 |
| 1999 | 3.24 | 2.42 | 4.10 | 2.93 | 4.25 | 2.95 | 2.66 |
| 2009 | 3.99 | 2.91 | 5.24 | 3.76 | 5.01 | 3.59 | 3.19 |
| 2019 | 3.80 | 2.92 | 5.82 | 4.11 | 5.11 | 4.04 | 3.71 |
| 2019/1989 | 1.30 | 1.40 | 1.81 | 1.71 | 1.20 | 1.50 | 1.29 |

**Table 3　Crop production of Southeast Asia during these 5 years.**

a) maize (million t, except "C. V." rows)

| Year | Mainland | | | | Insular | | |
|---|---|---|---|---|---|---|---|
| | Myanmar | Thailand | Vietnam | Total | Indonesia | Philippines | Total |
| 2015 | 1.75 | 4.73 | 5.29 | 13.68 | 19.61 | 7.52 | 27.34 |
| 2016 | 1.83 | 4.39 | 5.24 | 13.68 | 23.58 | 7.22 | 30.96 |
| 2017 | 1.91 | 4.82 | 5.11 | 13.78 | 28.92 | 7.91 | 36.99 |
| 2018 | 1.98 | 5.07 | 4.87 | 14.14 | 30.25 | 7.77 | 38.18 |
| 2019 | 1.99 | 4.31 | 4.76 | 13.18 | 30.69 | 7.98 | 38.80 |
| C.V.* | 5.4% | 6.7% | 4.6% | 2.5% | 18.2% | 4.1% | 14.7% |

b) rice (million t, except "C. V." rows)

| Year | Mainland | | | | Insular | | |
|---|---|---|---|---|---|---|---|
| | Myanmar | Thailand | Vietnam | Total | Indonesia | Philippines | Total |
| 2015 | 26.21 | 27.70 | 45.09 | 112.44 | 61.03 | 18.15 | 82.00 |
| 2016 | 25.67 | 31.86 | 43.11 | 114.74 | 59.39 | 17.63 | 79.82 |
| 2017 | 26.55 | 32.90 | 42.76 | 116.77 | 59.43 | 19.28 | 81.34 |
| 2018 | 27.57 | 32.35 | 44.05 | 118.44 | 59.20 | 19.07 | 80.96 |
| 2019 | 26.27 | 28.36 | 43.45 | 112.40 | 54.60 | 18.81 | 76.41 |
| C.V. * | 2.6% | 7.9% | 2.1% | 2.3% | 4.1% | 3.7% | 2.8% |

* C. V. stands for coefficient of variance.

**Table 4　Sugarcane production of Southeast Asia during these 30 years (million t, except "2019/1989" rows, whose values are unitless).**

| Year | Mainland | | | | Insular | | |
|---|---|---|---|---|---|---|---|
| | Myanmar | Thailand | Vietnam | Total | Indonesia | Philippines | Total |
| 1989 | 2.35 | 36.67 | 5.34 | 44.36 | 26.81 | 25.26 | 52.08 |
| 1999 | 5.36 | 50.33 | 17.76 | 73.46 | 23.50 | 23.78 | 47.28 |
| 2009 | 9.56 | 66.82 | 15.61 | 91.99 | 26.40 | 22.93 | 49.33 |
| 2019 | 11.85 | 131.00 | 15.27 | 158.12 | 29.10 | 20.72 | 49.82 |
| 2019/1989 | 5.05 | 3.57 | 2.86 | 3.56 | 1.09 | 0.82 | 0.96 |

**Table 5　Sugarcane yield of Southeast Asia during these 30 years (t/ha, except "2019/1989" rows, whose values are unitless).**

| Year | Mainland | | | | Insular | | |
|---|---|---|---|---|---|---|---|
| | Myanmar | Thailand | Vietnam | Average | Indonesia | Philippines | Average |
| 1989 | 48.68 | 55.60 | 40.37 | 48.22 | 78.88 | 96.52 | 87.70 |
| 1999 | 42.75 | 54.86 | 51.60 | 49.73 | 60.09 | 58.85 | 59.47 |
| 2009 | 60.58 | 69.34 | 58.77 | 62.90 | 59.80 | 56.76 | 58.28 |
| 2019 | 65.03 | 71.39 | 65.43 | 67.28 | 70.97 | 54.63 | 62.80 |
| 2019/1989 | 1.34 | 1.28 | 1.62 | 1.40 | 0.90 | 0.57 | 0.72 |

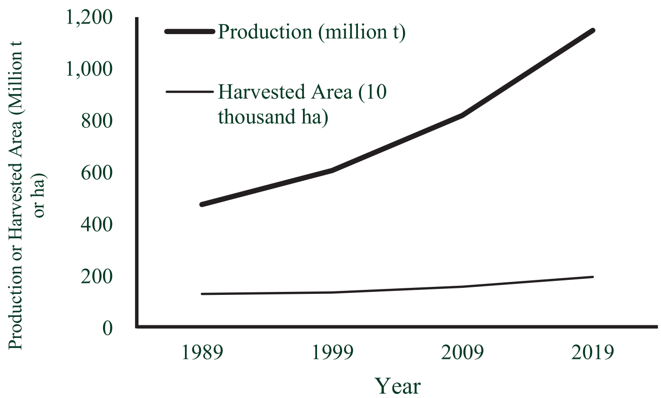
**Table 6 Sugarcane production of Southeast Asia during these 30 years (million t, except "C. V." rows).**

| Year | Mainland | | | | Insular | | |
|---|---|---|---|---|---|---|---|
| | Myanmar | Thailand | Vietnam | Total | Indonesia | Philippines | Total |
| 2015 | 10.14 | 94.14 | 18.34 | 122.62 | 27.00 | 22.93 | 49.93 |
| 2016 | 10.44 | 94.14 | 16.31 | 120.89 | 28.00 | 22.37 | 50.37 |
| 2017 | 10.37 | 93.09 | 18.36 | 121.81 | 28.00 | 29.29 | 57.29 |
| 2018 | 11.40 | 135.07 | 17.95 | 164.42 | 29.50 | 24.73 | 54.23 |
| 2019 | 11.85 | 131.00 | 15.27 | 158.12 | 29.10 | 20.72 | 49.82 |
| C.V. | 6.8% | 19.7% | 8.0% | 15.8% | 3.5% | 13.7% | 6.3% |

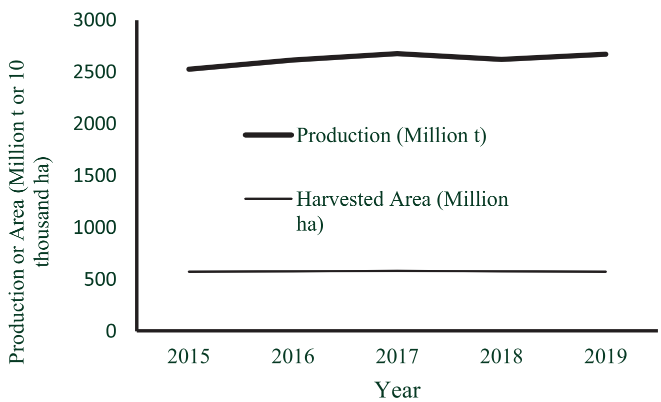
**Table 7 The ratios of input energy against calorific value of food in Japan***

| Ratio of input energy against calorific value | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Food | | | | | | | | | | | |
| Rice | Wheat | Potato | Legume | Fruit | Leafy Vegetable | Spirit | Fish | Meat | Egg | Milk | Fat |
| 0.89 | 0.66 | 0.18 | 0.8 | 2.93 | 3.85 | 0.51 | 3.25 | 2.38 | 1.75 | 1.9 | 1.3 |

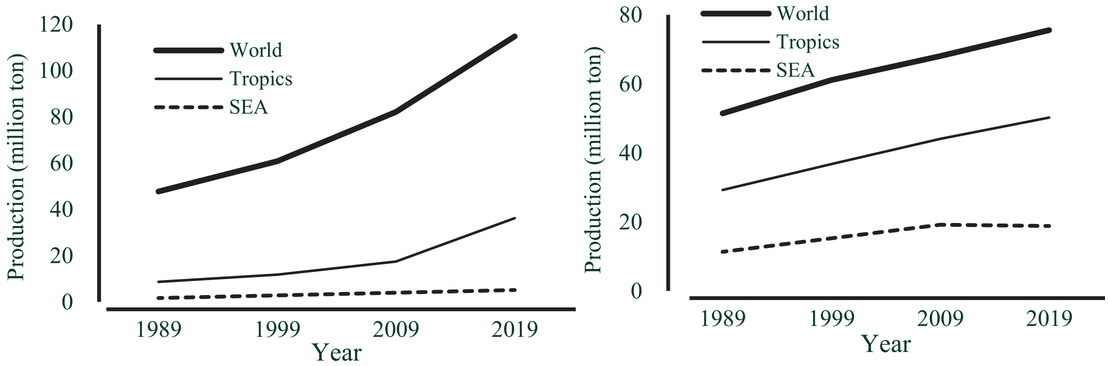
* Adopted from Yoshimoto & Ogimoto (1994)



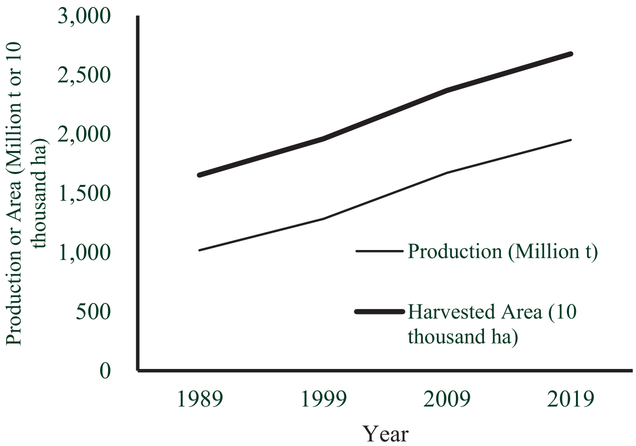

◄ Fig. 1 World major 3 cereals production during these 3 decades



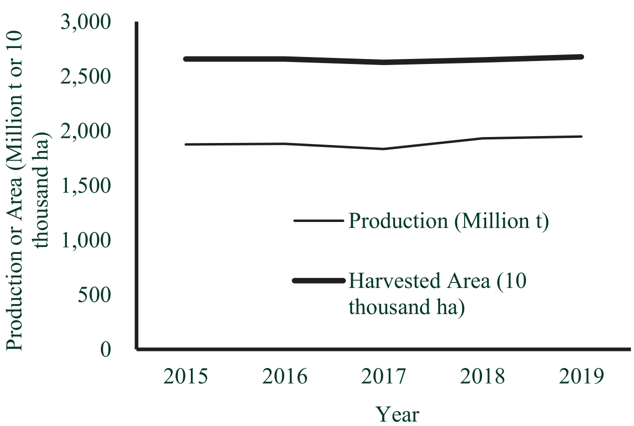

◄ Fig. 2 World 3 major cereals production during these 5 years.



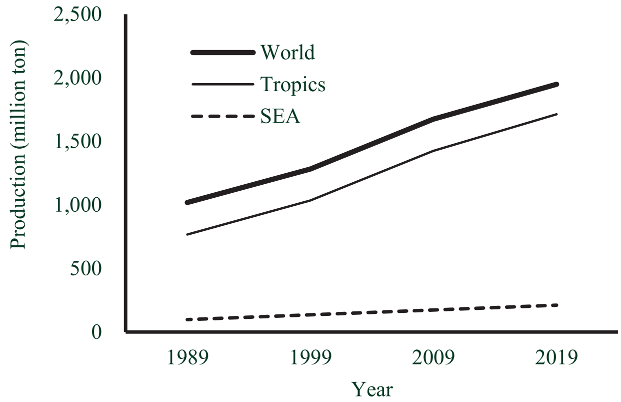

▲ Fig. 3 Production of maize (left) and rice (right) in the world, tropics and Southeast Asia during these 3 decades.




◄ Fig. 4 World production and harvested area of sugarcane during these 3 decades.




◄ Fig. 5 Production and harvested area of sugarcane in the world during these 30 years.




◄ Fig. 6 Production of sugarcane in the world, tropics and Southeast Asia during these 30 years.

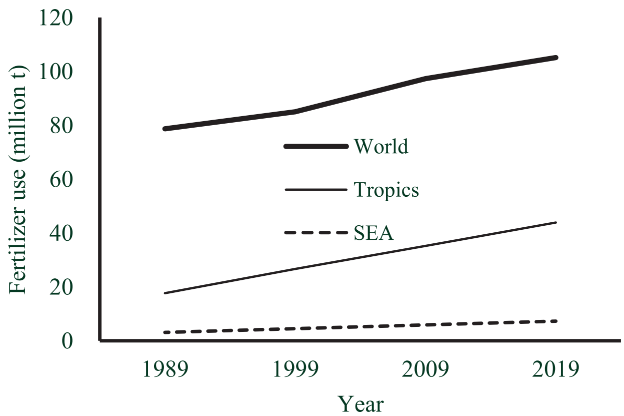



Fig. 7 Fertilizer use in the world, tropics and Southeast Asia during these 30 years.

# Microbial based solutions to low carbon sustainable crop management ~ Multifunctional Bacillus-based probiotics

Tzu-Pi Huang[1234]* Jenn-Wen Huang[23]

## Abstract

As global warming exacerbate the impact on crop cultivation, environmental sustainability, and food security, all countries aim to meet the goal of "net zero emission" by 2050. Here, we proposed a Microbial Based Solutions for reducing the use of chemical fertilizers and pesticides, the increase of carbon sink, and the value-added application of agriculture by-product. Our team discovered three Bacillus-based probiotics (Bacillus licheniformis EC34-01, Bacillus subtilis 151B1, and Bacillus subtilis WMA1), and demonstrated their high potential for application in crop health care and bioremediation of agricultural pollutants. B. licheniformis EC34-01 and B. subtilis 151B1 were isolated from the plant rhizosphere, and B. subtilis WMA1 was isolated from natural environment in Taiwan. Our results indicated that both EC34-01 and 151B1 strains could promote growth of various plants including strawberry, tea, and cucumber plants, and suppress plant diseases such as Fusarium wilt, damping off downy mildew on cucumber seedlings. They also possessed plant growth promoting traits including production of protease, amylase, cellulase, lipase and IAA, and phosphorus-solubilizing activity. These two strains exhibited ability to induce

the expression of plant defense genes such as PAL, POX and PR1a in cucumber seedlings. B. subtilis 151B1 was found to produce C14- and C15- family surfactins and C14- and C15- family iturin A to trigger apoptotic-like cell death, reduce mitochondrial membrane potential and interfere with the energy metabolism of the pathogen. All three Bacillus strains were great biofilm formers, and could colonize well on plant roots. Addition of agriculture by-product in the culture could further enhance the biofilm formation by these strains. They also could enhance the stress tolerance of plants to drought and flooding. Moreover, both EC34-01 and 151B1 strains exhibited activities in degradation of pesticides malathion and deltamethrin, and a fungicide tricyclazole. The influence of introducing these Bacillus-based probiotics on the microbiome of the plant rhizosphere were also assessed indicating the increase in beneficial bacterial and fungal communities, but the reduction in pathogenic ones compared to the water control. In conclusion, the Bacillus-based probiotics developed possessed multiple functions and could be as solutions for low carbon sustainable crop management and achieving net zero emission in agriculture.

**Keyword:** Bacillus, Biocontrol, Probiotics, Stress tolerance, Pesticide degradation

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# Crop rotation: An effective system to improve crop production efficiency and minimize C footprints

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## Abstract

Crop rotation has long been recognized as a beneficial management practice that increases crop productivity, break disease and insect cycles, and reduces the seed bank of stubborn weeds. However, its ecological services and environment benefits have not been systematically measured and analyzed. In this presentation, I will use two case studies to demonstrate the dual benefits of crop rotation for crop productivity and environmental carbon (C) footprint in the Eastern Canadian Mixedwood Plains Ecozone. Case 1 is an on-going study testing a maize-dominated cereal and legume crop rotation since 1992. It consists of three cropping systems: maize-soybean (MS), maize-forage legume (MF), and continuous maize monoculture (MM). Maize plots were fertilized with varying levels of nitrogen fertilizer and dairy manure during the maize phase of crop rotation. Case 2 was a four-year, four-crop, canola-dominated phase rotation and conducted over two cycles (2011-2018) at three sites in eastern Canada. In each rotation type, both crops appeared each year. For example, MS and SM, soybean-canola (SC) and CS, etc. occurred simultaneously at each site each year to account for the annual environmental influence on crop rotation effects, thereby total greenhouse gas (GHG) emissions and C footprint could be estimated annually. The following main points can be drawn from these projects: 1. The continuous maize monoculture produced the lowest grain yield, while maize in rotation with forage-legume yielded the highest; 2. Repeated manure application could provide up to 100% of the N required for the maximum maize yield; 3. N replacement values (NRV) ranged from 40 to 120 kg ha-1 for maize-soybean, and from 130 to 180 kg ha-1 for maize-forage legume rotation systems; 4. The magnitude of C footprint reduction varied with N fertilizer application rates, and maize treated with 100 kg N ha-1 in MS rotation produced the greatest economic yield with relatively low GHG emissions and C footprint; 5. Diversified cropping systems increased crop yields by an average of 32% and reduced the C footprint by 33%; and 6. Planting soybeans as a previous crop to canola is a promising strategy to increase canola crop productivity and N uptake, thereby reducing the carbon footprint of canola production. Our findings suggest that increased maize yields and reduced C footprints can be achieved through appropriate N application and crop rotation with forage legumes or soybeans, and that planting canola after soybeans or wheat following canola is a viable and sustainable strategy in eastern Canada.

**Keywords:** Cropping system, Carbon footprint, Sustainable production, Greenhouse gas emission intensity, Nutrient use efficiency

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# The opportunities and challenges of circular agriculture in Taiwan

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## Abstract

Changes from the consumer side towards a healthier and less-meat diet and from the production side to reduce environmental pressures are urgently needed in response to the continuous growing population and concerns of unsustainable agricultural practices. Circular agriculture (CA) can be a technology measure for keeping the food system within environmental limits. Although the concepts, definition and principles of CA are various and might not be able to directly transfer from the concepts of circular economy (CE), some principles and strategies from CE can be quite useful after adapted. Narrowing, closing and regenerating are the three main strategy aspects, which aims for optimizing the use of resources, reusing agricultural materials and preserving and enhancing natural capital, respectively. However, all the existing indicators of evaluating the effect of the strategies have their own strength and weakness. Therefore, the effect of a CA practice needs to be evaluated using multiple indicators that cover different aspects. National meta-analyses summarizing the existing CA experiments will be needed for evaluating and presenting the geographical, climatical, and agronomical variances to allow policy makers to interpret and make relevant decision easily. Within all the technical strategies to improve CA, the reuse of biomaterials (food wastes, plant residuals, and animal manures), either as biofuel, biofertilizers or the feedstock of biochar, has great potential to both closing the nutrient loop and enhancing soil health. However, as these biomaterials are not standardized, the nutrient balance (both macro- and micro-nutrients), toxic element contents in the materials and their following effects on soil properties, crop nutrition and environment highly depend on their sources, the processing methods and the application methods, of which careful and comprehensive evolution is required. In Taiwan, except for cereal crops, most of the vegetables, fruits, eggs and meat are produced locally, which make the implementation of mixed crop-livestock strategy more possible. The re-utilizing livestock manure can be therefore the most promising approach to improve the sustainability and circularity of agriculture in Taiwan. However, evaluating and tracking data of quantifying the reduced application of artificial fertilizers, especially those dominantly imported, driven by the application of organic fertilizers from different sources, and their further impact on soil and crop nutrition is currently lacking. This makes it difficult to strategically evaluate the impact of the sources and types of organic fertilizers and, in turn, difficult to adjust and improve the systems. Relevant investigation and national meta-analyses of the effect of different approaches and the use of different biomaterials will be most required and challenging.

**Keywords:** Sustainability, Circular agriculture strategies, Manure management, Nutrient cycling

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## How to maintain the sustainability of agriculture? – we need to change

The global population is expected to grow by about a third and the global income is expected to triple in 2050. Over this period of time, it is projected that about 2 billion people are going to enter the global middle class with expected increased wealth and more resource-intensive consumption, including eating more animal product (Grumbine et al., 2021). However, in the 2023 UN summit, the United Nations reported that there were still above 30 percent of the world population moderately or severely food-insecure, lacking regular access to adequate food. This implies that the current global food production and distribution system is problematic and unsustainable.

The fourth goals of SDG2 by 2030 is "to ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality." The global averaged agricultural land use per capita drastically dropped in 1910 and has been decreasing in the last century from 1.56 ha in 1910 to 0.66 ha in 2016 (Our World in Data, https://ourworldindata.org/land-use). This implies that the current land use efficiency is actually increasing, which can be partly attributed to the use of artificial fertilizers and agricultural mechanization that greatly increase the quantity of food production. However, 'how long can we produce food like this?' has been questioned, especially in face of global growing population and more extreme weather events. It is projected that within 60 years, all of the world's topsoil could become unproductive if the current agricultural practices and soil degradation continue (Maximillian et al., 2019).

Springmann et al. (2018) published an article on Nature, in which they estimated that the environmental pressure of the food system is going to increase by 50-92% for each indicator in 2050 (GHG emissions 87%, cropland use 67%, blue water use 65%, phosphorus application 54%, nitrogen application 51%) in the absence of technological change and other mitigation measures. They proposed some potential options for keeping the food system within environmental limits. With regards to the effect on reducing environmental pressures, compared to the projected pressures in 2050, dietary change contributed the most (29%: change to a healthier diet, 56%: change to a plant-based diets) to the reduction of GHG emissions. Technological changes that increase the efficiency of production, such as increasing N use efficiency, P recycling, water management, improving manure management etc., can reduce the most (by 3-30%) in other environmental pressures (including cropland use, blue-water use, N application and P application) of food systems. However, they also reported that no single measure is enough to keep the effect on reducing environmental pressures within all planetary boundaries. The goal of keeping the environmental impacts within 15% or less than the present impacts can only be achieved by combining all the measures. In other words, to maintain the sustainability of agriculture, it is clear that we need a systematical change from both the production side (for example, increasing nutrient and water use efficiency) and the consumption side (reducing food waste and changing to a healthier or plant-based diets) (Dobermann et al., 2022). It is deemed that the coming 10-20 years will be critical for making transition to a global food system in which we produce and consume food in a more sustainable way (Dobermann et al., 2022).

In terms of the dietary changes, Chen et al. (2019) studied the nutritional quality and impacts on environment, economy (daily food expenditure) and human health of nine alternative dietary scenarios (healthy Swiss diet, healthy global diet, vegetarian, vegan, pescatarian, flexitarian, protein-oriented and meat-oriented diets and a food greenhouse gas tax diet). They found that achieving a sustainable diet requires a high reduction in the intake of meat and vegetable oils and a moderate reduction in cereals, roots and fish products and at the same time increased intake of legumes, nuts, seeds, fruits and vegetables (Chen et al., 2019). However, dietary choice of humans is highly depending on personal habits and preferences, of which the alteration requires time, education and societal consensus.

The technology measure in Springmann et al. (2018) include increasing N use efficiency and P recycling, improving water use efficiency, adopting agricultural mitigation strategies, changing manure management strategies etc. Since resource use efficiency and recycling is a large part of circular agriculture (CA), the following discussion will be focusing on how the design and concept of CA can serve the ultimate goal of agricultural sustainability, what are the technologies and practices we can use, and what are the challenges we are faced with.

## The concept, definition and principles of circular agriculture

The concept and definition of circular agriculture (CA) varies. Some describe it from the technical side as a closed-loop system in which nothing is wasted, and some explain it as a system that mimics the natural processes of regeneration (Marinova & Bogueva, 2022), and some recognize it as a concept transferred from circular economy (CE) (Velasco-Muñoz et al., 2021). One of the challenges of designing CA is related to debates about whether to narrowly frame food systems as only about technological issues (increase crop yields, close nutrient loops, re-couple crop-livestock links, etc.) or whether to include social and demand-side issues (improve smallholder livelihoods, create sustainable supply chains, promote dietary shifts, etc.)(Grumbine et al., 2021). For the convenience of discussion, this article is only focusing on the discussion of technological design, of which the advances can reduce the environmental pressure by 3-30% according to Springmann et al. (2018).

In regards to the boundaries of CA, Marinova & Bogueva (2022) argued that it is better to differentiate CE and CA, with the latter only relates to the closed-loop cycle of food production. Marinova and Bogueva (2022)’s argument makes sense since the concepts and models of CE cannot be directly transferred and applied on CA, because CE focuses on technical products and CA, biological products. For example, the idea of ‘repaired’ and ‘remanufactured’ of a technical product cannot be applied on biological product, such as tomatoes, which cannot be repaired once it is damaged.

Even though, Velasco-Muñoz et al. (2021) reviewed about 700 existing studies that have tried to adapt the concept of CE to agriculture. In their literature review, some useful strategies and indicators that we might be able to use in improving and monitoring the effect of CA were proposed, which are presented in the next paragraph. Some main principles were also well extracted from about 700 studies and summarized by Velasco-Muñoz et al. (2021), which include three main principles:

(i) Resource efficiency (資源有效利用): adopting technological or economic practices to ensure greater added value and maintain resources within the production system for as long as possible. Methods include optimizing processes to minimize resource use and avoid waste.

(ii) Sustainability (經濟、環境與社會永續性): (1) economic sustainability: CA should become a pillar of the economy rather than a subsidized sector (2) environmental sustainability: ensure the conservation of biodiversity and productivity over time in its agroecosystems (3) social sustainability: provide food security, eradicating poverty, and improve health and living conditions.

(iii) Regenerative (再生性): agriculture must evolve to include regenerative systems that close nutrient loops, minimize leakage, and maximize each loop's long-term value.

Based on the above principles, the authors defined CA as "the set of activities designed to not only ensure economic, environmental and social sustainability in agriculture through practices that pursue the efficient and effective use of resources in all phases of the value chain, but also guarantee the regeneration of and biodiversity in agro-ecosystems and the surrounding ecosystems"

## Strategies, practices and indicators of circular agriculture

Some strategies, practices and relevant indicators of a CA system are extracted from literature and summarized in Table 1. The listed three aspects of strategies: narrowing, closing and regenerating are adapted from CE, which aiming for optimizing the use of resources, reusing agricultural products and regenerating, respectively. Practices that relate to each strategy is extracted from studies and allocated to each column in Table 1. In the aspect of narrowing, focuses have been lasered on the use efficiency of land (to produce crops, animal feed or biofuel), water and fertilizers. In the aspect of closing, much attention is placed on reducing and reusing agricultural wastes. In the aspect of regenerating, the maintenance of soil health by means that reduce soil erosion and increase soil fertility and biodiversity has been predominantly discussed. The indicators to assess the level of circularity of each practice is strategically important. However, it should be noted that each indicator has its strength and weakness, and no single indicator is able to reflect all the aspects of a CA system (Velasco-Muñoz et al., 2021).

## A good meta-analysis example

Studies of a farming practice conducted at different conditions, such as crop species, soil properties, time frame, and regional climates, can have different effect and outcomes. To provide comprehensive information for farmers and policy makers, a study that summarizes the outcomes of different studies and delivers visualized and clear messages is required. A good example of such study is presented by (Zhao et al., 2020). Using meta-analysis method, they calculated the results extracted from 214 observations of 45 studies that involved ‘crop rotation’ in China, which were filtered from 4392 English and 586 Chinese publication, respectively, and excluded those reporting on the same trial. The effect of crop rotation was well presented as confidential intervals (effect % on yield) compared to monoculture (0%). They showed that crop rotation overall could improve about 20% on yield. However, the effect varied by geographical location (the most in southwest and least in east), weather, soil (such as soil texture, organic carbon and nitrogen contents), and crops. They also showed that the rotation effects were greatest when legumes were the pre-crops; when the rotation was conducted over three cycles, the effect became insignificant.

Study like this, presenting variances between factors and the overall effect of a farming practice (crop rotation here) in a visualized way, can help readers understand and interpret the meaning of the data easily. More studies like this are required in Taiwan to summarize the existing studies that evaluated the effect of different CA practices. Building on such comprehensive analysis, researchers and government can have opportunities to allocate resources and scientific power to those has not been investigated and can have stronger scientific evidence for policy making.

## Enhancing nutrient cycling with agricultural wastes

Within the strategies of 'closing' and 'regenerating' in a CA system, reusing agricultural wastes, such as food wastes, plant residuals, and animal manures, as alternative soil fertilizers has great potential of both closing the nutrient loops and improving the soil quality. Additionally, animal manures can also be a source of biogas, which serves as a source of renewable energy. However, farmed animals per se consumed more than one third of the world's cereal grain, leading to low nutrient use efficiency in the whole food chain and causing large GHG emissions (Dobermann et al., 2022). The current livestock production system therefore needs to become more sustainable, which can involve shifting to pasture-based systems and introducing mixed crop-livestock systems (Dobermann et al., 2022), in which the plant residuals can be used as the feed for animals and animal manures can be used as alternative source of fertilizers and soil organic matter.

Despite of the multiple functions of animal manures, some challenges still exist and need further investigation. For example, by spreading manures on farmland based on the N content of manure, farmers often end up applying onto soils 5-10 times the crop P requirement, because of the low N:P ratio (3:1 or less) of stored manures compared to the ratio required by crops (close to 5:1 or 6:1) (Rosemarin et al., 2020). The over-applied P from manures can accumulate in soil and becomes so-called legacy P, of which the accessibility to crops, the potential toxicity driven by high concentrations, and the impact on the uptake of other nutrients need to be carefully evaluated.

Another concern of applying those agricultural wastes in soil, especially animal manures, is that for some micronutrients, their phyto-availability in soil can be reduced by the application of animal manures. For example, Kao et al., (2023) reported decreased concentration and accumulation of selenium (Se) in perennial ryegrass than the control when the soil received sheep excreta (Fan et al., 2008) reported decreased Se concentrations in wheat grains after farmyard manure application in a long-term experiment at Rothamsted Research, UK. Wang et al. (2016) also reported lower Se accumulation in wheat and maize compared to the control and the soil applied with inorganic N, P K fertilizers. This raised a concern that although utilizing agricultural wastes can benefit the recycling of nutrients, such as N and P, its long-term effect on nutrient balance and the recycling rate of some micronutrients may be hindered.

Micronutrient deficiencies are a widespread and growing problem in both crop plants and human populations worldwide (Assunção et al., 2022). Prof. Ismail Cakmak has raised the concern of hinder hunger (micronutrient deficiency) in a FAO report (https://www.fao.org/fsnforum/comment/9021), which may be driven by the current agricultural fertilizer practices. Micronutrient deficiency can affect the tolerance of crops against pest, pathogens and other environmental stress and, in turn, affect the crop production and nutritional quality. Assunção et al. (2022) called for awareness of the importance and relevance of micronutrients in crop production and quality, of which science is relatively lacking. Although the deficiency of micronutrients can be easily balanced by applying foliar fertilizers and synthetic chelators, it was commented that some deficiency symptoms are often related to nutritional imbalance rather than the lack of a single element per se (Assunção et al., 2022). It therefore deserves further research to understand the impact of applying different agricultural wastes, on the ultimate nutrient recycling and crop nutrition from a more holistic point of view.

## Using biochar – benefits, risks and prospects

The application of biochar that derived from agricultural wastes has been thought to be a potential solution of reducing wastes and increasing soil carbon sequestration simultaneously. However, applying biochar in agricultural soils is still a highly controversial topic, because there have been trade-offs between increasing soil C and improving crop growth and nutritional quality. Furthermore, biochar application might be beneficial to some aspect, for example increasing soil organic carbon, it can be harmful to other aspects, such as increasing soil heavy metal concentrations (Jindo, Sánchez-Monedero, et al., 2020). The effects of biochar on crop growth and nutrient cycling highly depends on the feedstock types and the pyrolysis conditions, and, sometimes, the soil application rates. For examples, biochar pyrolyzed at low temperature can enhance denitrification and, in turn increase N2O emission, whilst biochar pyrolyzed at high temperature was reported to decrease denitrification and N2O emissions; whether or not the application of biochar can reduce soil NH3 emissions is determined by both the adsorption capacity of NH4+ and the pH of a substrate, which depends on both physiochemical properties of both soil and biochar; although more phosphorus (P) will be transformed into orthophosphate (a plant-available P form) with increasing pyrolysis temperature, the ultimate P availability to crops still highly depends on soil pH (in acidic soil, biochar application has more positive effect on increasing plant-available P) (Jindo, Audette, et al., 2020).

Other than used as alternative soil fertilizer or soil amendment, biochar has also been tested as growing media and composting additive. Huang & Gu (2019) reviewed 32 studies and reported that the application rate of biochar under 25% generally resulted in similar or higher plant growth compared to the commercial substrates. Nevertheless, there are still concerns regarding the high salinity, high alkalinity and potentially high concentrations of heavy metals and polycyclic aromatic hydrocarbons (PAHs) of biochar in comparison to peat, which would require pre-washing, addition of natural acids, and a careful selection of the appropriate feedstock and pyrolysis conditions, respectively (Jindo, Sánchez-Monedero, et al., 2020). Adding biochar into composts is probably the most promising use of biochar. Studies have shown that adding biochar in composts changed the bacterial communities, accelerating composting rate, enhancing humification, and reducing losses of NH3 and N2O (Agyarko-Mintah et al., 2017; Gong et al., 2023; Wu et al., 2017). Furthermore, the combination of biochar and compost can significantly improve soil conditions and crop performance compared to traditional agricultural practices or the single use of biochar (Jindo, Sánchez-Monedero, et al., 2020).

Overall, when it comes to using biochar in agriculture system, because biochar is not a standardized material, the differences in the feedstock type and pyrolysis conditions should be taken carefully into account, especially when used as alternative substrates, soil organic fertilizers and soil amendment. Some possibly negative impact of biochar amendment to soil, such as potential increase in P leaching and high salinity, should also be taken into consideration (Jindo, Audette, et al., 2020). When used as soil fertilizers, due to the low N content (generally less than 0.01%), it requires adding extra N fertilizers to ensure a good C-N ratio for plant growth.

To evaluate the general impact and variance between different variables of using biochar, national or global meta-analyses like (Zhao et al., 2020) is needed. It should be awarded that there is still lacking experimental data regarding the effect of long term and repetitive additions of biochar to the soil, and a proper combination among biochar type, the purpose of its use and optimum application rate should be explored (Jindo, Sánchez-Monedero, et al., 2020).

## The opportunities and challenges of circular agriculture in Taiwan

A great part of a CA design is using the land efficiently. In 2022 in Taiwan, 8,139 and 78,000 hectares of land was used for animal husbandry and arable farming, respectively, which were approximately 0.225% and 2.16% of the national land, respectively. They overall provided in average 31.3% of food (including 26.3% cereals, 84.3% vegetables, 86.0% fruits, 100% eggs, and 76.5% meat, calculated by calories), with the rest imported. For those imported, it is difficult to use their agricultural wastes to close the nutrient loop and benefit the production land. Fortunately, most of our vegetables, fruits, eggs and meat are produced locally, of their agricultural by-products and wastes have great potential to be used for the ‘closing’ and ‘regenerating’ strategies. However, as mentioned in the previous paragraphs, the use of agricultural and/or urban wastes needs careful evaluation on their sources, contents of harmful substances and their nutrient balances (including macro- and micro-nutrients).

The challenges of using animal manures as alternative fertilizers include social acceptability, their proven and perceived risks for heavy metals and pathogens, and the geographical mismatch between livestock farms and crop production systems, which hinders the transportation from the manure production site to where it is needed (Rosemarin et al., 2020). Fortunately, since 1999, Taiwan has started a series work related to reusing husbandry resources, including setting up soil treatment standards, evaluating the potential pollutions in soil and water bodies, and investigating different manure management techniques (Fig. 1).

The estimation of replaced quantity of artificial fertilizers by livestock manures is currently lacking. The available statistical data from the Ministry of Agriculture in Taiwan (Table 2) provided information of the quantities (by weight) of the imported and exported fertilizers and the amount of production and use. Within the commonly-used artificial fertilizers, only potassium sulfate and calcium superphosphate are produced locally, and the production of calcium superphosphate requires phosphate rock powder which is imported. Other artificial fertilizers, including calcium ammonium nitrate, calcium cyanamide, phosphate rock powder, urea and potassium chloride are dominantly imported, meaning that the agricultural land is still highly dependent on imported fertilizers. Furthermore, Fig. 2 shows that the use of chemical fertilizers (or artificial fertilizers), although is decreasing, is still outweighing the use of organic fertilizers. It should be noted that the data of organic fertilizers shown in Table 2 and Fig. 2 only include oil meals with the data of animal manures unavailable. Therefore, without the statistical data of the use of organic fertilizers derived from animal manures and composts, the results of Fig. 2 might be misleading. Further investigation and calculation of the replacement of inorganic fertilizers (quantified by total N, P and K) replaced by organic fertilizers from difference sources are needed for the evaluation of the improvement of agriculture circularity.

Finally, a national evaluation of the effect of the different CA strategies, such as implementing cover crops and crop rotation to improve soil health, using meta-analysis technique is important and required. Such meta-analysis, as mentioned previously, can help estimate the geological, climatical, agronomical and other environmental variances, with which the circularity of agriculture can be hopefully improved more precisely. Currently, the government has built a data platform (https://agriinfo.tari.gov.tw/), from which some shared data can be retrieved. However, it is still lacking relevant data extracted from individual field experiments of CA practices in the past. The lack of adequate amount of local data and the relevant meta-analysis will be another challenge for improving the sustainability and circularity of agriculture.

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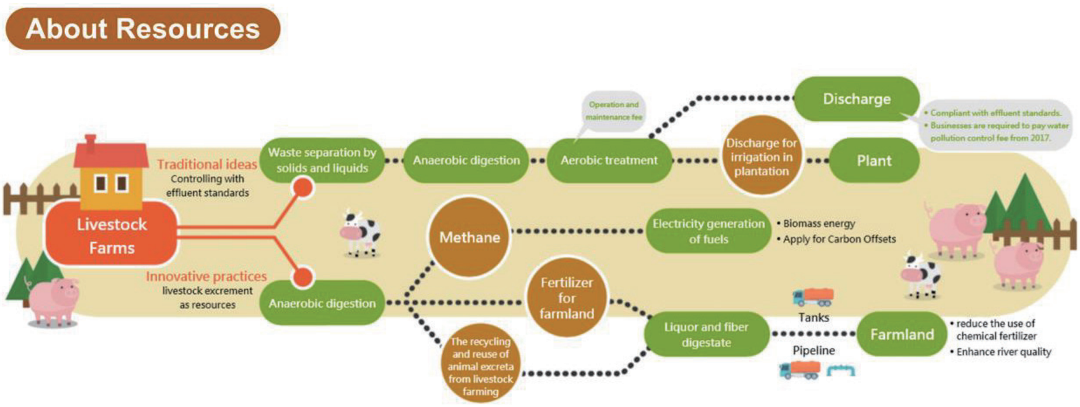
**Table 1 The strategies, practices and indicators of CA systems**

| | Strategies (adapted from CE, (Velasco-Muñoz et al., 2021)) | | |
|---|---|---|---|
| | Narrowing ( 限縮 ) | Closing ( 封閉 ) | Regenerating ( 再生 ) |
| Strategy aims | Aimed at optimizing the use of resources | Aimed at reusing agricultural materials, but for different applications than the original, following the resource cascading approach | Aimed at preserving and enhancing natural capital |
| Practices | · [1,3]Reducing meat consumption<br>· [1]Smart land-use<br>- Agroforestry<br>- Urban agriculture<br>- Vertical farming<br>- Drip irrigation<br>- Adopting drones for planting and monitoring<br>- Applying N-fixing bacteria<br>- Floating vegetable gardens | · [1,10]Reducing food loss and waste<br>· [1,3,11]Using residual biomass as animal feed or bio-fertilizers<br>· [4,10,12] Using urban wastes in agriculture (opposed to the principle of 1)<br>· [3,12]Manure management techniques:<br>- Anaerobic digesters<br>- Biogas production<br>- Membrane filtration systems<br>- Worm composting<br>- Solid-liquid manure separation<br>- Manure drying and pyrolysis (biochar)<br>- Algal cultivation<br>- Fungal digestion | · [1]No-till farming<br>· [1,11] Using leguminous plants, animal manure and other bio-wastes to replace synthetic fertilizers<br>· [1]Or ganic farming<br>· [1,2]Crop rotation<br>· [12]Planting of buffer zones that can help trap runoff water containing N and P<br>· [12]Planting cover crops that can trap and fix N |
| 4Indicators | · [5]The allocation and tenure of land for new bioenergy production<br>· [6]Food and feed autonomy<br>· [7]N use efficiency and recycling index<br>· [8]Overall greenhouse gas balance | · [9]Circularity indicator of components<br>· [10]Self-sufficiency index<br>· [10]Waste output index<br>· [7]N use efficiency and recycling index | · [5]Soil quality<br>· [5]Biological diversity in the landscape<br>· [11]Botanical species richness<br>· [5]Consumption of fossil-P fertilizers |

[1](Marinova & Bogueva, 2022); [2](Zhao et al., 2020); [3](Grumbine et al., 2021); [4](Velasco-Muñoz et al., 2021); [5](Zabaniotou, 2018); [6](Fernandez-Mena et al., 2020); [7](Tadesse et al., 2019); [8](Casson Moreno et al., 2020); [9](Cobo et al., 2019); [10](De Kraker et al., 2019); [11](Mosquera-Losada et al., 2019); [12](Rosemarin et al., 2020)

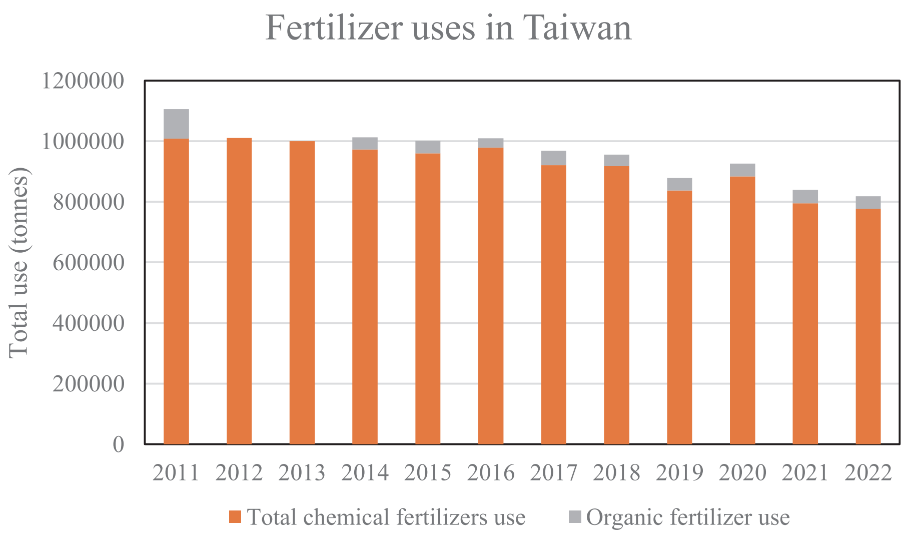



▲ Fig. 1 The concept of treating and reusing livestock excreta in farmland (retrieved from the website of Husbandry Excrement Resources Web of Taiwan https://epafarm.epa.gov.tw/EN/Default.aspx)

**Table 2 Fertilizers production, export, import and use in Taiwan (year 2022)***

| Fertilizers (Unit: tonnes) | Production in Taiwan | Export | Import | Usage |
|---|---|---|---|---|
| Total chemical fertilizers | 1274084 | 375546 | 424569 | 777380 |
| Calcium ammonium nitrate ( 硝酸銨鈣 ) | 1,151 | N.D. | N.D. | 750 |
| Ammonium sulfate ( 硫酸銨 ) | 317,852 | 174,450 | 5,385 | 84,235 |
| Potassium sulfate ( 硫酸鉀 ) | 206,185 | 188,267 | 228 | 5,281 |
| Calcium Cyanamide ( 氰氮化鈣 ) | N.D. | N.D. | 1,171 | N.D. |
| Phosphate rock powder ( 磷礦粉 ) | N.D. | N.D. | 89,627 | 1,151 |
| Urea ( 尿素 ) | N.D. | 304 | 48,937 | 30,513 |
| Potassium chloride ( 氯化鉀 ) | N.D. | N.D. | 180,078 | 11,112 |
| Calcium Superphosphate ( 過磷酸鈣 ) | 68,270 | N.D. | N.D. | 20,588 |
| Compound fertilizers ( 複合肥料 ) | 681,640 | 12,044 | 53,296 | 616,190 |
| Other artificial fertilizers( 其他化學肥料 ) | 137 | 481 | 44,696 | 8,711 |
| Organic fertilizers ( 有機質肥料 ) | 40,900 | 4,944 | 65,900 | 41,356 |

*Data is retrieved from the statistics of the Ministry of Agriculture of Taiwan (https://agrstat.moa.gov.tw/sdweb/public/official/OfficialInformation.aspx). N.D.: No available data.




▲ Fig. 2 The uses of chemical (orange bar) and organic (gray bars) fertilizers in Taiwan. The organic fertilizers only include oil meals from animals and plants (fertilizer number: 5-01). The organic fertilizers produced from the animal manures are not included.

# 作物模式應用於水稻灌溉策略之研擬

劉力瑜[1*]　李昇峰[1]

## 摘要

臺灣受氣候變遷的影響，雖然年總雨量變化不明顯，但極端降雨量發生的頻率提高，作物更易遭受乾旱或淹水的逆境，因應氣候變遷衝擊和挑戰，臺灣農業生產作物品質，需發展更有彈性的調適策略。本研究以 DSSAT CERES-RICE 作物模式，以網格化的土壤與氣象重建資訊，配合臺灣由南至北不同的插秧日期，模擬‘台稉 9 號’、‘台南 11 號’、‘台南 16 號’、‘桃園 3 號’、‘台農 71 號’等五種臺灣主要栽培稻品種在無灌溉情境下的產量，藉以評估水稻於乾旱逆境下的減產風險。未來還能根據不同情境規劃更精緻的灌溉供水排程模擬，作為農業耕作調適參考之基礎。

**關鍵詞：**水稻、灌溉、作物模式、調適策略

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# 前言

氣候變遷的衝擊下，全球農業生產受到程度不一的衝擊，進而影響農產品之國際交易市場。因氣候變遷對作物生產造成的威脅中，以乾旱對全球產量的衝擊最大，因此乾旱對作物生理或生產造成之影響的研究也最深入 (Snowdon et al., 2021)。缺水影響作物的生長發育與產量，例如減數分裂時小麥和水稻的缺水會導致籽粒減少 35-75% (Saini and Aspinall, 1981; Sheoran and Saini, 1996) 或收穫指數降低 40% (Garrity and O’Toole, 1994)，大豆籽粒充實階段乾旱影響下產量可能減少高達 42% (Maleki et al., 2013)。乾旱逆境除了受降雨量頻率與降雨分佈的影響，也可能是其他環境因素的晝夜波動 ( 如高光強度等 ) 導致根系吸水率和冠層蒸發速率之間的不平衡所造成。氣候變遷下年降雨量不一定發生顯著變化，但降雨的頻率和分佈產生變化下，可能導致供水時間與植物需求不一致 (Bönecke et al., 2020)。此外，春季溫度的小幅上升可能導致作物提早或加速生長，在發育階段初期消耗更多的水量導致夏天供水不足 (Lian et al., 2020)。乾旱和高溫逆境的綜合影響，比起各自對作物生產造成的影響更具破壞性：溫度升高導致光合作用的關鍵酵素 Rubisco 遭受破壞，迫使作物停止光合作用，導致產量更大幅度的降低 (Raza et al., 2019)。

評估農業生產受氣候變遷的影響，包含 (a) 氣候變遷對各種生產系統的直接影響，以及 (b) 受到影響之生產系統的經濟評估，以提供農民或其他利害關係人最適切的調適選項，前者常使用作物或禽畜模擬模式來達成，並且已經有相當大量的案例研究文獻 (Thamo et al., 2017)。過去作物模式發展的方向，是將環境對作物生長的生理機制模式化，以對不同氣候或土壤情境提供使產量最優化的生產管理建議，因此過去作物模型以應用於單一田區、單一作物為主，研究者可藉以調整主要栽培管理的條件，也已經發展出模擬數個季節不同作物輪作或休耕的模擬模式，可在田區小規模評估特定作物受氣候變遷的影響 (Bindi et al., 1996; Semenov et al., 1996)。隨著對評估大區域 ( 國內地區、全國、數國範圍、甚至全球等 ) 氣候變遷對作物生長影響的逐漸重視，近期的作物模式必須能應用在較大區域的模擬，目前也有文獻探討不同模型模擬的不確定性 (Rötter et al., 2012)，放大尺度的可行性 (Ewert et al., 2011)，及應用在評估極端氣候的影響與調適 (Rötter et al., 2018)。

本研究藉助於國際常用的作物模式決策支持系統 Decision Support System for Agro-technology Transfer ( 簡稱 DSSAT) 的水稻作物系統模型 CERES-RICE (Jones et al., 2003)，模擬‘台稉 9 號’(Taiken9)、‘台南 11 號’(Tainan11)、‘台南 16 號’(Tainan16)、‘桃園 3 號’(Taoyuan3)、‘台農 71 號’(Tainung71) 等五種臺灣主要栽培稻品種在無灌溉情境下的產量，藉以評估臺灣本島各個地區種植水稻的減產風險，本研究目的除了呈現作物模式模擬結果可做為評估各地點生產力之客觀依據，亦可應用於輔助大區域生產調適策略的擬定，做為農業耕作調適參考基礎。

# 材料與方法

## 一、DSSAT CERES-RICE作物模式參數設定

DSSAT CERES-RICE 作物模式模擬的輸入資料包含環境數據 ( 氣象與土壤 )、栽培管理資訊 ( 包含種植品種、插秧日期、種植密度、施肥與灌溉日期用量等 )，不同種植品種亦需各自提供其對應之作物參數。必須輸入的氣象數據包含每日最高溫 (° C)、最低溫 (° C)、雨量 (mm)、日輻射量 (MJ/*m*2)，本研究採用「臺灣氣候變遷推估資訊與調適知識平臺」(TCCIP) 所產製的 2019 年「臺灣歷史氣候重建資料」(TReAD，https://tccip.ncdr.nat.gov.tw/ds_03_mall.aspx)，空間尺度為 2 km ( 黃，2022)。欲模擬乾旱情境必須輸入環境土壤資訊，最少需輸入的資訊為土壤分類，為了能忠實反映臺灣實際土壤多樣性，本研究沿用施 (2021) 將臺灣詳測土壤圖資所建立的 DSSAT 臺灣農地土壤檔，選擇氣象網格點最鄰近之土壤資料，將土壤與氣象資料合併後共獲得469個臺灣農地網格點。

栽培管理數據參考黃 (2022)：行距為 30 cm、種植密度為 22 叢 /m2，依據模擬網格所在緯度指定插秧日期，以符合臺灣第一期作由南至北陸續插秧的現況：從最南端 (21.95° N) 至最北端 (25.3° N) 等比例分為 7 個區域，插秧日期依序為 1/1、1/11、1/21、2/1、2/11、2/21、3/1；其次，氮肥施用管理設定為：於插秧首日施予每公頃 36 公斤的基肥、插秧後 30 日施予每公頃 54 公斤的追肥、插秧後 45 日施予每公頃 30 公斤的穗肥；灌溉則分為無灌溉 ( 看天田 ) 及自動灌溉兩種模式，自動灌溉參考黃亭禎 (2022) 之參數設置：IMDEP ( 灌溉管理深度 ) = 30 cm、ITHRL ( 觸發自動灌溉的可用水量下限 ) =

50%、ITHRU ( 灌溉完成之可用水量上限 ) = 100%。最後，‘台稉 9 號’、‘台南 11 號’、‘台南 16 號’、‘桃園 3 號’、‘台農 71 號’等五種臺灣主要栽培稻品種作物參數參考吳 (2022) 設定。

### 二、風險評估

透過 DSSAT CERES-RICE 模擬，分別得到每一個網格無灌溉 ( 看天田 ) 及自動灌溉的產量後，以 R 軟體繪製產量地圖呈現各網格之產量差異，並計算第 i 個網格無灌溉的風險程度 (Ri)，定義如式 (1)：

$$Ri = \max(0, [AUTOi - RAINi]/Ai \times 100\%) \qquad (1)$$

AUTOi：第 i 個網格自動灌溉之產量模擬結果；

RAINi：第 i 個網格無灌溉 ( 看天田 ) 之產量模擬結果。

## 結果與討論

‘台稉 9 號’、‘台南 11 號’、‘台南 16 號’、‘桃園 3 號’、‘台農 71 號’等五種臺灣主要栽培稻品種在自動灌溉情境下的產量模擬摘要統計值如表一，各地模擬產量介於 2,000 至 9,000kg/ha。比較無灌溉 ( 看天田 ) 及自動灌溉的模擬產量，並計算各個網格無灌溉風險程度，所得五個品種風險分佈圖如圖 1。全臺 469 個網格點中，約有 38% 之風險值為零，顯示這 些地點在 2019 年第一期作生育期的雨量充沛，並未造成水稻減產。其他地點則造成比例不同的減產效應，不同品種的減產效應相當，大約有 50% 的地點造成減產超過 20%。依據減產比例製作的風險地圖如圖 2，可觀察到無論品種，高減產風險 (75-100%) 集中在緯度較低的高雄縣與屏東縣，中度風險 (25-75%) 的地區則落在雲林縣、嘉義縣、臺南縣及部分臺東縣。

紀錄 DSSAT CERES-RICE 水稻自動灌溉用水量，可比較水稻不同生育期之需水量 ( 圖 3)，發現孕穗期 (Panicle initiation) 需水量最大，平均佔全生育期用水之 50%，而分

蘖期 (Juvenile-to-PanInit) 及穀粒充實期 (Grain filling) 需水量次之。但各品種需水量模擬結果近似。根據黃 (2022) 年分時期探討減產風險之結果，顯示水稻在孕穗期缺水減產的風險最大，以高屏地區約一月中下旬插秧、模擬結果顯示孕穗期大約發生於二月下旬至三月中旬間，期間若提供足夠的灌溉水，即使其他時期未灌溉，減產風險可降至 50% 以下，並且灌溉用水可節省 38-73%。

## 結論

本研究以 2019 年的氣候資料進行模擬，若有評估未來氣候變遷情境下的生產狀況，能將不同未來情境下的氣候預測資料、土壤資料、具調適潛力之作物品種對應參數納入 DSSAT 模型，大規模批次性建立風險地圖，可助於建立動態調整調適策略，作為氣候智慧生產的參考，以最大限度地減少農民的損失。

## 誌謝

本研究感謝科技部計畫「臺灣氣候智慧調適與跨領域氣候風險評估之研究 - 糧食生產於未來氣候風險下之智慧調適策略評估」(MOST 108-2621-M-002-021-MY3) 之經費支持。

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**表 1　五種臺灣主要栽培稻品種自動灌溉模擬產量 (kg/ha) 摘要統計值**

**Table 1　Summary statistics of simulated yield (kg/ha) under automatic irrigation for the five rice cultivars.**

| Summary Statistics | Cultivar | | | | |
|---|---|---|---|---|---|
| | Taiken9 | Tainan11 | Tainan16 | Taoyuan3 | Tainung71 |
| Minimum | 2,871 | 2,178 | 2,054 | 2,025 | 2,391 |
| Medium | 7,299 | 5,899 | 4,973 | 6,318 | 7,490 |
| Mean | 7,114 | 5,754 | 4,851 | 6,140 | 7,297 |
| Maximum | 8,708 | 7,027 | 5,952 | 7,610 | 8,925 |

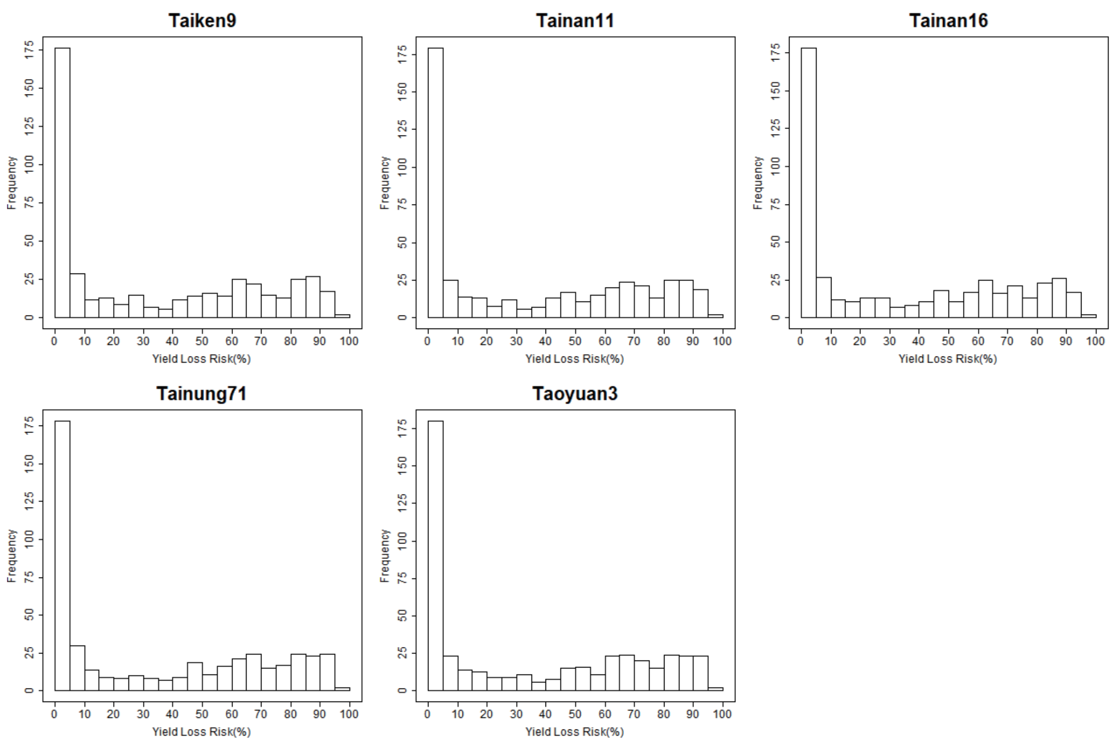


圖 1　DSSAT CERES-RICE 模擬五種臺灣主要栽培稻品種 2019 年第一期作無灌溉風險分佈圖

Fig. 1　The distributions of the simulated non-irrigation risks for the 5 rice cultivars in the 1st cropping season on 2019 by DSSAT CERES-RICE.

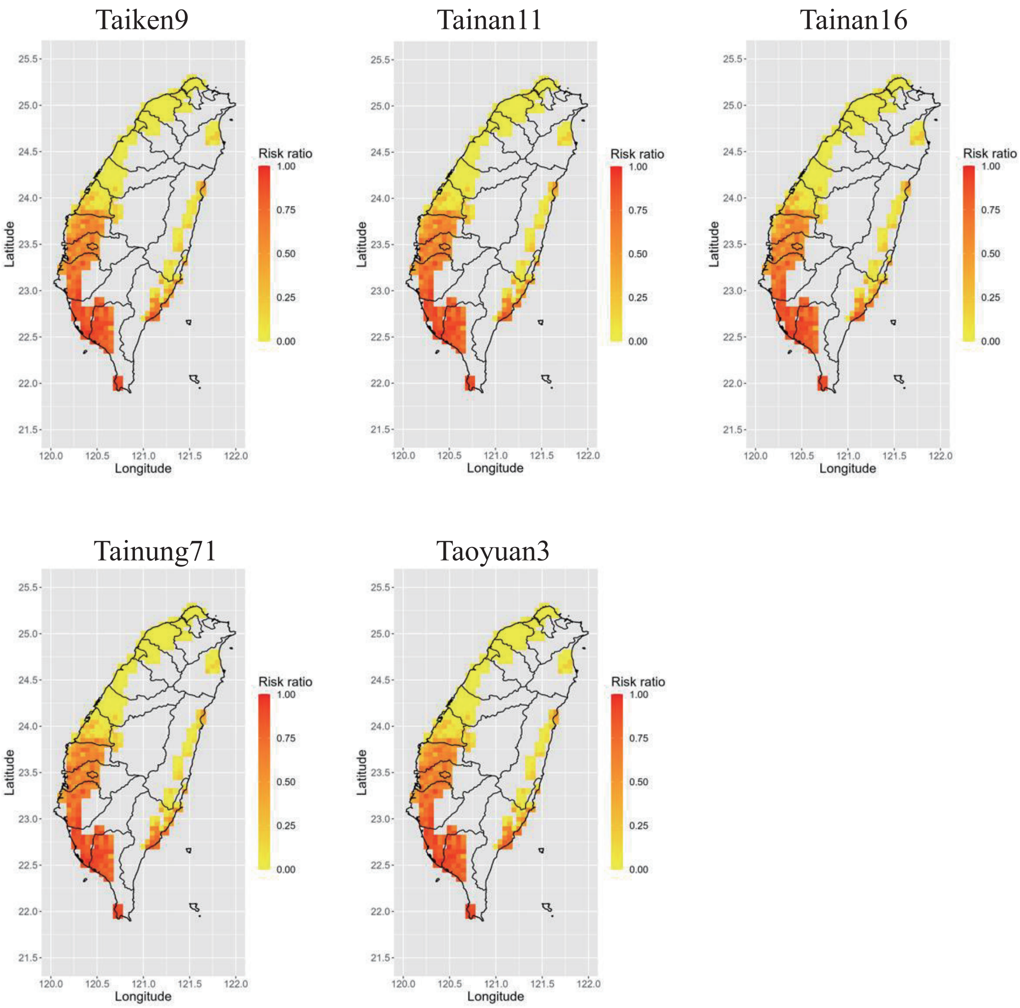


圖 2　DSSAT CERES-RICE 模擬五種臺灣主要栽培稻品種 2019 年第一期作無灌溉風險地圖

Fig. 2　The simulated non-irrigation risk maps for the 5 rice cultivars in the 1st cropping season on 2019 by DSSAT CERES-RICE.

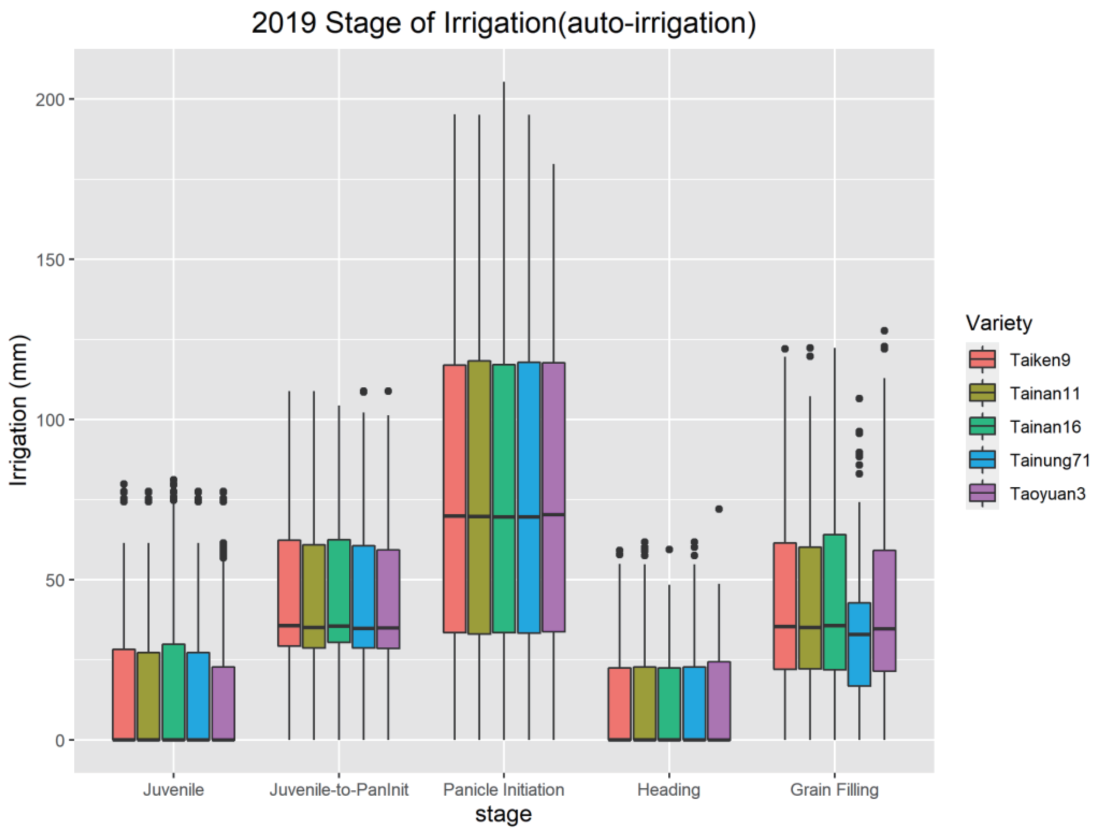


圖 3　DSSAT CERES-RICE 模擬五種臺灣主要栽培稻品種 2019 年第一期作各生育期灌溉用水量

Fig. 3　The amount of irrigation water for the 5 rice cultivars in the 1st cropping season on 2019 simulated by DSSAT CERES-RICE.

# Application of crop modeling in developing rice irrigation strategies

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## Abstract

Impacted by the forces of climate change, Taiwan's annual rainfall has remained relatively constant; however, there has been a discernible rise in the occurrence of intense rainfall events. This heightened frequency of extreme precipitation renders crops increasingly susceptible to the dual challenges of droughts and flooding. In light of these evolving climatic influences, the agricultural sector in Taiwan must actively cultivate more resilient and adaptable strategies to bolster both production and crop quality. This study employs the DSSAT CERES-RICE crop model, coupled with gridded soil and meteorological data reconstruction. Accounting for varying transplanting dates from south to north Taiwan, the study simulates the yields of five rice cultivars, including Taiken 9, Tainan 11, Tainan 16, Taoyuan 3, and Tainung 71, under non-irrigated conditions. The aim is to assess the risk of reduced rice yields under drought stress. Furthermore, future endeavors could involve the refinement of irrigation and water supply scheduling simulations under different scenarios, serving as a foundational reference for agricultural cultivation adaptations.

**Keyword:** Rice, Irrigation, Crop model, Adaptation strategy

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# 應用DNDC模擬作物生育與溫室氣體排放

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## 摘要

愈來愈多證據顯示人類活動與氣候變遷的相關性，降低溫室氣體排放減緩暖化的速率愈顯重要，由於耕作系統溫室氣體的排放受土壤性質、氣象、耕作制度、作物種類、田間管理品種特性等影響，有鑑於此，許多國家針對重要品項採用方法三 (Tier 3) 以實測或模式進行溫室氣體排放計算，其中 DNDC (Denitrification-Decomposition) 模式是廣為使用的農業溫室氣體排放模擬模型之一，本研究目的在於利用本土的水稻、大豆與落花生田間觀測數據進行模式的校正與測試，水稻的田間試驗於 111 年二期作與 112 年一期進行，包含慣行的湛水處理與節水栽培處理兩個處理，從整地到種植期間以密閉罩法監測甲烷排放量。大豆與落花生田間試驗進行於 112 年春作，包含 0、40、80 kg N ha-1 等三種施氮處理，種植期間進行生育調查並以密閉罩法監測氧化亞氮排放量。水稻試驗結果顯示，二期作的甲烷排放量較一期作高，節水栽培處理可減少兩個期作 33-35% 甲烷排放量，比較 DNDC 模式模擬與實測的甲烷排放量，可觀察到模式能夠表現不同期作、水分管理對於水田甲烷釋出的影響，但也發現一期作高估而二期作低估的現象。DNDC 模式能夠反應不同氮投入量對於大豆與落花生產量的影響，田間氧化亞氮觀測結果顯示主要的峰值發生於施肥或灌溉後，DNDC 模式可以顯示灌溉與氮投入對於氧化亞氮排放的影響。

**關鍵詞：**溫室氣體、減緩策略、DNDC

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# 前言

聯合國政府間氣候變化專門委員會 (Intergovernmental Panel on Climate Change, IPCC) 於 2019 出版了用於揭露國家溫室排放清冊編寫計算依據的指南，其以 2006 年版修正及精進。依據分類，溫室氣體計算方法有三階，方法一 (Tier1)，指南提供之預設係數；方法二 (Tier2)，地區或國家排放係數；方法三 (Tier3)，實測或模式應用。部分國家為提高碳排量的準確與精確性，在一些特定排放源的計算上已採用方法三，如美國與日本在水稻種植分別使用 Daycent、DNDC-rice 作為模擬計算，荷蘭在氮的間接碳排使用「NEMA」和「STONE」進行模擬計算。

我國農業部門的溫室氣體排放約佔整體的 1.17%，遠低於工業與能源部門，但是農業部門在甲烷與氧化亞氮排放分別佔 41.97% 與 28.08%，仍有減排的空間，其中水稻種植與農耕土壤的溫室氣體排放分別佔 18.0% 與 36.8% ( 行政院環境保護署，2022)。影響水稻田甲烷排放因素包含灌溉管理、有機物添加、土壤類型、水稻品種、硫酸鹽、氮施用量及氣候 ( 溫度 ) 等 (Nikolaisen et al., 2023)，在水稻田的水位管理上，慣行作前淹水水位在 2-5 公分間，水田甲烷排放主要途徑為水稻、冒泡及擴散。

DNDC 模式 (Denitrification-Decomposition) 是最廣為使用之土壤有機質變動、農業溫室氣體排放模擬之模型，該模式最早由李長生教授團隊所發展 (Li et al., 1992)，並持續使用不同的田間觀測資料進行模式比對、機制更新，在各區域之模式比對結果顯示出模式之穩健性 (Guest et al., 2017；Vogeler et al., 2013 )。應用於作物生長預測、氣候變遷因應、水資源管理、土壤氮流佈與溫室氣體排放等，依據地區環境的差異而進行優化，亦發展出多種衍伸模型，如 Forest-DNDC、Manure-DNDC Model、US-DNDC 和 DNDC-Rice 等 (Gilhespy et. al., 2014)。模式的輸入為每日之氣象、作物種類、土壤資訊與栽培期間田間操作 ( 耕犁、灌溉、施肥 )，輸出則為每日之作物生長、土壤有機質變動與溫室氣體 (CO2, N2O, CH4) 排放。

目前國內排放清冊所引用的本土水稻甲烷排放係數多引自 Yang 等人 (2009) 發表之報告，距前人量測調查至今已逾十多年；以中彰投地區為例水稻單位面積生產量因品種、管理或氣候等因素影響有所變化，相較於 2001 年，2020 年之水稻一期作單位面積產量

約增加 18%、二期作約 44%，若以水稻殘體及收穫量比等於 1 估計，代表水稻殘體掩埋量增加 18% 以上，在平均溫度上，亦約有 1 度的增加，二氧化碳增加以每年 1.5-2.5 ppm 增加，皆可能影響甲烷排放量；整體環境的改變，使當時水稻排放係數至今可能已失準。雖然 2021 年起之國家排放清冊，排放係數已更新部分地區係數，但其與先前調查之水稻田排放係數有明顯差異。

本研究應用田間觀察資料建立 DNDC 模式所需水稻、落花生本土化參數，比較模式模擬與實際量測結果，分析模式在我國栽培環境下進行溫室氣體模擬之可行性。

## 材料與方法

### 一、田間處理

水稻試驗區位於臺中區農業改良場之試驗田，包含一般慣行及節水處理兩種水分管理方式，一般慣行除插秧、曬田期間外，盡可能維持淹水或飽和狀況；節水處理是在插秧約 10 日後進行節水處理，在 111 年二期作採 0-5 公分管理，112 年一期作加強至 -15 至 5 公分處理。111 年二期與 112 年一期作插秧時間分別為 8 月 5 日與 2 月 23 日，施肥量依氣候狀況調整，111 年二期作施用量分別為氮 185 kg ha-1、磷酐 58 kg ha-1、氧化鉀 55 kg ha-1，112 年一期施用量分別為氮 265 kg ha-1、磷酐 115 kg ha-1、氧化鉀 110 kg ha-1。

落花生與大豆試驗區位於農業試驗所之試驗田，處理包含 3 種施氮變級，分別為 0、40、80 kg-N ha-1，每處理 3 重複，採完全隨機設計，每小區 36 m2，種植花生品種為‘臺農 11 號’、大豆品種為‘高雄選 10 號’，播種日期為 112 年 3 月 16 日。分別於播種前 1 天、播種後 44 天各施用 50% 氮，以尿素施加之，每處理皆施用磷酸鈣與氯化鉀，施用量為磷酐 60 kg ha-1、氧化鉀 60 kg ha-1，全部的磷於基肥一次施用，鉀分別於基肥與追肥各施用 50%。

### 二、溫室氣體與作物生育資料量測

本研究利用密閉罩法 (chamber) 調查田間之甲烷與氧化亞氮氣體排放作為模式比較

之驗證，將底座固定於土壤後以密閉罩蓋住底座，將管線連接氣體分析儀，分析罩內溫室氣體累積 (CH4、N2O) 變化。氧化亞氮調查設備為 Picarro G2508 與 Face EB-3200，將密閉照罩住約 30 分鐘後量測 10 分鐘。甲烷調查設備為 ABB GLA131-GGA、Licor li-7810。水稻種植時蓋住水稻植體進行量測。將密閉罩罩住約 5-15 分鐘，每一樣區進行 3 重複量測。

生育期間每 7-10 天進行採樣，每小區逢機採集 5 株，分為葉、莖、莢殼、籽粒等部位，洗淨後置入紙袋中烘乾 72 小時，測定乾重，將植體磨碎均質化，再以元素分析儀測定碳氮濃度。

**三、模式**

本研究使用之 DNDC 模式為 9.5 版，下載自新罕布夏大學網站，網址為 https://www.dndc.sr.unh.edu/。模式所需的輸入資料包括氣象、土壤、管理，氣象資料取自農業試驗所與臺中區農業改良場氣象站，兩地點的土壤特性如表 1 所示。

## 結果與討論

臺中場田間水田甲烷排放調查結果顯示，一期作初期水田甲烷排放量明顯低於二期作 ( 圖 1)，2022 年二期作慣行水田甲烷排放量約 410 kg-CH4 ha-1、節水處理 276 kg-CH4 ha-1，2023 年一期作調查結果，慣行水田甲烷排放量約 86 kg-CH4 ha-1、節水處理 56 kg-CH4 ha-1，兩種水分管理二期作的甲烷排放量為一期作的 4.7、4.9 倍。依據 IPCC 計算指南，前期作植體耕入時間越短、淹水越長，選用的甲烷排放係數越高。對比兩個期作，一期作種植初期為低溫並有較長的準備時間，二期作種植初期溫度較高播種前的準備時間較短，顯示本研究的結果與 IPCC 計算指南相近。從田區調查結果，也可觀察到水稻在二期作前之整地淹水後，就開始有甲烷排放產生 ( 圖 1) 一直持續到插秧，因此在水田的甲烷排放量計算的調查上，建議應由殘體耕入後開始進行監測與計算，以減少在計算水田甲烷排上有所遺漏。兩個試驗期作的結果顯示節水栽培的甲烷排放量為慣行處理之 67% 與 65% ( 表 2)，顯示水稻生育期間歇性灌溉可減少甲烷的排放約 33-35%。

DNDC 模擬設定如下，臺中區農業改良場土壤質地實際為黏土，但模式測試上使用中質地土壤，排放趨勢與排放量才會接近田間調查結果，可能參數之土壤物理性質尚需進一步調整，另雖有紀錄田間水位資訊，但 DNDC 載入水位資料後，無法正確演算土壤氧化還原電位，故仍使用預設 10cm、5 至 -5cm 的水位設定，依據田間管理狀況拆分 4 個灌溉管理期，插秧前 10 至 20 日、插秧後 10 日為 10cm 淹灌；插秧後 11 日至曬田及曬田後至收穫前 5 至 10 日，慣行採 10cm 淹灌設定、節水採 5 至 -5cm 的水位設定，其餘依照實際田間管理記錄設定，將相同耕作管理設定，連續模擬三年，最後以 2023 年資料進行比較。

比較 DNDC 模式模擬兩個期作不同水分管理的甲烷排放與實際觀測之時序變化 ( 圖 1)，可觀察到 DNDC 模式能夠顯示不同期作、不同水分管理對於甲烷排放的影響，模式與實際觀測的結果均顯示 2022 年二期作慣行處理主要的排放時間，為從插秧到 8 月底約 1 個月，此段時間內模擬與實測結果相近 ( 圖 1)，然而模式有低估後期甲烷排放之情形。整體而言，模式低估二期作兩種水分管理甲烷排放量、略為高估一期作節水處理之甲烷排放之趨勢 ( 表 2)。

三種不同氮施用量處理之落花生氧化亞氮排放量如圖 2 所示，三種不同施氮量處理的氧化亞氮排放量呈現隨著氮施用量增加的趨勢，但差異並不顯著，由於落花生具有固氮能力，氮投入量較其他作物來得低，因此處理間的差異對於氧化亞氮排放量的影響較少。另外，也可發現到灌溉後有氧化亞氮峰值的產生，後續在監測上應更強化施肥與灌溉後的監測頻率。DNDC 模式可以顯示灌溉與氮投入對於氧化亞氮排放的影響，但是有低估兩次灌水期間氧化亞氮排放的趨勢。

DNDC 的作物輸出檔包含每日之根、莖、葉與穀粒之每公頃碳與氮累積量 (kg/ha)，在本研究將果莢乾重視為穀粒乾重，將各部位的碳含量除以碳濃度計算生質量，落花生與大豆之生物量模擬結果與實測分別如圖 3 與圖 5 所示。經過調參的模式，模擬之收穫期的莖葉和果莢生質量與實測值的接近，此外模式能夠顯示出不同但處理對於穀粒產量的影響，DNDC 模式對於植物地上部的乾重相對簡單，是以氮累積為主要的植物生長機制，並納入缺氮、高溫、缺水對於生長的抑制 (Li et al., 1994)，在本研究中可發現模式對於最終產量模擬的穩定性。在發育期的模擬上，DNDC 模式是以播種到收穫全施用期

的累積溫度轉換為 0 至 1 的植物生長指標 (plant growth index)，該數值從播種期 ( 生長指標 0) 隨著累積溫度線性增加至收穫期 ( 生長指標 1)，當植物生長指標達 0.5 時則穀粒開始有乾物質分配 (Krobel et al., 2011)。在本研究當中，選擇果莢開始生長之始莢期 (R3) 計算累積溫度，再以該累積溫度值的兩倍作為全生育期的累積溫度值，結果顯示模擬的果莢生長趨勢與實測值趨勢接近 ( 圖 3、圖 5)。

相較於果莢的模擬，模式有高估莖葉生長的趨勢，本研究的觀察結果顯示莖葉的生長較接近前期與後期緩慢、中期接近線性生長的 S 曲線，模式的莖葉乾重在生長初期即呈現線性生長，這現象與 Krobel 等人 (2011) 指出 DNDC 模式有高估萌芽與幼苗階段之情形相似。雖然在調參過程中，可透過改變碳氮比來調整乾重的累積速率，但植株的實際碳氮比與真實觀測值則會有落差，因此未進一步進行參數的測試。DNDC 模擬地上部的乾物重的主要目的，為應用於後續模擬植物體堆置回環境中，對於土壤碳匯的影響，最主要的植物碳氮產量為收穫期的乾物重，從本研究可觀察到 DNDC 模式能提供具有參考性的收穫期產量資訊。

## 結論

本研究應用田間觀察資料進行 DNDC 模式比對，顯示模式能針對莖葉與果莢產量提供具有可信度的模擬結果，水稻試驗結果顯示，節水栽培處理可減少兩個期作 33-35% 甲烷排放量，比較 DNDC 模式模擬與實測的甲烷排放量，可觀察到模式能夠表現不同期作、水分管理對於水田甲烷釋出的影響，氧化亞氮排放量呈現隨著氮施用量增加的趨勢，但差異並不顯著，主要的峰值發生於施肥或灌溉後，DNDC 模式可以顯示灌溉與氮投入對於氧化亞氮排放的影響。

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**表 1　水稻、大豆與落花生試驗區土壤性質**
**Table 1　The soil characteristic of paddy rice, soybean and peanuts farmland.**

| | pH | SOM (%) | Soil Texture | BD |
|---|---|---|---|---|
| 落花生與大豆試驗區 | 5.6 | 1.28 | Loam | 1.28 |
| 水稻試驗區 | 7.6 | 2.08 | Clay | 1.33 |

**表 2　水稻慣行與節水處理田間甲烷排放量 (kg CH4 ha-1)，調查時間量包含由整地翻耕至收穫**
**Table 2　The methane emission (kg CH4 ha-1) of conventional and AWD paddy rice, the monitoring period started from land preparation to harvest.**

| | 慣行 | | 節水 | |
|---|---|---|---|---|
| | 田間調查 | DNDC 模擬 | 田間調查 | DNDC 模擬 |
| 2022 二期作 | 410 | 286 | 276 | 202 |
| 2023 一期作 | 86 | 86 | 56 | 66 |

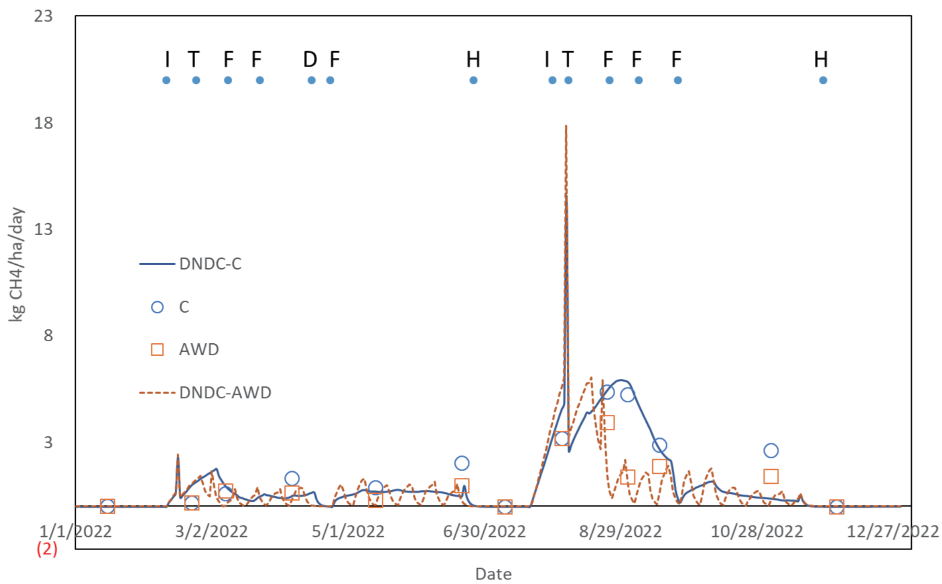


圖 1　水稻田間甲烷調查結果與 DNDC 模擬之比較
Fig. 1　The field observed and DNDC model simulated methane emission of paddy rice farmland.

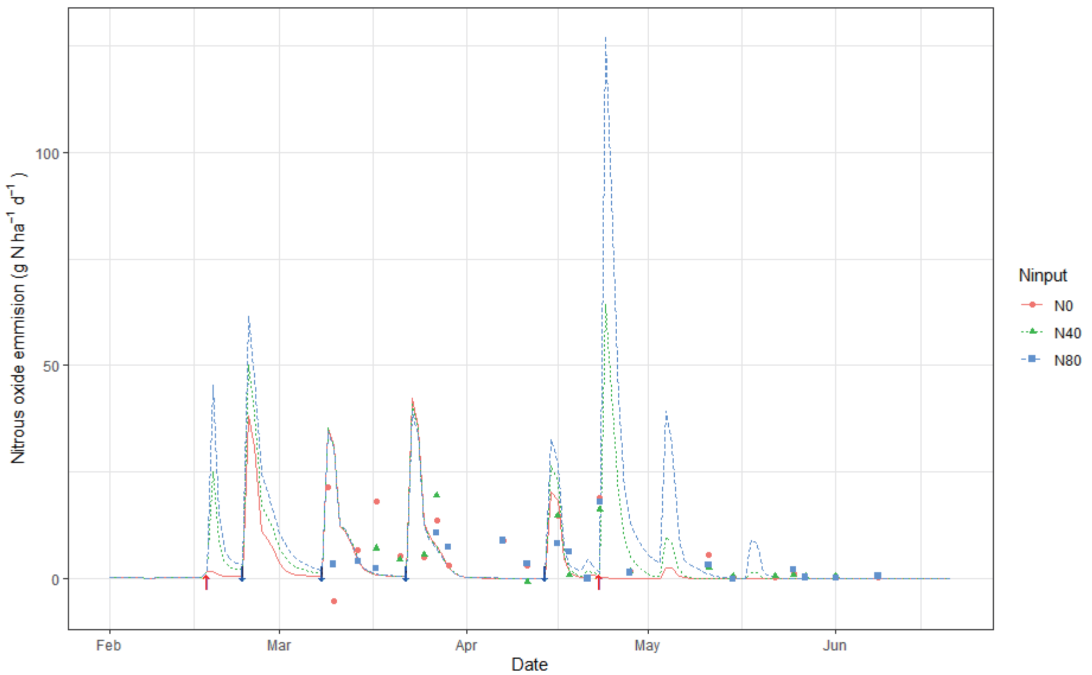


圖 2　落花生試驗區三種施氮處理之氧化亞氮調查結果與 DNDC 模擬比較，施氮處理分別為 0、40、80 kg N ha-1，紅色往上箭頭代表施肥日期，藍色向下代表灌溉日期

Fig. 2　The field observed and DNDC model simulated nitrous oxide emission from peanut farmland of three nitrogen application treatments. The nitrogen treatments includes 0、40、80 kg N ha-1, the upward arrows represent fertilization dates and downward arrows represent irrigation dates.

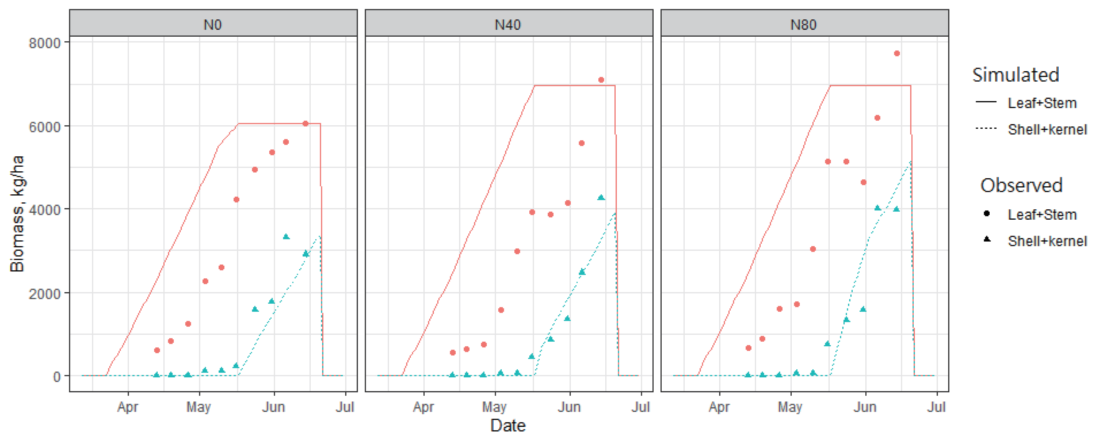


圖 3　落花生試驗區三種施氮處理之生物量 (kg ha-1) 調查結果與 DNDC 模擬比較，施氮處理分別為 0、40、80 kg N ha-1

Fig. 3　The field observed and DNDC model simulated plant biomass of peanut from three nitrogen application treatment (0, 40, 80 kg N ha-1).

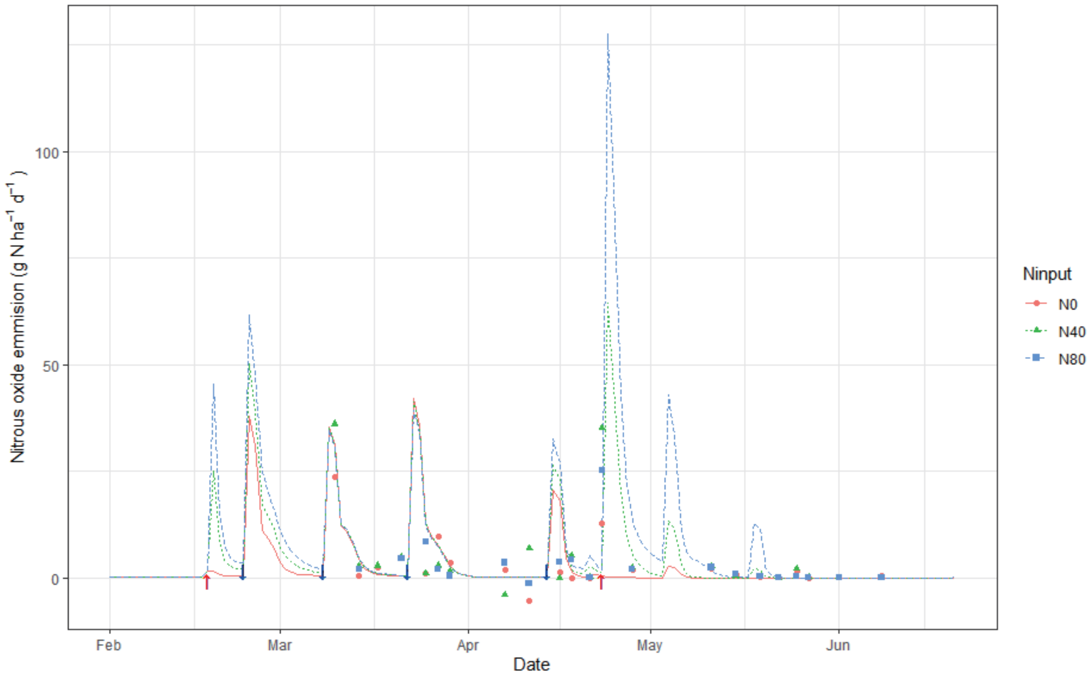


圖 4　大豆試驗區三種施氮處理之氧化亞氮調查結果與 DNDC 模擬比較，施氮處理分別為 0、40、80 kg N $ha^{-1}$，紅色往上箭頭代表施肥日期，藍色向下代表灌溉日期

Fig. 4　The field observed and DNDC model simulated nitrous oxide emission from soybean farmland of three nitrogen application treatments. The nitrogen treatments includes 0、40、80 kg N $ha^{-1}$, the upward arrows represent fertilization dates and downward arrows represent irrigation dates.

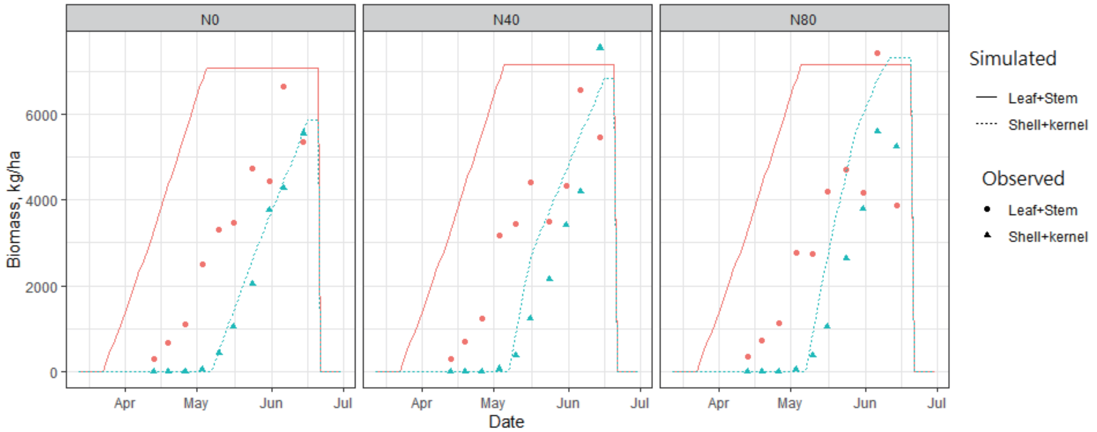


圖 5　大豆試驗區三種施氮處理之生物量 (kg ha-1) 調查結果與 DNDC 模擬比較，施氮處理分別為 0、40、80 kg N ha-1

Fig. 5　The field observed and DNDC model simulated plant biomass of soybean from three nitrogen application treatment (0, 40, 80 kg N ha-1).

# Simulation of crop growth and greenhouse emission with DNDC model

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## Abstract

More and more evidence indicates the correlation between human activities and climate change. Therefore, it is important to reduce greenhouse gas emissions to mitigate the pace of global warming. The greenhouse gas emissions from farming systems are affected by soil property, weather condition, farming system and field management activity. In views of this, more and more countries use Tier 3 to calculate greenhouse gas emissions by actual measurement or model for important items. DNDC model is one of the widely used agricultural greenhouse gas emission simulation models. The purpose of this study is to establish local parameter and test the DNDC model by using field observation data of rice, soybean and peanut. The field experiment of rice was carried out in the 2022 second crop of and the 2023 first crop and the treatments included the conventional irrigation practice and alternate wetting and drying (AWD). Methane emissions were monitored by close chamber method from soil preparation to harvesting for both treatments. The soybean and peanut field experiment was carried out in the 2023 spring crop, including three nitrogen treatments of 0, 40, and 80 kg N ha-1. The crop growth parameter and the nitrous oxide emission were monitored during the crop growth period. The rice experiment results show that the methane emission of the second crop was higher than that of the first crop, and the AWD treatment can reduce the methane emission by 33-35%. The DNDC model simulated methane emission in acceptable agreement with observed in different planting season and irrigation management, but it is also found the model overestimated methane emission in first crop and underestimated in second crop. In the crop simulation, the model simulated the yield of soybean and peanut from different nitrogen application in reasonable results. Field nitrous oxide observations show that the main peak occurs after fertilization or irrigation. The DNDC model can reflect the effects of irrigation and nitrogen inputs on nitrous oxide emissions.

**Keyword:** Greenhouse gas, Mitigation strategy, DNDC

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# 水稻減碳生產技術策略

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## 摘要

水稻是臺灣最重要的糧食作物，其生命周期各階段會帶來溫室氣體排放，加劇氣候變遷與全球暖化。因此為抑制暖化朝 2050 年淨零碳排的目標進行，須先進行生命周期評估的碳排資訊建立，再依其中的「熱點」進行調整，以達到整體減碳。稻米生命周期的碳排熱點，在於田間栽培階段、加工碾米階段及運輸階段。田間栽培階段方面，可應用間歇灌溉、合理化施肥或肥料種類的選擇來降低甲烷與氧化亞氮排放;加工碾米階段，則可以採用稻殼混合烘乾技術來節能與減少二氧化碳；運輸階段，則可以在地生產或以大量運輸方式來減碳。總結以上，除了應用技術來減碳之外，仍應考量經濟層面的市場交易與社會層面的糧食分配，以達到最佳的減碳效益。

**關鍵詞：**水稻、生命周期評估、甲烷、氧化亞氮、間歇灌溉、合理化施肥

1 本文為第一作者博士論文之一部分。

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# 前言

氣候變遷與全球暖化是目前人類所面臨最重要的挑戰，諸多證據顯示 20 世紀後的全球暖化乃是由於工業革命後的大量化石燃料使用所排放的各種溫室氣體，加劇了固有的溫室效應，導致氣溫的升高，並引發各種異常氣候 (IPCC, 2022)。農業受到氣候變遷的影響是所有產業中最顯著者，然而農業也對氣候變遷的加劇有所貢獻，農業活動排放的溫室氣體如二氧化碳、甲烷與氧化亞氮正是加劇暖化的元兇。聯合國糧農組織 (Food and Agriculture Organization, FAO) 有鑑於此，早在 2010 年即定義氣候智慧型農業 (Climate Smart Agriculture, CSA)，主要目標為 1. 增加農業生產與收益；2. 建立農業對氣候變遷的適應力與彈性；3. 降低溫室氣體的排放及增加其吸存。而以「調適 (Adaptation)」與「減輕 (Mitigation)」二方向來進行 (FAO, 2010)，其中「減輕」即為藉由生產方式的調整，設法降低溫室氣體排放，以達到減緩暖化的效果。研究指出，必須在 2050 年全球達到溫室氣體的淨零排放，也就是排放與吸存量彼此平衡，才能使全球升溫抑制在 1.5oC 之下 (IPCC, 2022)，因此，各產業更須加緊腳步進行減碳策略的擬定，然而，減碳策略擬定之前，需要先瞭解現行產業的碳排資訊，也就是須先藉由「生命周期評估 (Life Cycle Assessment, LCA)」進行碳排資訊建立，再依其擬定相對應的減碳策略，諸如低碳栽培管理、運輸規畫、加工效率等，以期收事半功倍之效。本文將以稻米為例，說明水稻生產過程中的碳足跡、減碳栽培管理以及其他階段的減碳方式，作為未來稻米產業的重要參考。

# 生命周期評估與稻米生產的碳足跡

「生命周期評估」是環境工程學上評估環境衝擊的方式，依照 ISO 14040 的規範，生命周期評估係指產品從原料生產、加工、包裝、運輸，以至於後段的上架、販售、使用，以及最後的廢棄處理等所有過程 ( 即生命週期 )，進行整個過程中對於環境的影響評估，評估面向包括資源使用、人類健康與生態的影響，再藉由定義、調查、評估與闡釋，將產品之生命過程對環境之影響得到詳細的分析 (ISO, 2006)，而其評估的衝擊種類

之一即為溫室效應潛勢 (Global Warming Potential, GWP)，或稱之為碳足跡，目前碳足跡的生命周期評估亦有國際標準規範明定於 ISO 14067。而生命周期評估的主要意義在於分析各產品的環境衝擊總量，以及依評估結果，篩選出影響此衝擊的關鍵步驟，或顯示出衝擊最顯著的階段 ( 稱之為「熱點」)，進而依此修正關鍵步驟以達到環境親和的目標。

稻米的生命周期，從稻種準備、育苗、整地、灌溉、插秧、施肥、噴藥、收穫，以至乾燥、碾製、加工、包裝、運輸等，每個階段都造成各種環境衝擊，包括目前最為人重視的溫室氣體排放。例如，機械使用與投入資材的製造端耗用的能源如汽油、柴油、電力，而汽油、柴油或其他燃油在燃燒後，將排放溫室氣體之一的二氧化碳，貢獻碳排放。而水稻在農業生產中，溫室效應潛勢最嚴重的，來自湛水之下的田間土壤。土壤在湛水缺氧狀態下，還原態的土壤電位容易促使有機碳被甲烷生成菌進行無氧分解，產生甲烷，每單位質量貢獻 28 倍二氧化碳當量的溫室效應潛勢。此外，肥料製造的過程亦十分重要，化學肥製造時需要投入大量的能源，尤其是化學氮肥製造時需要高溫高壓環境進行哈柏法 (Smil, 2004)，研究指出化學氮肥的製造耗能就占全球總耗能的 1% (FAO, 2017)，這些能源在製造的過程，都會帶來二氧化碳的排放；而有機肥在製造過程的堆肥化步驟中，因堆肥化環境為有氧或無氧，會分別產生二氧化碳與甲烷，亦成為溫室氣體的間接排放源 (Maeda et al., 2013 ; Ge et al., 2016)。再者，田間溫室氣體排放，其單位質量溫室效應潛勢最高者為氧化亞氮，是 298 倍的二氧化碳當量。研究指出，農田產生的氧化亞氮來自土壤中未被作物吸收氮素的分解，但排放量則與施加氮肥的種類、施用量、施用時機、土壤含水量、微生物活性、土溫等因素有關。基於上述說明，水稻的碳足跡主要來自甲烷、氧化亞氮及二氧化碳的直接與間接排放，茲就此 3 種溫室氣體的減排可能策略進行論述。

## 田間甲烷減排

據統計，大氣甲烷的濃度正以每年 1 % 的速度上升中，甲烷主要由有機碳在缺氧環境下被甲烷生成菌 (methanogen) 分解所產生，因此主要來源為牛、羊等草食動物的腸胃排放及農田土壤釋放，而二者都和農業操作的方式與細節有關。甲烷生成菌在缺氧的環

境，也就是土壤氧化還原電位低的時候，具有良好的活性，並大量將有機碳轉變為甲烷釋放，也就是「湛水缺氧」與「土壤有機碳」是影響甲烷排放最重要的因子，研究指出，水田湛水的深度、時間長短、水稻品種都會影響甲烷釋放量 (Kesheng and Zhen, 1997；Aulakh et al., 2001)，甚至有機栽培常用的稻鴨共生法，因鴨子在田間游動使得田水溶氧增加，間接降低甲烷生成 (Huang et al., 2005)；然而有機農法施用的有機肥含有大量有機碳，在水田轉為大量甲烷生成 (Vibol and Towprayoon, 2010)。

由於甲烷排放源主要在田間，品種、灌溉、施肥等皆扮演重要角色，早在 20 年以前，已有學者提出栽培不同水稻品種的田間甲烷排放量具有差異 (Shao and Li, 1997)，近年栽培品種同樣具有差異性 (Riya et al., 2012)，品種造成甲烷排放量差異的原因在於稻株的形態，包括根系活性、根系多寡、莖葉多寡、根部通氣組織大小 ( 曹等，2005；葛，2016)，因此可以推測，根系吸水力、通氣組織、莖葉多寡等皆相關於稻株吸水與蒸散效率，效率越高者，甲烷排放量越大，也由於吸水蒸散效率相關於根、莖、葉及整體植株生理，因此無法單就地上部株型作為品種篩選的依據 (Zhang et al., 2015)，育種上的挑戰較為複雜。灌溉方面，水稻為水田式栽培，為抑制雜草，常執行深水灌溉，但深水灌溉之土壤缺氧狀態導致甲烷產生，故若適當應用間歇灌溉，即湛水後讓田水自然消退，待水位降至土面無水再進行灌溉，提高土壤氧氣含量，將有效降低甲烷的生成 ( 黃等，2000；Cabangon et al., 2002；Islam et al., 2018；Rahman et al., 2019)，且在最高分蘗期與成熟期進行間歇灌溉，效果更加顯著 (Yagi et al., 1997)，此外，間歇灌溉亦具有降低水資源耗用、能源耗用、優養化潛勢等優點 (Gathorne-Hardy et al., 2016)，間歇灌溉的減碳效益，近年已在國際稻米研究中心 (IRRI)、泰國、孟加拉的研究中證實 ( 表 1)，在有機栽培之下甚至可減降 60 % 的 GWP(Maneepitak et al., 2019；Islam et al., 2020)。然而，過度進行間歇灌溉，將由於降低最終稻穀產量，而甲烷排放未呈現持續減量，導致環境效益反而降低 (Fertitta-Roberts et al., 2019)。另一方面，許多有機水稻栽培會在田水種植滿江紅 (Azolla 屬浮水植物 )，作為覆蓋作物及生物性肥料，滿江紅可藉由在田水中釋放氧氣的方式，間接降低田間甲烷排放 (Bharati et al., 2000；Ali et al., 2015)。施肥方面，一般來說，化學肥的有機質含量較低，較少有機碳的投入，將減少生成甲烷的原料，進而降低其生成排放，然而，有機肥的種類繁多，包括植物性堆肥、動物糞便堆肥、沼渣肥、

綠肥、作物殘體等，不同的有機肥將有不同的甲烷的排放影響 ( 劉等，1999；Bacenetti et al., 2016；Fusi et al., 2017)，施用完全腐熟的堆肥較新鮮有機質 ( 作物殘體、綠肥 ) 有較低的甲烷排放 (Yagi and Minami, 1990；Jeong et al., 2018)，且不管在有機栽培或半有機栽培都呈現相同趨勢 (Jeong et al., 2019)。推測原因在於堆肥過程將使其總有機碳、碳氮比降低，使得施用時的碳投入減少，降低甲烷生成，另一方面，堆肥化亦將提高有機肥的 pH 值、總氮含量 ( 陳，2007)，除增加施肥效率外，增加的 pH 值更可抑制甲烷及氧化亞氮的生成。再者，一般堆肥的碳氮比約在 20-30(Guo et al., 2012)，而沼渣肥的碳氮比則多在 10 上下 (Rejis et al., 2005)，沼渣肥的低碳氮比，將降低甲烷的生成 (Li et al., 1997)，但卻可能增加氧化亞氮的排放風險 (Vallejo et al., 2006)。

## 田間氧化亞氮減排

根據統計，在綠色革命之後，意即 1970 年以後，短短 20-30 年間，全球的肥料使用量呈現倍增的現象，在 1990-2000 年期間，氮肥的使用量更增加了 10 Mt 之多；同時科學家注意到此時大氣中的氧化亞氮、NOx 與 N2 濃度增加了 35 % (Desjardins et al., 2007)，意即可以推測氧化亞氮的排放量上升可能來自增施的氮肥，前人研究亦指出，60 % 的氧化亞氮增加量是來自於農業的氮肥分解排放及其他間接排放 ( 楊，2008)。據研究，臺灣農田的氧化亞氮排放量為 8.8 Kt，依照田間栽培管理的不同 ( 尤其是灌溉管理 )，將有多達 20 倍以上的排放量差異 ( 錢等，2010)，且氧化亞氮排放量隨著氮肥施用量增加而上升 (Scheer et al., 2008)，在濕潤條件之下更將促進其排放 (Weitz et al., 2001)，然而，氮素在土壤中分解為氧化亞氮的反應需要氧氣的參與，故水稻田在湛水狀況下，產生的氧化亞氮極少，遠不及旱田 (Nishimura et al., 2005)，因此水稻生產時的氧化亞氮排放，主要集中在栽培中期的排水曬田期，以及遭遇缺水灌溉的情況 ( 錢等，2010)。

基於以上前人研究，減量施肥可有效降低氧化亞氮排放 (Cole et al., 1997；Freney, 1997)，除了施肥量，施肥時機亦決定氧化亞氮的排放量 (Hao et al., 2001)，前述試驗結果指出二期作的排放高於一期作，是由於施肥時機的溫度較高，氮肥礦化反應速度快所

導致，應盡可能選擇在氣溫涼爽的時機施肥。此外，氮肥與空氣的接觸將促進其氧化作用並造成氮氧化物 ( 包括氧化亞氮 ) 的釋放 (Millar et al., 2010)，除減少氮肥製造與儲存時與空氣的接觸之外 (Hasler et al., 2015)，水稻田在施肥後立即灌溉，隔絕氮肥與空氣也是一個方式 ( 賴，1997；Cai et al., 1997)，或是使用土壤深層施肥技術，除增加氮素利用效率，更可減低氧化亞氮排放 (Liu et al., 2006)，再者，許多國家應用不整地或低度整地栽培，降低下層土壤與空氣接觸，亦可減緩土壤氮素被分解為氧化亞氮散失 (Mummey et al., 1998)，且更有助於土壤有機碳的累積，降低二氧化碳及甲烷的排放 (Alam et al., 2019)。施用的氮肥種類也與氧化亞氮排放息息相關，臺灣水稻栽培常用的氮肥有銨態氮及尿素，前人研究指出，尿素較容易被礦化生成氧化亞氮，故使用分解較慢的硫酸銨作為氮肥為佳 (Tenuta and Beauchamp, 2003；Schellenberg et al., 2012)，若仍要使用尿素，則可在尿素中添加尿素酶抑制劑及硝化抑制劑，將可減緩氧化亞氮排放 (Mosier et al., 1996)，此外，為提高氮素利用效率與節約施肥次數，農業上常使用緩釋性肥料，對氧化亞氮減量同樣有助益 (Yan et al., 2000)，主要原因在於緩慢釋放的有效氮素，被作物吸收的比率提高，即降低氮素被礦化分解的可能 (Snyder et al., 2007)。

## 生命周期二氧化碳減排

二氧化碳方面，儘管農作物生長行光合作用會吸收二氧化碳，但形成的生物量多半會經由呼吸作用或微生物分解再回歸大氣，若未將生物量以穩定的形式固定 ( 如深層土壤有機碳、木材、媒炭等 )，則難以進行二氧化碳吸存與形成碳匯，因此一般田間栽培階段的作物及土壤之二氧化碳排放，為碳循環的一部分，通常不計入整體碳足跡的排放計算 (Hokazono and Hayashi, 2012)。而在農業活動所消耗的能源，若非來自綠能，都將直接或間接造成二氧化碳排放，而能源耗用的二氧化碳排放，才是水稻生命周期中關於二氧化碳的碳排計算來源。

研究結果顯示，能源耗用的熱點在於資材製造端、收穫後加工、運輸過程，不同肥料的製造過程的耗能存在差異，舉例來說，依 SimaPro 資料庫，單位氮素的尿素製造過程溫室氣體排放，較硫酸銨高出 23%，而各種肥料製造端的環境衝擊亦不盡相同 (Hasler et al., 2015)，選擇低碳的資材使用是重要的第一步。其次，收穫後加工的階段，最主要的耗能在於稻穀的烘乾，然而，耗能多寡取決於烘乾的時間長短，烘乾時間則由收穫後的稻穀含水率決定，因此若能在田間稻穀完全成熟後，即稻穀含水率在 24-28% 再進行採收，將可降低此階段的二氧化碳排放，值得注意的是，碾米過程的副產物—稻殼，近年來常直接置於在烘穀機內燃燒，替代熱能來源，間接降低化石燃料耗用，減少二氧化碳排放，前人研究指出，將稻殼直接燃燒替代能源之下，每 kg 稻殼可獲得 1 kg 的二氧化碳減排效益 ( 何，2001)，就生命周期評估的整體觀點，在溫室效應潛勢、酸化潛勢及優養化潛勢則分別有 97%、88% 及 80% 的減量效益 (Quispe et al., 2019)，再者，應用稻殼的乾燥系統更可能結合預熟米的製程，傳統預熟米的預熟處理之溫室效應潛勢占總量的 23-24% (Roy et al., 2007；Nunes et al., 2017)，新型稻穀乾燥系統可降低預熟米加工過程超過 85% 的溫室效應潛勢 (Kwofie and Ngadi, 2017)，甚至燃燒後的稻殼灰，可作為水泥的添加物，改善水泥的製造成本、溫室效應潛勢及工業特性 (Gursel et al., 2016；Henry and Lynam, 2020)。最後，是變動幅度最大的運輸階段，此階段的碳足跡關聯到運輸的距離，一般來說，臺灣的水稻生產，不管是原料與資材的運移，或是收穫後稻穀載至碾米廠，大抵符合在地作業的模式，然而在工廠產出白米產品，運送至販售地點的階段，其里程則大幅增加，臺灣的人口集中在北部，但主要稻米產區則在中南部，產品由南向北運輸的流向顯著，目前多以貨車運輸，實際上，火車運輸的單位貨物碳足跡僅有貨車的 10% (Reich, 2012)，原因在於單次輸送貨物量大，但火車運輸較偏向於長距離與共同目的地，仍需要系統性的規畫。亦有其他研究指出，除了減少進口農產品的依賴，城市農業或城郊農業，將可大幅減少食物里程 (food mileage) 而降低運輸的碳足跡 (Lee et al., 2015)。

## 結語

水稻生產過程，各階段都帶來多寡不一的碳排，總結來說，機械密集度高、肥料施用量大、灌溉時間長，會導致大量的溫室氣體排放，然而，減少投入的策略，例如改以自然農法栽培系統，雖然單位耕地面積的碳排降低，但由於稻穀產量的低落，最終的稻

米產品碳足跡也未必具有優勢，因此，須考慮各種減碳策略施行之下，在維持產量與品質的前提，並評估未來氣候環境的交感，發展「整合型的低碳栽培體系」。此外，在生命周期的後半，包括運輸階段與使用階段，則相關於交易市場與糧食分配，以及是否有分配不均以致貯存階段碳排增加或品質劣化的疑慮，也是未來在稻米產銷規畫上，必須進行的調整。整合農業技術的生產層面、交易市場的經濟層面、糧食分配的社會層面，方能達到整體性的「低碳稻米」。

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**表 1　間歇灌溉在熱帶亞洲國家稻田的減碳效益**

**Table 1　Benefits of carbon decreasing of alternative wetting and drying irrigation in tropical Asian countries.**

| | | IRRI[a] | | 泰國[b] | | 孟加拉[c] | |
|---|---|---|---|---|---|---|---|
| | | 傳統灌溉 | 間歇灌溉 | 傳統灌溉 | 間歇灌溉 | 傳統灌溉 | 間歇灌溉 |
| 單位耕地面積[d] | 慣行 | 2.89 | 1.59 | 5.51 | 4.01 | 8.86 | 5.74 |
| | 有機 | 8.90 | 2.80 | -- | -- | -- | -- |
| 單位白米產量[e] | 慣行 | 0.41 | 0.24 | 1.53 | 0.96 | 1.56 | 1.05 |
| | 有機 | 1.61 | 0.49 | -- | -- | -- | -- |

資料來源 : [a]Islam et al., 2020a ; [b]Maneepitak et al., 2019 ; [c]Islam et al., 2020b

[d] 單位 ton CO2 eq / ha

[e] 單位 kg CO2 eq / kg 白米

# Strategies of rice production for carbon emission reduction

Yi-Chien Wu[12]* Chong-Yi Liao[2] Chi-Yong Deng[2] Chen-Hong Lee[2] Huu-Sheng Lur[3]*

## Abstract

Rice is the most important food crop in Taiwan, and its life cycle will bring about greenhouse gas emissions, exacerbating climate change and global warming. Therefore, in order to curb global warming and move towards the goal of net zero carbon emissions by 2050, it is necessary to establish life cycle assessment carbon emission information first, and then adjust according to the "hot spots" in order to achieve overall carbon reduction. The carbon emission hotspots in the rice life cycle are in the field cultivation stage, rice processing and milling stage, and transportation stage. In the field cultivation stage, alternative wetting and drying irrigation, rationale fertilization or selection of fertilizer types can be applied to reduce methane and nitrous oxide emissions. In the rice processing and milling stage, rice husk mixed drying technology can be used to save energy and reduce carbon dioxide. In the transportation stage, local production or shipped in bulk to reduce carbon emissions. To sum up the above, in addition to the application of technology to reduce carbon emissions, market transactions at the economic level and food distribution at the social level should still be considered to achieve the best carbon reduction benefits.

**Keyword:** Rice, Life cycle assessment, Methane, Nitrous oxide, Alternative wetting and drying, Rationale fertilization

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# Improvement of water-use efficiency of crops using symbiotic microorganisms: A potential sustainable approach to water management in cropping systems

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## Abstract

This study focuses on a collection of endophytes comprising plant-living bacteria and yeast isolated from native Salicaceae trees in Washington State of the United States. The article demonstrates the agricultural potential of these endophyte isolates through laboratory and greenhouse experiments conducted under abiotic stress conditions, highlighting their capacity for biological nitrogen fixation (BNF) and other growth-promoting traits. Among the various benefits observed, this article discusses explicitly the enhanced water use efficiency (WUE) observed in host plants that could be utilized in agricultural water management in cropping systems. Elite endophyte strains were carefully selected based on their growth-promoting characteristics, BNF capacity, and in vitro phytohormone production profiling, confirming their ability to synthesize ABA and other hormones. Furthermore, a consortium of these endophytes successfully colonized rice plants and significantly increased biomass under N-limited conditions. In a subsequent study on leaf physiology, rice leaves inoculated with the endophytes exhibited reduced stomatal conductance during the daytime and decreased stomatal density. These responses were likely attributed to increased ABA content in the inoculated plants, resulting in reduced transpiration and improved WUE without compromising

photosynthetic capacity. Even with less opening stomata the inoculated rice plants were able to maintain photosynthetic capacity. This may due to re-assimilation of respiratory CO2 from the endophytes. Additionally, the endophytes facilitated electron transfer and CO2 diffusion in rice leaves, particularly under elevated CO2 conditions. These findings suggest that the enhanced WUE conferred by endophytes is closely related to stomatal responses in the host plant. The effects were particularly pronounced under N-limited, drought stress, and elevated CO2 conditions. However, the specific contribution of increased ABA synthesis, CO2 re-assimilation, or both remains unclear, necessitating further mechanistic investigation.

**Keyword:** Plant-endophyte symbiosis, Water relations, Photosynthesis, Respiration, Water-use efficiency

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# Introduction

Climate change poses a significant challenge to agriculture, affecting crop yields and increasing the demand for food production due to the growing global population (Cai et al., 2015). Sustainable methods are needed to enhance crop resiliency and improve yield while reducing the reliance on chemical inputs and irrigation. Water usage, mainly through irrigation, is a significant concern, and innovative approaches to water use efficiency (WUE) are necessary due to unpredictable precipitation patterns and extreme weather events (Flexas, 2016).

To achieve higher crop sustainability, efforts include increasing plant water use efficiency through genetic manipulation (Franks et al., 2015), drought-tolerant genotype selection (Condon et al., 2004), and canopy structure optimization (Drewry et al., 2014). However, these techniques still need to be developed and may not be practical for large-scale implementation.

Endophytes, microorganisms living within plants, have been found to enhance plant fitness and performance under stressful conditions (Döbereiner, 1992). They offer a promising avenue to increase crop WUE and yields. Previous studies have demonstrated the benefits of endophytes in improving plant fitness under low water availability, including water stress tolerance (Gagne-Bourque et al., 2016；Khan et al., 2015；Khan et al., 2016). The use of endophytic symbioses in agriculture has the potential to supplant current methods and enhance crop resilience.

Endophytic bacteria and yeast were isolated from Salicaceae plants and have shown potential symbiotic traits, such as phytohormone production and N fixation (Doty et al., 2009). Previous studies demonstrated increased biomass and yield potential in rice when inoculated with endophytes (Kandel et al., 2015). However, the physiological benefits and mechanisms underlying these effects have yet to be fully explored.

Some endophytes produce abscisic acid (ABA), a hormone in stomatal control and development. Studies have shown that endophytes producing ABA can trigger stomatal closure and affect stomatal development, potentially contributing to drought tolerance in host plants (Khan et al., 2016).

Rice is an isohydric species sensitive to water demand during the daytime (Parent et al., 2010). The control of stomatal openings is crucial for managing water resources and photosynthesis. The effects of endophytes on stomatal control have shown conflicting results in different plant species.

A series of greenhouse experiments were conducted using rice to understand endophyte effects on host-plant water relations comprehensively (Rho et al., 2018b). The study investigated physiological attributes such as stomatal responses, water use, and biomass gain upon endophyte inoculation. The effects of different endophyte strains and environmental conditions, such as water deficits, elevated CO2, and light levels, were also examined.

The study also explored the potential role of endophytes in mitigating the down-regulation of photosynthesis under elevated CO2 conditions(Rho et al., 2020). Like rhizobium bacteria in legumes (Ainsworth and Rogers, 2007；Rogers A. et al., 2009), endophytes may help alleviate down-regulation by facilitating carbon (C) and nitrogen (N) metabolic processes.

The respiratory activity of endophytes contributes to their energy requirements, derived from carbohydrates provided by the host plant (Rho et al., 2018a). The release of CO2 during respiration can be re-assimilated by the host plant for photosynthesis (Bloemen et al., 2013), potentially reducing the need for stomatal openings to take up atmospheric CO2. The re-assimilation of respiratory CO2 can benefit plants by providing an additional source of CO2 for photosynthesis.

Further investigations are needed to understand the respiratory behaviors of endophyte-symbiotic plants and the metabolic costs and benefits associated with endophytic symbiosis.

Overall, the study provides insights into the mechanistic impacts of endophyte symbiosis on water relations and photosynthesis in rice plants, offering valuable knowledge for enhancing crop sustainability and water management in agriculture.

## Material and Methods

### Experiment 1: A greenhouse study using multiple endophyte strains

*1.1 Origins and inoculation preparation of endophytes*

Nine strains of diazotrophic endophytic bacteria and yeast used in this study were previously characterized by Doty et al. (2009). These strains (WP1, WP5, WP9, WP19, WPB, WW5, WW6, WW7C, and PTD1) were isolated from wild black cottonwood and willow trees at the Snoqualmie River, Western Washington, while PTD1 was isolated from hybrid poplar (Doty et al., 2005). These strains have shown potential diazotrophic activity and positive effects on biomass increase in host plants (Doty et al., 2009；Kandel et al., 2015；Khan et al., 2015；Khan et al., 2016；Knoth et al., 2013；Knoth et al., 2014). We used the same inoculation method developed in prior studies.

The selected endophytes were grown on a N-limited combined carbon medium (NL-CCM) to maintain their N fixation ability. After confirming growth, cell suspension cultures were initiated in flasks with NL-CCM broth. The optical density of the bacterial culture was measured after 3-5 days using a spectrophotometer (UV-1700, Shimazu America Inc., Columbia, MD, USA). The final inoculation concentration was adjusted to OD600 = 0.1 (~1 × 107 cells) using sterile deionized water and N-free liquid media (Doty et al., 2009). A mock inoculum was prepared as a control. All procedures were conducted using sterile techniques.

*1.2 Preparation of plant and microbial materials*

Three bacterial strains (WP5, WPB, and PTD1) were selected to study host plants' water relations, particularly stomatal behaviors. Experiment 1 was conducted from October 15th, 2014, to March 28th, 2015.

The M-206 rice variety (Oryza sativa subsp. japonica M-206, very-early to early-maturing variety) was chosen and surface-sterilized using 3% NaOCl. Seeds were rinsed with sterilized deionized water to eliminate the remaining NaOCl. Although this technique may not remove all internal microorganisms, it ensures surface cleanliness for studying endophyte effects.

Seeds were planted in 1-gallon pots with horticultural root media (Sunshine Mix #2 Sun Gro Horticulture, Agawam, MA, USA). Four treatment groups (WP5, WPB, PTD1, and CTRL) with ten replicates each were arranged in a randomized complete block design. The greenhouse had controlled temperature, relative humidity (RH), and lighting conditions. After inoculation, plants received a N-free liquid nutrient solution and water.

*1.3 Measurement of stomatal conductance*

On the 163rd day after germination, at approximately the R3-4 growth stage, diurnal changes in stomatal conductance (gs) were measured at 3-hour intervals from 9 am to 6 pm using steady-state leaf porometers (SC-1, Decagon Devices, Inc., Pullman, WA, USA). The instruments were calibrated on-site before the initial measurements taken at 9 am.

**Experiment 2: Growth chamber study with endophyte consortia**

To gain mechanistic insights into stomatal conductance responses, we repeated Experiment 1 in the same greenhouse facility from March 23rd to July 20th, 2017. The objective was to test the hypothesis that endophyte consortia producing ABA would increase in vivo ABA concentrations in host plants.

*2.1 Plant material preparation and inoculation*

We followed the protocols from Experiment 1 for preparing the plant and microbial samples and conducting the inoculation process. In summary, 32 rice plants were grown in 3-gallon pots in four sunlit chambers. Half of the surface-sterilized plants were inoculated with the nifH endophyte consortium seven days after germination. The plants were cultivated under well-watered and N-limited conditions, and measurements and sampling were carried out over 104 days. The average air temperature, recorded using a data logger (CR1000, Campbell Scientific, Logan, UT, USA), was 21/17 °C (day/night). The average daily light integral (DLI) was 10.8 mol m−2 d−1 of photosynthetically active radiation (PAR) with a 16/8-hour photoperiod of supplemental lighting. Air temperature and light intensity were recorded every 15 minutes. The average relative humidity (RH) was 57% during the day and 59% at night.

### *2.2 Measurement of stomatal conductance*

At 66 days after germination, around the V6-7 growth stage, gs of the youngest fully expanded leaves was measured at 12 pm and 6 pm using steady-state leaf porometers (SC-1). The measurement procedure described in Experiments 1 and 2 was applied.

### *2.3 In vivo ABA assay*

Diurnal changes in in vivo ABA content were determined biochemically using the Phytodetek enzyme-linked immunosorbent assay (ELISA) kit (PDK 09347/0096, Agdia, Elkhardt, IN, USA). At 96 days after germination, rice leaf samples were harvested around the R3-4 growth stage at 12 pm and 6 pm. The fully expanded youngest leaves were frozen in liquid N in centrifuge tubes and stored at −80 ˚ C until further analysis. The samples were ground into a fine powder, and approximately 100 mg of each powder was transferred to a microtube. ABA was extracted using 1 mL of 80% methanol at 4 ˚ C overnight. The mixture was centrifuged at 10,000 rpm for 5 minutes, and the supernatant was collected. The pellet was resuspended, and the extraction process was repeated with 1 mL of fresh 80% methanol at 4˚ C overnight. After centrifugation, the supernatant was combined with the previous day’ s extracts. The pooled supernatant was dried using a vacuum concentrator until approximately 50 $\mu$L of liquid remained. The dried extract was diluted with TBS buffer (25 mM Tris-HCl pH 7.5, 100 mM NaCl, 1 mM MgCl2, 3 mM NaNO3) to a final volume of 500 $\mu$L. The diluted sample was further analyzed for ABA using the Phytodetek ELISA assay kit, and ABA concentrations were measured using a multichannel spectrophotometer (Multiskan FC, Thermo Fisher Scientific, Waltham, MA, USA). Each sample (CTRL/MIX) at each time point had eight replicates.

**Experiment 3: Water deficit study with endophyte consortia**

Experiment 3 aimed to assess endophyte effects on long-term water use efficiency (WUE) under well-watered and water deficit conditions. The trial was conducted from July 14th to October 6th, 2015, using M-206 rice. Differences from previous experiments included endophyte treatment and fertilization/irrigation conditions outlined below. Measured metrics were weekly pot-based transpiration and biomass allocation at harvest.

*3.1 Plant material preparation and inoculation/water deficit treatments*

The average air temperature (day/night) was 29/20 °C. The average DLI was 35.8 mol m−2 d−1 of PAR with a 16/8-hour photoperiod. The average RH was 57%/71% (day/night).

Following seed surface sterilization, four rice seeds were planted in 1-gallon pots with horticultural root media (Sunshine Mix #4). Thirty-two pots were prepared and placed in plastic buckets. Half of the samples were inoculated seven days after germination with an endophyte consortium. Each plant received a 2-mL inoculum of the consortium (MIX) using the described technique. The other half received a mock inoculum (CTRL).

Similar to Experiment 1, a randomized complete block design was used. Six pots without plants were used to measure weekly soil evaporation rates. Every week, 200 mL of full-strength N Hoagland solution was supplied, and pots were fully irrigated. After six weeks, half of the pots experienced water deficit (S), while the other half remained non-stressed (NS). The design included non-stressed control (NS_CTRL), non-stressed inoculated (NS_MIX), stressed control (S_CTRL), and stressed inoculated (S_MIX) groups, each with eight replications. Soil water potential was measured using a psychrometer (SC-10).

*3.2 Calculation of water use efficiency*

Weekly transpiration was recorded until harvest after four weeks of induced water deficits. Total transpiration was calculated. Measured dry weights were divided by total transpiration after 72-hour drying at 70 °C. Pot-based total transpiration and dry weights were used to calculate WUE.

WUE of productivity = total biomass gain (g)/total transpiration (L/pot).

**Experiment 4: $CO_2$ enrichment study with a single endophyte strain**

In this experiment, we aimed to investigate the stomatal responses influenced by endophytes under two different atmospheric $CO_2$ concentrations.

*4.1 Preparation of plant material and inoculation with endophytes*

The host plant species chosen was M-206 rice. Seeds were surface-sterilized with 3% NaOCl solution and incubated in sealed Petri dishes on water agar. After germination, seedlings were transferred to pots filled with horticultural media. Endophyte-inoculated treatment (E+) received 2 mL of the endophyte inoculum applied to the crown of the seedlings, while the mock-inoculated control (E−) received an equal volume of endophyte-free solution. The pots were placed in plastic buckets for easy water and fertilizer supply. Each chamber accommodated both E− and E+ pots and an empty pot for monitoring soil evaporation. Weekly fertilizer supply and full irrigation were maintained.

*4.2 $CO_2$ treatment and inoculation*

The experiment followed a 2 × 2 factorial design, with two atmospheric $CO_2$ concentrations (ambient $CO_2$, AMB, and elevated $CO_2$, ELE) and two inoculation statuses (E− and E+). Four chambers were used, two for AMB and two for ELE. $CO_2$ concentrations were controlled using air ducts and flowmeters. Each chamber accommodated eight pots and an empty pot for evaporation monitoring. Temperature, humidity, light intensity, and $CO_2$ concentration were recorded. The average temperature was 23/19 °C, RH was 60/66% (day/night), and the DLI was 9.1 mol $m^{-2}$ $d^{-1}$ of PAR.

*4.3 Stomatal conductance measurements*

At 128 days after germination, gs of the youngest fully expanded leaves was measured at

3-hour intervals using leaf porometers (SC-1). The measurement procedure was consistent with Experiment 1.

*4.4 Simultaneous leaf gas exchange and chlorophyll fluorescence measurements*

Leaf gas exchange and chlorophyll fluorescence parameters were measured on the second youngest fully expanded leaves. Parameters such as net CO2 assimilation rate (A), gs, transpiration rate (E), and electron transport rate (ETR) were recorded using portable gas analyzers equipped with leaf chamber fluorometers. Intrinsic and extrinsic water-use efficiencies (iWUE and eWUE) were calculated. CO2-response curves (A/Ci curves) were constructed under ambient and low oxygen conditions to estimate photosynthetic parameters. The low-[O2] method was used to estimate leaves’ mesophyll conductance (gm)(Bunce, 2009).

**Experiment 5: A controlled environment in vitro and in vivo study using a single endophyte strain for respiration measurement**

*5.1 Leaf respiration measurements*

Leaf samples were collected to measure CO2 release and O2 consumption to determine rice plants' respiration rates. One plant was randomly selected per pot 100 days after germination (DAG). The total leaf area of each plant was measured using a leaf area meter. The leaves were then placed in Petri dishes covered with aluminum foil to promote respiration. After dark adaptation, the Petri dishes were inserted into a soil flux chamber of a gas exchange measurement system to measure CO2 efflux. The CO2 release data was divided by leaf area measurements to estimate the area-based respiration rate. Immediately after the CO2 measurements, leaf samples were excised to obtain two leaf disks. The leaf disks were incubated in a chamber of an O2 electrode to measure O2 consumption. The leaf disks were collected, dried, and weighed to calculate a mass-adjusted respiration rate. This rate was then used to adjust the area-based rate by multiplying it by the specific leaf area.

*5.2 Quantification of endophytic bacteria in planta*

A separate experiment was conducted to quantify endophytic bacteria in rice plants. Surface-sterilized seeds were grown in pots under the same conditions as the main experiment. Half of the seedlings were mock-inoculated, while the other half were inoculated with WP5. The plants were grown under fully irrigated conditions until the panicle initiation stage. Bacterial extraction was performed on 100 DAG. Leaf, stem, and root tissues were separated and surface sterilized. Samples were homogenized and spread on agar plates for bacterial counting.

*5.3 Estimation of microbial respiratory CO2 in planta*

The assumption that rice provides sufficient carbohydrates for endophytic respiration was supported by measuring the soluble sugar content in the rice sap. The microbial respiratory CO2 release in planta (Rmic) was estimated by multiplying the bacterial density (CFU), the respiration rate (R), and the fresh weight (FW) of each tissue. Using a portable gas exchange measurement system, these estimates were compared to A measured by gas exchange measurements. Combined with the in vitro bacterial respiration survey data set, the estimates of microbial respiratory CO2 release in planta (Rmic) was determined using the following equation.

$$R_{mic}(\mu mol\ g^{-1}s^{-1}) = CFU\ (cells\ FW\ g^{-1}) \times R\ (\mu mol\ s^{-1}g^{-1}) \times FW(g)$$

**Statistical analysis**

Statistical analysis was conducted using R version 3.2.2 for all experiments. The specific procedures varied depending on the design of each experiment. Experiment 1 used a contrast matrix to compare control plants with three single-strain inoculated plants, with a blocking effect included in the model. For Experiment 2, a simple t-test procedure was applied at each time point to identify significant differences between control and inoculated plants. Experiment

3 employed a 2 × 2 factorial design with blocking effects on the experimental plot. Two-way ANOVA was used to analyze the response variables. In Experiment 4, a split-plotted CO2 treatment design was used. The chamber effect was found to be non-significant, and therefore, a two-way ANOVA was applied to the variables corresponding to the factorial design. The number of replications for Experiments 1, 2, 3, and 4 were eight, ten, eight, and eight, respectively.

Experiment 4 used a mixed-effect model due to the split-plot design and random effects. The N treatment was set as a random effect, and the inoculation treatment and CO2 treatment were considered fixed effects. The chamber effect was tested as a random effect in Experiment 4-2 and was determined to be insignificant. Two-way ANOVA was performed using a linear mixed-effect model regression, and Tukey's HSD method was used for within-group separation.

In Experiment 5, a standard two-sample t-test procedure was employed to test the statistical significance of differences in all measures. Blocking effects were removed in the analysis.

All statistical analyses were conducted using R version 3.2.2 (R Core Team, 2020).

## Results and Discussion

### Decreases in stomatal conductance during daytime by endophytes

The daytime decreases in gs were observed in E+ plants inoculated with multiple strains of bacteria (PTD1/WP5/WPB). These strains resulted in an average 27% decrease in gs at 12, 3, and 6 pm in Experiment 1 (Fig. 1), with significance levels of $P = 0.124$, 0.005, and <0.001, respectively. At noon, there were no significant differences in gs and in vivo ABA content between E− and E+ rice leaves (Fig. 2). However, at 6 pm, there was a significant decrease in gs ($P = 0.043$) and an increase in in vivo ABA concentrations ($P = 0.006$) in E+ rice leaves (Fig. 2). Overall, endophyte inoculation caused a nearly three-fold increase in in vivo ABA concentrations in rice leaves.

Similarly, in Experiment 4, inoculating a single strain endophyte resulted in a significant daytime decrease in gs. There was an average 18% decrease in gs at 12, 3, and 6 pm (Fig. 4) with significance levels of $P = 0.037$, 0.013, and 0.081, respectively. No statistical differences were found in other time points between AMB and ELE conditions. At 9 am, there were no differences in measurements between E− and E+ plants ($P = 0.195$, Fig. 4). During the peak time of the photosynthetic gas exchange (12-3 pm), the differences in gs became more pronounced, showing 20 to 21% decreases in E+ plants. High CO2 levels reduced gs by 29% across both E− and E+ treatments (Fig. 4).

Consistent patterns of afternoon decrease in gs were observed in Experiments 1, 2, and 4 (Fig. 1, Fig. 2A, and Fig. 4). These experiments, conducted under different environmental conditions, showed similar patterns of decreased gs in the afternoon.

Two potential mechanisms explain the afternoon reduction in stomatal conductance. Firstly, it could be attributed to the effects of endophyte ABA production. ABA is a critical hormone in stomatal control, and the inoculated plants may have had higher ABA levels due to the additional ABA provided by the endophytes, leading to faster stomatal closure. Additionally, endophytes may induce faster circadian clock responses to environmental cues, enabling more efficient water use by the host plants. The two-fold increase in WUE observed in Experiment 3 under water deficit conditions supports this hypothesis (Fig. 3C).

The second explanation involves microbial respiration and the recycling of CO2 by plants. As gs decreased in the afternoon, CO2 supply from the atmosphere would drop in E+ plants. However, the increases in WUE suggest that E+ plants could maintain photosynthetic CO2 assimilation with less CO2 through stomata. It is possible that respired CO2 by endophytes in the intercellular spaces of leaves could be readily available for the Calvin cycle, avoiding the need for diffusion over longer distances. Previous studies have shown the re-assimilation of respired CO2 by plant tissues, highlighting the significance of respired CO2 sources in the assimilation process.

In contrast to our findings with bacterial and yeast endophytes, a meta-analysis by Auge et al. (2015) reported an average 24% increase in gs by mycorrhizae under water-stressed conditions. The mechanisms underlying these two symbiotic interactions differ, with mycorrhizae aiding in water absorption from the rhizosphere to enhance drought tolerance. At the same time, endophytes, as observed in this study, contribute to water conservation mainly by reducing gs.

**Increases in WUE of hosts**

We observed increases in biomass and WUE in rice plants under both non-stress (NS) and water deficit stress (S) conditions (Fig. 3). The water deficit treatment significantly affected all three measures: a 62% decrease in biomass ($P< 0.001$, Fig. 3A), an 85% decrease in total transpiration ($P< 0.001$, Fig. 3B), and a 221% increase in WUE of productivity ($P = 0.002$, Fig. 3C) for all plants (CTRL and MIX combined). E+ plants exhibited a 16% increase in biomass compared to E− plants under water deficit treatments ($P = 0.039$, MIX in Fig. 3A). The effect of endophytes in reducing total transpiration was more pronounced under the S treatment compared to the NS treatment ($P = 0.009$, interaction effect – INT – in Fig. 3B), with decreases of 30% and 22% in S and NS, respectively ($P = 0.096$ and $<0.001$).

The endophyte treatment significantly increased the WUE of the combined NS and S plants (84% increase, $P = 0.047$, Fig. 3C), primarily due to decreases in total transpiration (26% decrease, $P< 0.001$, Fig. 3B) rather than increases in biomass (16% increase, $P = 0.039$, Fig. 3A). The effectiveness of endophyte treatment was more pronounced under S, with WUE increases more than two-fold compared to NS (116% vs. 52% in Fig. 3C).

The alterations in stomatal development and diurnal behaviors, accompanied by plasticity in cell water relations, give host plants an advantage in water conservation during the daytime, particularly under high light and warmer conditions when evapotranspiration demand is high. Although stomata were closed and the supply of atmospheric $CO_2$ to the intercellular spaces was reduced, photosynthetic $CO_2$ assimilation was not affected by endophyte inoculation. This advantage will likely accumulate over the entire growth period, indicating that it can have a more significant impact if there are more sunny days than cloudy and overcast days.

The decreases in cumulative total transpiration of the inoculated plants were more significant under water deficit conditions (Fig. 3B). The beneficial effects of endophytes on host plants under stress conditions have been reported in numerous studies. These microorganisms appear to activate the defense mechanisms of plants by signaling stress response pathways even before the stress is imposed, thereby enhancing the host's ability to cope with various stress conditions (Pandey et al., 2012).

**Alleviation of photosynthetic down-regulation by endophytes under elevated CO2 conditions**

The A/Ci curve analysis revealed that the ELE treatment led to photosynthetic down-regulation at the panicle initiation stage in E− plants under both high N (HN) and low N (LN) conditions (Fig. 5). However, the A/Ci curves of E+ plants showed higher asymptotes compared to E− plants.

In E− plants, the FvCB photosynthetic biochemistry parameters (Vc,max, Jmax, and TPU) of the A/Ci curves were decreased by the ELE treatment compared to E+ plants under ambient (AMB) conditions (Table 1). Under HN conditions, E− plants exhibited decreases of 10% in Vc,max, 3% in Jmax, and 21% in TPU in response to the ELE treatment. Under LN conditions, E- plants showed a 16% decrease in Jmax and a 2% decrease in TPU. In contrast, E+ plants did not show reductions in these parameters. Under ELE conditions, E+ plants had increases of 5% in Vc,maxand 14% in Jmax compared to E− plants under HN conditions. The increases were more pronounced under LN conditions, with E+ plants showing a 33% increase in Vc,max, a 7% increase in Jmax, and a 22% increase in TPU. These increases in parameters in response to endophyte inoculation were all significant (Table 1, $P < 0.01$). Significant interaction effects of INOC×CO2 were observed for Jmax and TPU ($P = 0.031$ and $P = 0.010$, respectively).

The down-regulation of C3 photosynthesis typically involves decreases in the initial slope

(Vc,max) and the asymptote (Jmax) of the A/Ci curve, as observed in our results (Fig. 5). This down-regulation starts with the accumulation of non-structural carbohydrates (NSCs) and starch in chloroplasts of source tissues exposed to long-term elevated CO2. This accumulation leads to a reduction in Rubisco turnover rates and ultimately decreases the content and activity of Rubisco and associated enzymes involved in CO2 assimilation in the Calvin-Benson cycle as a negative feedback response (Drake et al., 1997). Interestingly, E+ plants showed higher FvCB C3 photosynthetic parameters values, with higher Vc,max, Jmax, and TPU than E− plants under ELE conditions, regardless of N levels (Table 1). This pattern of A/Ci curves resembles the photosynthetic responses of legumes to ELE conditions reported by Ainsworth and Rogers (2007). They found that legumes showed fewer down-regulation symptoms compared to other C3 crop species in studies using FACE facilities worldwide, as evident from A/Ci curves and parameterizations. This phenomenon was attributed to the ability of legumes to utilize N derived from BNF to sustain Rubisco content and capacity under ELE conditions, as well as the increased sink strength provided by nodules formed by symbiotic rhizobium bacteria in legume roots. Ainsworth et al. (2004) experimentally demonstrated the source-sink relationship between plant hosts and symbiotic bacteria under elevated CO2 levels by manipulating the sink strength of the plant. They found that a decrease in sink capacity due to the absence of nodules resulted in significant down-regulation of photosynthesis. Furthermore, endophytes can fix N, which can be utilized for creating sink tissues and promoting biomass production (Kim et al., 2003).

In this context, a possible explanation for mitigating down-regulation in plants inoculated with N-fixing endophytes can be drawn from the legume-rhizobium symbiosis analogy. First, the BNF by endophytes is a well-established trait of plant-endophyte interactions, as supported by our previous study with Salicaceae endophytes (Knoth et al., 2014). Although we did not estimate the amount of N in the leaves originating from endophytes in the present study, the higher chlorophyll content in E+ plants compared to E- plants indicates an increase in leaf N status (Table 1). Leaf chlorophyll content is strongly correlated with leaf N content in rice. SPAD units are commonly used as indicators of leaf N status. Therefore, the increase in chlorophyll content may explain the overall improvement in photosynthetic performance in the presence of N-fixing endophytes. Second, although the biological sink strength of endophytes has not been quantified, they actively consume carbohydrates provided by the plant host. Considering that other symbiotic associations (such as rhizobium bacteria and mycorrhizal fungi) can cost the host plant 5-20% of total carbohydrates, it is likely that endophytes also drain a significant amount of carbohydrates from the host, serving as active biological sinks. Host plants can allocate more extensive carbon reserves when abundant environmental substrates are available, particularly under ELE conditions.

**Increases in ETR and gm under elevated CO2 with endophyte inoculation**

The ETR was higher in E+ plants compared to E− plants only under the ELE treatment, and endophyte inoculation increased ETR by 20% and 28% in HN and LN conditions, respectively (Table 1). No changes in ETR were observed under AMB conditions in either N regime. The INOC×CO2 interaction effect was significant.

Although the specific mechanisms underlying the increases in ETR in response to endophyte inoculation under ELE conditions are challenging to determine with our data, the response was consistent under both N-sufficient and N-limited conditions. Woodward et al. (2012) found that symbiotic tomato plants with fungal endophytes exhibited increased photochemical efficiency (ΦPSII) compared to non-symbiotic plants. The increase in ΦPSII can explain the increased ETR since the relationship between the two is positively linear (Baker, 2008). This suggests that more ATP and NADPH were produced in the light reaction of photosynthesis per unit of absorbed light energy in symbiotic plants compared to non-symbiotic plants, and these energy-rich molecules are consumed in the process of CO2 fixation, as seen in the increases in Amax (Table 1, Fig. 5).

Considering that plants under elevated CO2 will experience limitations in photosynthesis due to decreased regeneration of RuBP (Ainsworth and Rogers, 2007), the increases in ETR resulting from endophyte inoculation, along with other relevant PSII activities, are promising results.

Mesophyll conductance (gm) showed contrasting responses to endophyte inoculation depending on $CO_2$ levels (Table 1), and the INOC×$CO_2$ interaction effect was marginally significant ($P = 0.053$). Under ELE conditions, E− plants exhibited significant reductions in gm, with decreases of 29% and 70% under HN and LN conditions, respectively, while E+ plants showed an 18% increase with HN and a 27% decrease with LN. In response to endophyte inoculation under ELE conditions, plants showed increases in gm of 39% and 142% under HN and LN conditions, respectively. This was associated with increases in the ratio of intercellular to ambient $CO_2$ concentration (Cc/Ci) of 4% and 58% under HN and LN conditions, respectively (Table 2).

Higher gm facilitates the diffusion of $CO_2$ through the chloroplast walls and other layers along the pathway from the atmosphere to the site of carboxylation, allowing for a better supply of $CO_2$ to the photosynthetic machinery (Flexas et al., 2008).

Increases in gm were observed only under ELE conditions, coinciding with ETR increases (Table 1). The coordinated mechanisms of photosynthetic electron transport in PSII, together with the supply of bicarbonate to the thylakoid space, have been described and reviewed by Govindjee et al. (1993) and van Rensen and Klimov (2005). Under ELE conditions, plants produce more carbohydrates due to increased carboxylation substrate supply. Microorganisms residing in the intercellular spaces of host plants consume photoassimilates through respiration, releasing $CO_2$ that can readily dissolve into bicarbonate ions (Rho et al., 2018a). This may enhance the light-harvesting process in PSII, leading to an increase in ETR. Upregulating the activities of the PSII complex can also suppress stomatal opening without affecting $CO_2$ assimilation, resulting in increased WUE, as observed in our results (Table 1). With more $CO_2$ and NSCs under ELE conditions and, consequently, more microbial release of respiratory $CO_2$, symbiotic plants have a better chance of having more internal $CO_2$ available for assimilation. As a consequence, gm could be increased by this signal and further stimulate the entire assimilation process, as indicated by the increases in Amax in our data.

**Further increases in WUE with endophyte inoculation under elevated CO2 and low-N conditions**

Overall, there were no significant changes in intrinsic water use efficiency (iWUE) in E+ plants in response to the endophyte inoculation. However, a significant increase was observed in the effective water use efficiency (eWUE) (P = 0.028, Table 1). The 58% increase in the ratio of intercellular to ambient CO2 concentration (Cc/Ci) is consistent with this increase in eWUE (P = 0.096).

Under HN conditions, the endophyte inoculation did not change eWUE in plants. However, under LN conditions, a significant 20% increase in eWUE was observed in E+ plants (P = 0.045).

Furthermore, we found that the response of WUE in E+ plants was influenced by N supply, with more significant increases observed under LN conditions compared to HN (Table 1). In contrast, Rho et al. (2018b) showed that Salicaceae endophytes increased WUE by reducing stomatal aperture during the afternoon while maintaining photosynthetic capacity under AMB conditions. Under ELE conditions, endophytes appear to modulate internal leaf components in the presence of abundant resources, such as carbohydrates. More fundamental approaches at the molecular scale are required to gain a mechanistic understanding of these responses.

Endophyte inoculation under AMB conditions did not significantly alter physiological characteristics at the leaf level (Table 1). This aligns with the findings of Rogers Alistair et al. (2012), who observed increased biomass. However, no effects on photosynthetic parameters such as A, gs, and photosynthetic WUE (i.e., either iWUE or eWUE) in Enterobacter-inoculated Populusdeltoides cuttings. The authors suggested that the productivity increases were more related to increases in leaf area at the whole-plant physiological scale. Although some parameters showed varying effects, E+ plants in our study displayed similar responses to

E− plants under AMB conditions.

Nevertheless, several photosynthetic parameters showed significant INOC×CO2 interactions, includingAmax, ETR, Jmax, TPU, gm, and Cc/Ci (Table 1). This indicates that endophyte inoculation enhanced these photosynthetic properties, which may be more efficient under ELE conditions.

**Estimating microbial respiratory CO2 from endophytic bacteria in rice**

A series of in planta and in vitro assays were conducted to estimate the effects of the bacterial endophyte strain WP5 on rice plants. WP5, isolated initially from native poplar trees in Washington State, was identified as Rahnella sp. through 16S rRNA sequence analysis. In planta assays were performed using rice as a C3 model crop, while pure cultures of WP5 were grown in MG/L media plates for in vitro assays.

Results from in planta respiration measurements showed that E+ plants exhibited higher rates of CO2 release (Rc) and O2 consumption (Ro) compared to E− plants, as measured by a gas exchange measurement system and a Clark-type electrode, respectively (Fig. 6). However, there was a significant difference between the two methods of measurement ($P < 0.001$). The Ro method detected a significant 159% increase in respiration rate in endophyte-inoculated plants ($P = 0.004$), while the 24% increase observed using the Rc method was insignificant ($P = 0.215$).

Estimates of microbial respiratory CO2 release demonstrated that endophytic microbes, such as WP5, can contribute a substantial amount of CO2 to the system (Fig. 7). The total respiration estimate for WP5 was 0.143 $\mu$mol CO2 g−1 s−1, which was similar to the actual photosynthetic assimilation rate of 0.127 $\mu$mol CO2 g−1 s−1.

The hypothesis for this study was derived from previous research indicating plants' re-assimilation of respired CO2. Bloemen et al. (2013) demonstrated that the upper leaf tissues can re-assimilate a portion of CO2 respired by root tissues. Similarly, Busch (2020) showed that photorespired CO2 in C3 plants can be incorporated into photosynthetic assimilation processes. These findings provided the foundation for the prediction made in this study.

The estimated density of bacterial microbiota population on leaf surfaces is typically around 1 × 106-107 cells cm-2. Our microbial count information showed a similar range of microorganisms in the host plants. Based on our results, we estimated the bacterial respiration in rice plants to be 0.143 $\mu$mol $CO_2$ g−1 s−1, which could contribute significantly to the plants' $CO_2$ assimilation/production cycle. Although some respired $CO_2$ is lost during mass transport in root and stem tissues, approximately 20% of transported $CO_2$ could be re-assimilated. This suggests that an additional 0.071 $\mu$mol $CO_2$ g−1 s−1 from microbial respiration could potentially be available for photosynthesis in leaves, accounting for approximately 57% of the total assimilation (Fig. 7). The difference in in planta respiration rates between E− and E+ plants observed by the Rc method (24%) was not as pronounced as that observed by the Ro method (159%). This indicates that some portion of the respiratory $CO_2$ may reenter the photosynthetic assimilatory pathways and be incorporated into the plant before release, resulting in decreased detectable $CO_2$ release in E+ plants measured by the Rc method.

Further empirical evidence, such as employing the 13CO2 method to differentiate photo-assimilates, is needed to verify this hypothesis.

## Conclusion

In summary, our research aimed to assess the symbiotic impacts of Salicaceae endophytes on the eco-physiology of rice plants and evaluate the potential of using symbiotic microorganisms to enhance crop WUE for building sustainable cropping systems. Our focus was on carbon metabolism and water relations. The experiments were designed based on current knowledge of plant-microbe interactions.

The water relations study (Rho et al., 2018b) revealed that endophyte inoculations led to alterations in water relations and improved WUE in rice plants. Previous characterization of Salicaceae endophytes demonstrated their potential to produce ABA, a phytohormone that regulates stomatal responses. We observed decreased stomatal conductance and density in endophyte-inoculated rice plants, reducing transpiration and water consumption. Despite these changes, the photosynthetic capacity and biomass of the inoculated plants remained unaffected, leading to a significant enhancement in WUE.

In the photosynthesis study (Rho et al., 2020), we investigated the effects of endophyte inoculations on photosynthetic performance under elevated CO2 conditions. C3 plants typically experience down-regulation of photosynthesis in response to long-term exposure to elevated CO2, resulting in reduced biomass gain. With their ability to fix atmospheric N, we hypothesized that Salicaceae endophytes would mitigate this down-regulation. Indeed, endophyte-inoculated rice plants displayed improved photosynthetic enzyme activities, increased Rubisco capacity, and enhanced internal CO2 diffusion for carboxylation, particularly under N-limited conditions. Consequently, these improvements increased WUE in the inoculated plants, especially under elevated CO2.

Furthermore, our respiration study (Rho et al., 2018a)explored the possibility of re-assimilation of endophytic microbial respiratory CO2. We found that endophyte inoculations increased the respiration rates of the host plants. In vitro, characterization of microbial respiration revealed a positive correlation between microbial respiration rates, microbial cell numbers, and carbohydrate supplies. The density of endophytic bacteria in plant tissues was significantly higher in the inoculated plants. Based on these findings, we estimated that around 57% of the CO2 assimilated by photosynthesis was re-assimilated from microbial respiratory CO2. This re-assimilation could compensate for the reduced uptake of atmospheric CO2 due to stomatal closure induced by endophytes.

Overall, our study provides insights into the physiological mechanisms underlying the symbiotic impacts of Salicaceae endophytes on rice plants (Fig. 8). The findings highlight the potential of harnessing endophytic symbioses to improve crop WUE and contribute to sustainable cropping systems.

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**Table 1 Descriptive and inferential statistics of photosynthetic parameters at the operational points of the CO2 response curves (Fig. 5). The means of four and eight replicated responses are provided with the standard errors of the means in parentheses. F-statistics of two-way ANOVA test results for inoculation effect (INOC), [CO2] effect (CO2), and their interaction effects on various photosynthesis characteristics are presented with statistical significance codes. The corresponding P-values of the F-statistics are presented in parentheses. Adapted from Rho et al. (2020).**

| N | CO2 | INOC | n | Amax μmol CO2 m-2 s-1 | ETR μmol CO2 m-2 s-1 | Vcmax μmol CO2 m-2 s-1 | Jmax μmol CO2 m-2 s-1 | TPU μmol CO2 m-2 s-1 |
|---|---|---|---|---|---|---|---|---|
| HN | AMB | E− | 4 | 25.46 | 128.1 | 103.3 | 135.6 | 11.77 |
| | | | | (0.476) | (5.246) | (2.570) | (10.94) | (0.851) |
| | | E+ | 4 | 25.17 | 127.8 | 113.9 | 149.9 | 10.75 |
| | | | | (0.029) | (5.017) | (7.645) | (5.545) | (0.321) |
| | ELE | E− | 4 | 26.36 | 103.8 | 93.11 | 131.5 | 9.308 |
| | | | | (0.481) | (2.431) | (3.539) | (3.155) | (0.364) |
| | | E+ | 4 | 32.23 | 124.9 | 108.12 | 155.2 | 11.35 |
| | | | | (2.437) | (9.380) | (6.902) | (10.90) | (0.816) |
| LN | AMB | E− | 8 | 10.85 | 84.66 | 35.65 | 89.90 | 5.979 |
| | | | | (0.797) | (7.882) | (3.059) | (4.460) | (0.326) |
| | | E+ | 8 | 11.14 | 85.53 | 43.96 | 86.40 | 6.525 |
| | | | | (0.940) | (5.339) | (5.147) | (5.405) | (0.362) |
| | ELE | E− | 8 | 14.23 | 91.77 | 36.50 | 75.50 | 5.854 |
| | | | | (0.663) | (6.745) | (2.529) | (2.553) | (0.162) |
| | | E+ | 8 | 17.71 | 117.3 | 47.58 | 96.13 | 7.284 |
| | | | | (1.348) | (7.909) | (5.825) | (5.819) | (0.392) |
| INOC | | | | 9.441** | 4.910* | 9.780** | 8.923** | 6.989* |
| df = 1 | | | | (0.004) | (0.032) | (0.003) | (0.005) | (0.011) |
| CO2 | | | | 34.29*** | 2.308 | 0.118 | 0.060 | 0.101 |
| df = 1 | | | | (< 0.001) | (0.136) | (0.733) | (0.807) | (0.752) |
| INOC x CO2 | | | | 6.310* | 4.518* | 0.233 | 5.022* | 6.562* |
| df = 1 | | | | (0.016) | (0.039) | (0.632) | (0.030) | (0.014) |

| gs mol H2O m-2 s-1 | gm mol CO2 m-2 s-1 | Ci/Ca unitless | Cc/Ci unitless | E mmol H2O m-2 s-1 | iWUE mol CO2 mol-1 H2O | eWUE mol CO2 mol-1 H2O | SPAD unitless |
|---|---|---|---|---|---|---|---|
| 0.593 | 0.190 | 0.783 | 0.543 | 6.517 | 0.0046 | 0.393 | 41.57 |
| (0.091) | (0.023) | (0.032) | (0.028) | (0.329) | (0.0007) | (0.017) | (1.157) |
| 0.636 | 0.160 | 0.799 | 0.461 | 7.143 | 0.0042 | 0.369 | 42.77 |
| (0.047) | (0.007) | (0.016) | (0.028) | (0.335) | (0.0004) | (0.018) | (0.510) |
| 0.612 | 0.135 | 0.883 | 0.713 | 5.851 | 0.0047 | 0.473 | 40.75 |
| (0.095) | (0.009) | (0.020) | (0.020) | (0.702) | (0.0009) | (0.061) | (1.016) |
| 0.627 | 0.188 | 0.873 | 0.742 | 5.783 | 0.0052 | 0.558 | 43.35 |
| (0.041) | (0.027) | (0.009) | (0.013) | (0.044) | (0.0004) | (0.044) | (1.187) |
| 0.191 | 0.166 | 0.744 | 0.732 | 2.259 | 0.0058 | 0.484 | 38.42 |
| (0.016) | (0.031) | (0.014) | (0.066) | (0.191) | (0.0003) | (0.022) | (1.465) |
| 0.177 | 0.150 | 0.717 | 0.642 | 2.069 | 0.0065 | 0.540 | 38.62 |
| (0.021) | (0.049) | (0.011) | (0.056) | (0.139) | (0.0003) | (0.028) | (1.071) |
| 0.164 | 0.050 | 0.784 | 0.433 | 1.709 | 0.0097 | 0.844 | 37.36 |
| (0.026) | (0.014) | (0.022) | (0.076) | (0.116) | (0.0011) | (0.033) | (1.515) |
| 0.155 | 0.121 | 0.736 | 0.684 | 1.815 | 0.0121 | 1.013 | 41.85 |
| (0.018) | (0.022) | (0.020) | (0.069) | (0.204) | (0.0010) | (0.070) | (2.562) |
| 0.006 | 1.134 | 2.898° | 1.006 | 0.133 | 2.627 | 5.176* | 3.294° |
| (0.939) | (0.294) | (0.096) | (0.323) | (0.717) | (0.112) | (0.028) | (0.076) |
| 0.315 | 5.456* | 12.09** | 0.032 | 11.63** | 29.25*** | 74.17*** | 0.315 |
| (0.577) | (0.025) | (0.001) | (0.857) | (0.001) | (< 0.001) | (< 0.001) | (0.577) |
| 0.012 | 3.988° | 0.664 | 5.594* | 0.009 | 1.254 | 2.325 | 1.928 |
| (0.912) | (0.053) | (0.420) | (0.024) | (0.9 26) | (0.269) | (0.135) | (0.172) |

Statistical significance codes: o, *, **, and *** for $P < 0.10$, 0.05, 0.01, and 0.001 levels, respectively.

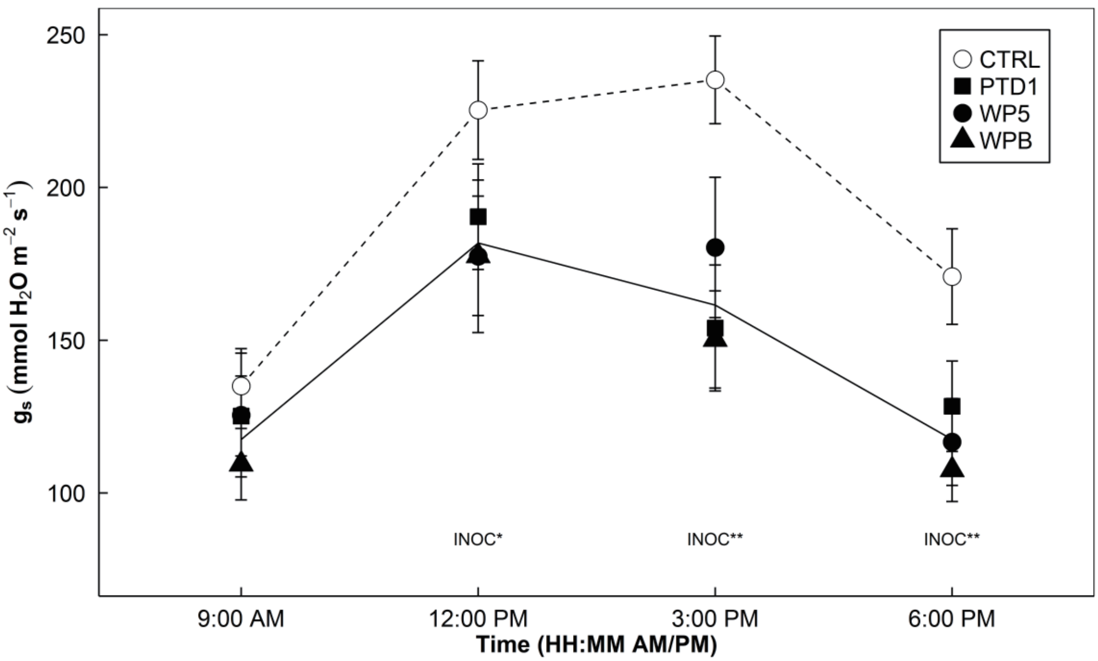


Fig. 1 Diurnal patterns of stomatal conductance (gs) of rice leaves on 163 days after germination in a greenhouse bench experiment (Experiment 1). Open symbols indicate mean gs of control groups, whereas closed symbols indicate mean gs of single strain-inoculated groups (square/circle/triangle = PTD1/WP5/WPB, individually). Error bars of the means represent ± 1 S.E. of replicated samples (n = 10). Single strain endophyte inoculation effect (INOC) is provided at P< 0.05 (*), 0.01 (**) levels. Contrast matrix was used to test CTRL vs. INOC (PTD1/WP5/WPB nested) comparison. Dotted and solid lines highlight mean responses of CTRL and INOC plants over time. Adapted from Rho et al. (2018b).

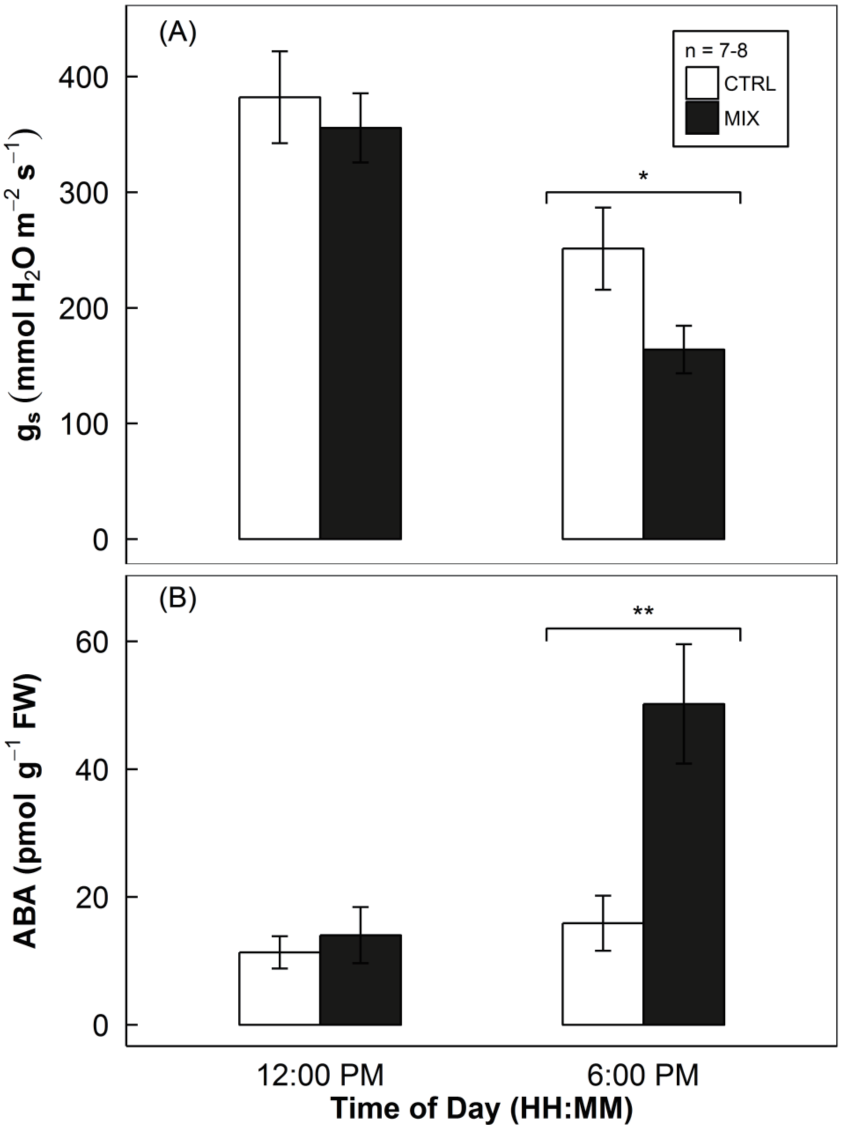


Fig. 2 Stomatal conductance of rice leaves at round V7-8 stage (top panel, A) and in vivo ABA concentrations (bottom panel, B) of rice leaves harvested at around R3-R4 stage in a greenhouse sunlit chamber experiment (Experiment 4). Open and closed bars indicate mean responses of mock-inoculated controls (CTRL) and endophyte consortium-inoculated (MIX) plants, respectively, provided with error bars as ± 1 S.E. of the means (n = 7-8). Endophyte inoculation treatment effect (INOC) is provided at $P < 0.05$ (*) and 0.01 (**) levels at each time point. Adapted from Rho et al. (2018b).

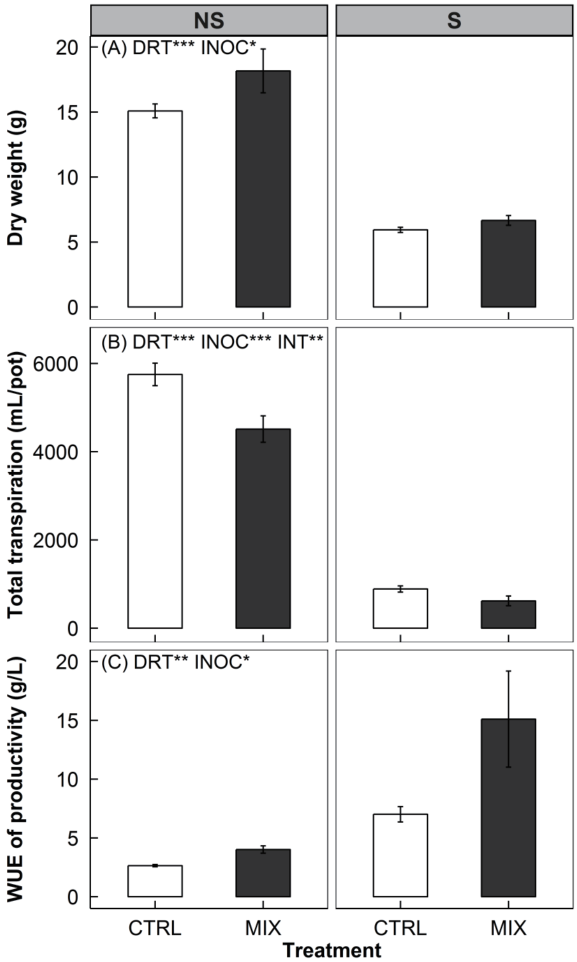


Fig. 3 Total biomass (top panels, A), total transpiration over time (middle panels, B), and water use efficiency (WUE) of productivity (bottom panels, C) of rice without (left panels, NS) and with (right panels, S) water deficits at harvest in a greenhouse bench experiment (Experiment 3). Open and closed bars indicate means of mock-inoculated controls (CTRL) and endophyte consortium-inoculated (MIX) plants, provided with error bars as ± 1 S.E. of the means (n = 8). Two-way ANOVA test results of the treatment effects are placed on each panel. Water deficit treatment effect (DRT), endophyte inoculation treatment effect (INOC), and interaction effect (INT = DRT x INOC) are provided at P< 0.05 (*), 0.01 (**), 0.001 (***) levels. Adapted from Rho et al. (2018b).

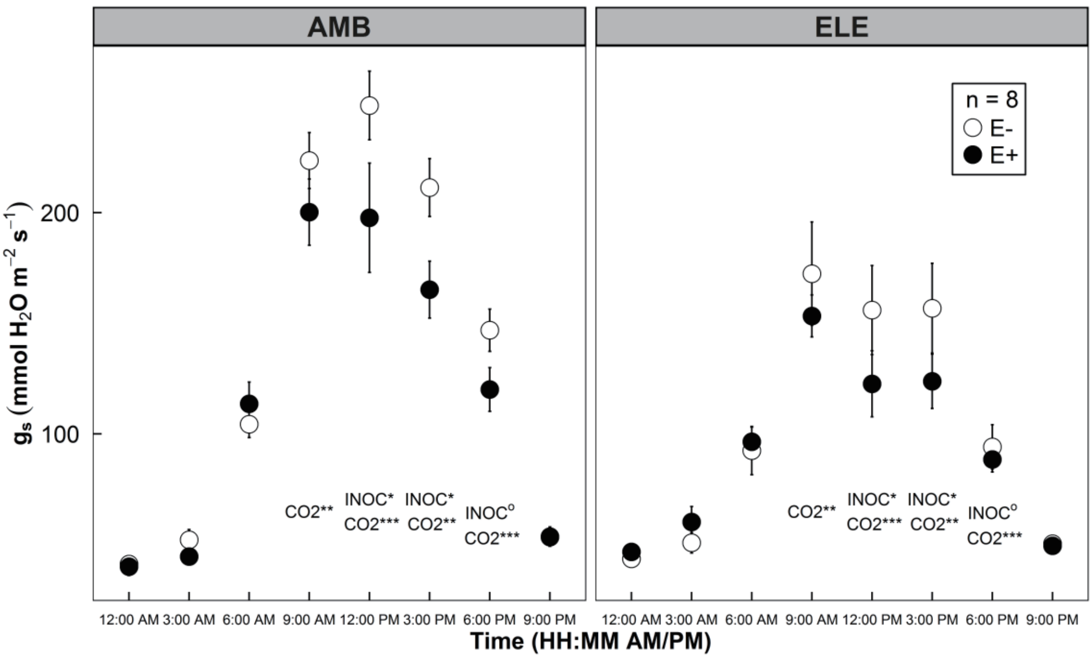


Fig. 4 Diurnal patterns of stomatal conductance (gs) of rice leaves grown under two atmospheric CO2 conditions: ambient (AMB, app. 400 ppm on the left panel) and elevated (ELE, app. 800 ppm on the right panel) in a sunlit chamber experiment (Experiment 2). Open symbols indicate mean gs of control groups (E−), whereas closed symbols indicate mean gs of WP5 inoculated groups (E+). Error bars of the means represent ± 1 S.E. of replicated samples (n = 8). Two-way ANOVA test results are indicated at each time point. CO2 treatment effect (CO2) and endophyte inoculation treatment effect (INOC) are provided at P< 0.10 (o), 0.05 (*), 0.01 (**), 0.001 (***) levels. Adapted from Rho et al. (2018b).

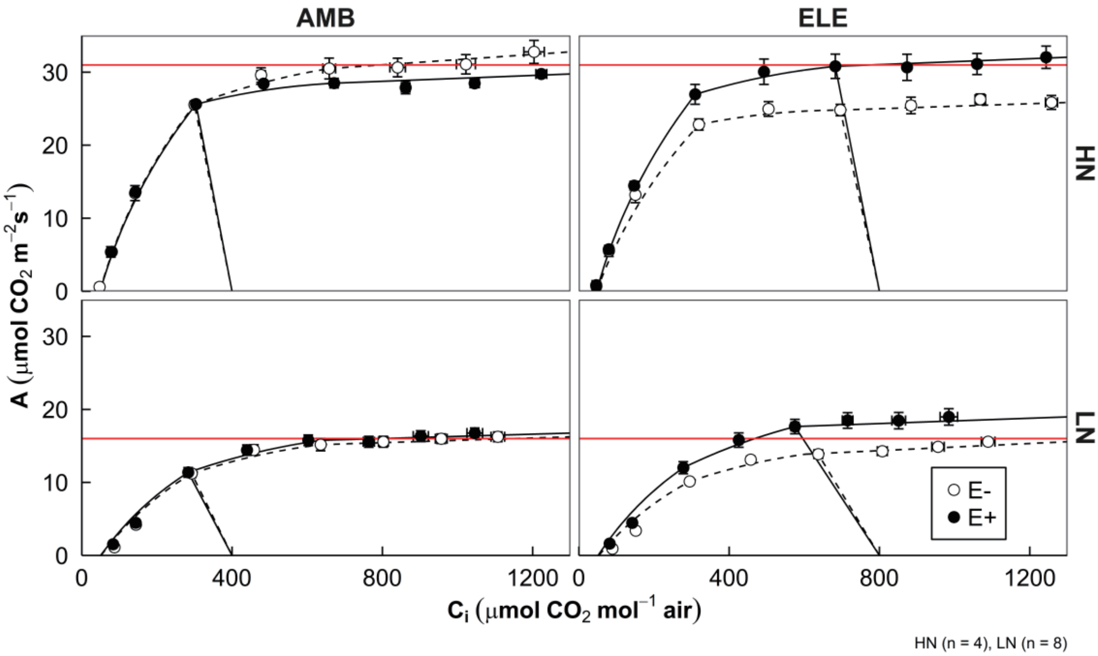


Fig. 5 CO2 response (A/Ci) curves of rice leaves at the panicle initiation stage following growth under ambient (AMB, ~400 ppm) and elevated [CO2] (ELE, ~800 ppm). The top panels show the responses of plants grown under high-N conditions (HN, n = 4) and the bottom panels show plants grown under low-N conditions (LN, n = 8). E–, mock-inoculated control plants; E+, endophyte-inoculated plants. Data are means (± SE). The solid horizontal lines indicate the asymptotes of the curves for E– plants under AMB conditions. Adapted from Rho et al. (2020).

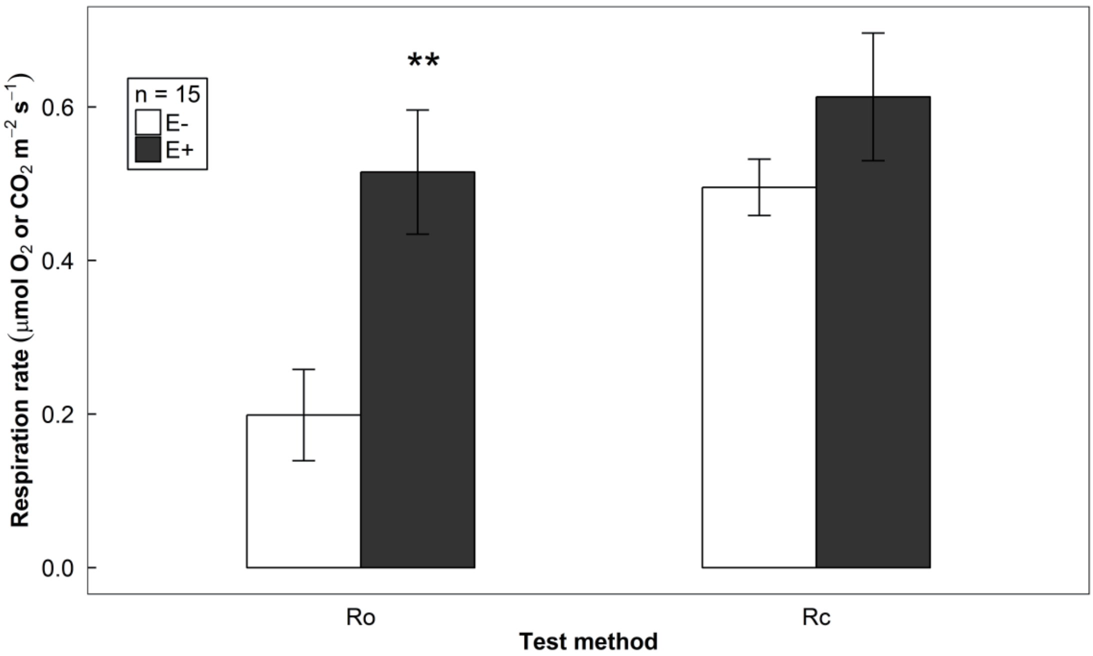


Fig. 6 In planta respiration rates of rice leaves at the panicle initiation stage. Respiration rates were determined by measuring the consumption of O2 (Ro) and the release of CO2 (Rc). Bars present the mean responses of mock-inoculated control (E−, open) and endophyte-inoculated (E+, closed) plants. WP5 (Rahnella sp.) was used to inoculate the plant samples. Error bars show ± 1 S.E.M. (n = 15). Using a 2-way ANOVA test, highly significant differences by method and by method × inoculation interaction were found at P< 0.001. Within each method, a t-test was used to detect a statistical significance in the differences between E- and E+ plants. Asterisks indicate significant difference between E− and E+ plants at the P< 0.01 level. Adapted from Rho et al. (2018a).

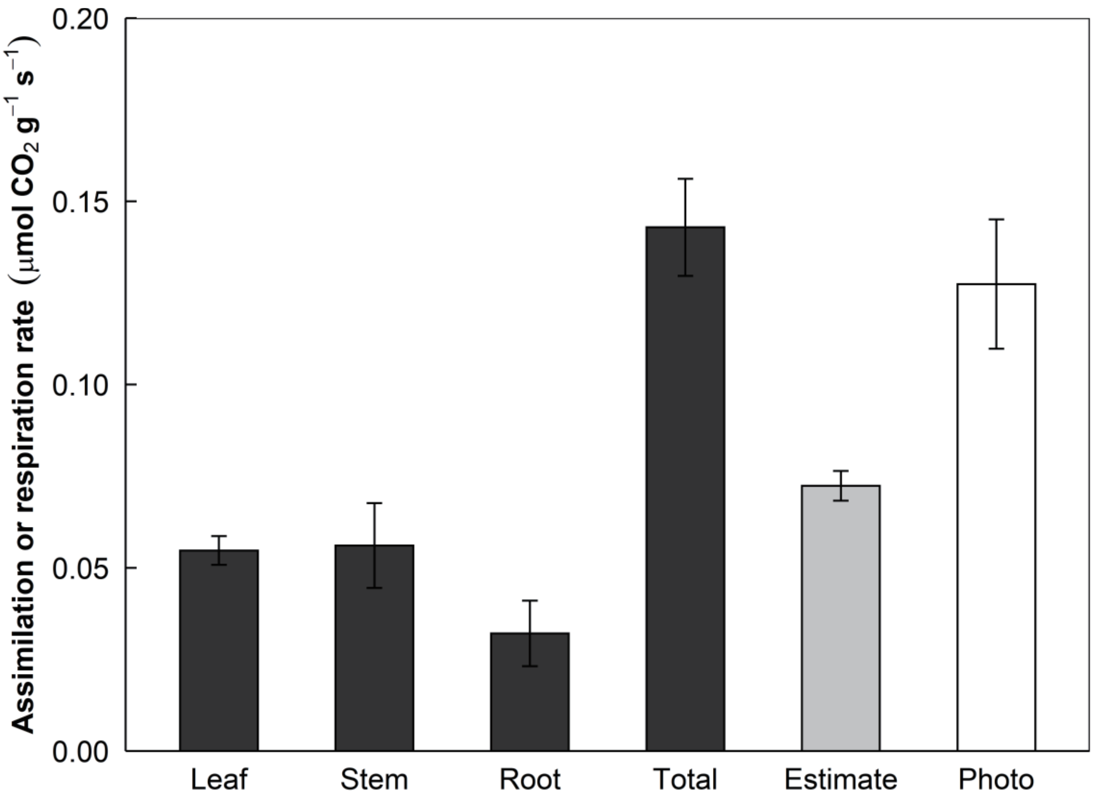


Fig. 7 Estimates of endophytic microbial respiratory CO2 release in planta separated by tissue (Leaf, Stem, Root, and Total, black bars). The estimated total possible microbial respiratory CO2 for re-assimilation is provided (Estimate, gray bar). The data are compared with photosynthetic CO2 assimilation of the leaves (Photo, white bar). Bars indicate the mean responses of WP5 (Rahnella sp.) endophyte-inoculated rice plants. Error bars indicate ± 1 S.E.M. (n = 4). Adapted from Rho et al. (2018a).

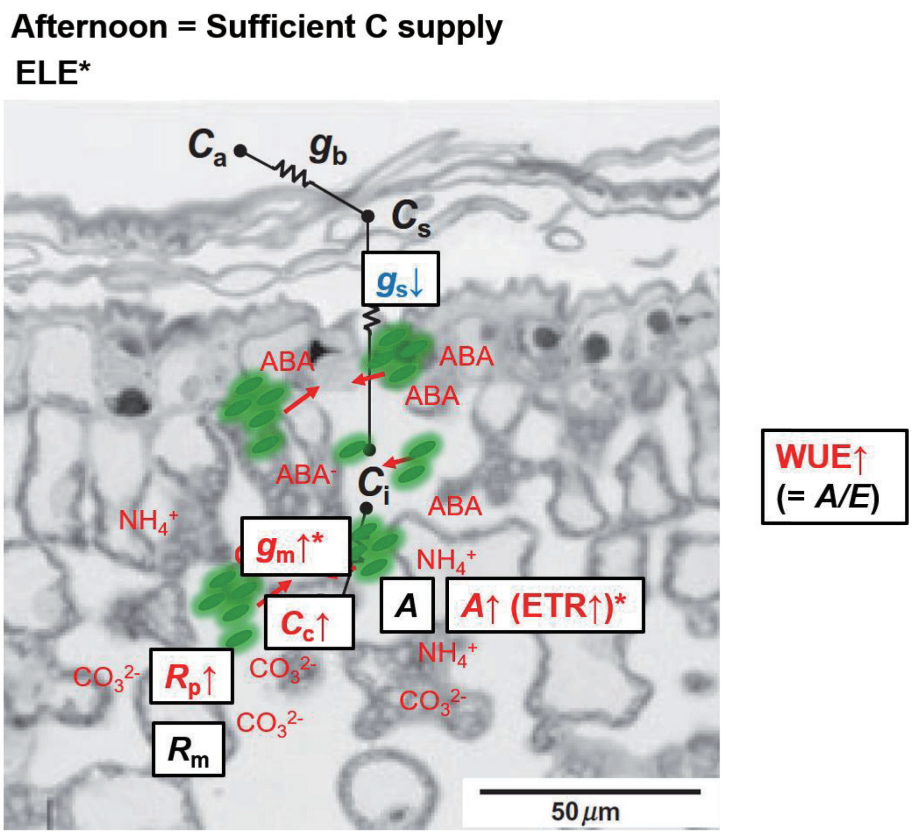


Fig. 8 A hypothetical model to explain the underlying mechanisms centered on leaf level transpiration, photosynthesis, and respiration of the host plant with endophyte inoculated. The microscopic image on the background is adapted and edited from Flexas et al. (2008).

# 永續設施生產：水養液有效利用零滲漏策略

陳葦玲[1*]　錢昌聖[1]

## 摘要

氣候變遷與環境永續議題促使設施生產者改善現有生產體系，封閉式設施無土栽培 (closed soilless cultivation) 除具高水分利用效率 (water use efficiency, WUE) 外，亦避免肥料和植物保護產品透過水排放，其水養液零滲漏 (zero emission) 管理策略包含：(1) 多元且質佳的水源，養液原水要求 EC<0.25 ms.cm-1、Na+ <0.1 mmol.L-1，多加利用雨水且儲水量達 800 L.m-2 溫室面積；(2) 原水及回收養液水質處理，包含曝氣氧化、過濾、酸鹼度調整、陽離子交換、逆滲透及殺菌等一系列操作；(3) 光輻射量及用水模式估算之灌溉水量數據應用；(4) 符合作物水分生理之養液管理，特別是循環利用下避免鈉離子累積造成鹽分逆境；及綜合上述 (5) 建構完善的水養液操作監控系統，目標為創造一個穩定的根區環境，從而實現零排放種植。

**關鍵詞：**設施栽培、零滲漏、水分利用效率、水質處理、鈉累積、蒸發散

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# 前言

聯合國糧食組織 (Food and Agriculture Organization, FAO) 在糧食與農業情勢 (The State of Food and Agriculture, SOFA) 報告指出，全球 70% 水資源為農業相關產業利用 (FAO, 2020)，隨著水資源的短缺和對淡水 (fresh water) 需求的增加，水分利用效率 (water use efficiency, WUE) 越受重視。設施栽培為水和肥料使用高投入的生產系統，若使用自由排放系統除損失水資源外，肥料和植物保護產品 (plant protection products, PPPs) 亦同時通過水從溫室排到地面以及地下水，影響環境永續性。因此當灌溉水能準確供給作物而排放水能回收再利用時，設施介質養液栽培是具有高水分利用效率 ( 圖 1)(van Kooten et al., 2008) 和生產永續性的。

# 國際借鏡～設施園藝大國荷蘭水資源規範演變

自 1994 年以來荷蘭設施栽培溫室必須遵循水資源環利用的要求，2000 年歐盟水框架 (EU Water Framework) 方針在提高水域的良好生態狀況，2013 年基礎設施和環境部 (Ministry of Infrastructure and Environment) 公告之氮排放標準限制溫室生產地區肥料和 PPPs 的排放 (Beerling et al., 2014)，2018 年則強制溫室排放水必須經過處裡，如除去 95% 的 PPPs，然目前養液偶爾排放仍常見，其主要原因還是與水質有關，例如 EC 過高、鈉積累 (>6-8 mmol.L-1，蘭花作物更低，1 mmol.L-1 Na+ 即會造成植株受傷 )、營養不平衡、病害及生長抑制物質等，另在栽培過程中灌溉設定錯誤、過濾時的沖洗水 (flush water)、多於養液滲漏等也會導致水連帶肥料和 PPPs 排放。

最新公告指出地表水和地下水的良好化學和生態品質 (good chemical and ecological quality of surface water and groundwater) 將於 2027 年強制執行，預計氮和磷標準的排放要降為零，以設施最大宗作物番茄來看，目前年氮排量約 75 kg N·ha-1·year-1 須再大幅度降低，因此荷蘭水務局與溫室園藝協會 (Land-en Tuinbouw Organisatie, LTO) 達成協議，要在 2027 年前全面達到溫室養液零排放 (zero-emission) 目標，其園藝產業業者亦同意在 2040 年實現完全二氧化碳中和 (CO2-neutral)。為了在短期內解決這些需求，生產者

需增加重複使用水量並淨化排放水 (drainage water)，以滿足當前的排放標準，因此促使朝向封閉式無土栽培 (closed soilless cultivation) 模式 (Beerling et al., 2017)。

## 溫室水養液零滲漏 Zero-emission 策略

為達到水資源高 WUE 及零滲漏 zero-emission，在封閉式無土栽培模式下其策略包含：(1) 多元且質佳的水源、(2) 水質處理、(3) 灌溉管理、(4) 符合作物所需及 (5) 完善的水系統 ( 圖 2)(Van Os et. al., 2020；van der Salm et al., 2020)，詳細說明如下：

( 一 ) 多元且質佳的水源

用水的品質，可分為物理性 (physical)、化學性 (chemical) 及生物性 (biological) 三部份。物理性指標有水溫、懸浮固體、氣味等，生物性指標如藻類、優養生物、微生物量等；而化學性指標是比較常檢測的項目，包含酸鹼值 (pH)、電導度 (electric conductivity, EC)、鹽度 (salinity)、陰陽離子含量 (cations and anions)、總可溶性固形物含量 (total dissolved solids, TDS)、鈉吸附率 (sodium adsorption rate, SAR)、氧化還原電位 (oxidation-reduction potential, ORP)、硬度 (hardness)、溶氧量 (dissolved oxygen, DO)、生化需氧量 (biochemical oxygen demand, BOD)…等，原水的水質可作為後續養液調配、水質處理及灌溉系統設計之依據。

1. 設施養液栽培用水等級

農業灌溉用水依水質中化學成分含量多寡可分為 5 個等級 ( 表 1)，若採用養液栽培強烈建議配置養液的原水水質至少在優或良等級，EC<0.5 mS/cm、pH=5.5-7.5、硬度 <150 ppm $CaCO_3$、有機質 <5 ppm、溶氧量 >3 ppm。在各離子含量方面，硝酸態氮 ($NO_3$-N)、氨態氮 ($NH_4$-N)、硫酸根 ($SO_4^{2-}$)、磷酸根 ($PO_4^-$) 及鉀 ($K^+$)<5ppm，碳酸根 ($CO_3^-$)<10ppm，鎂 ($Mg^{2+}$)<20ppm，鈉 ($Na^+$)、氯 ($Cl^-$)<30 ppm，鈣 ($Ca^{2+}$)< 40ppm；微量元素鐵離子 ($Fe^{3+}$)<1ppm，鋅 ($Zn^{2+}$)、銅 ($Cu^{2+}$)、錳 ($Mn^{2+}$)<0.5ppm，硼 ($B^+$)<0.3ppm( 表 2)(De Pascale et al., 2013; 高，2017)。

長期分析中彰投農友送樣原水水質，其中 EC (0.3-1.2 mS/cm)、pH(5.9-8.9)、

$Ca^{2+}$(50-120 ppm)、$Na^{+}$(20-50 ppm)、$Cl^{-}$ (30-50 ppm)、$Mg^{2+}$(40-70 ppm) 及 $Fe^{3+}$(3-12 ppm) 常超出建議水質範圍 ( 表 2)( 高 , 2017)。pH 值低於 5.5 或高於 7.5 則導致元素利用效率降低或在調配養液過程發生沉澱現象，除本身地下水鈣鎂離子過多呈現硬水狀態，經陽離子交換樹脂或 NaCl 軟水器過濾後也可能導致鈉離子及氯離子過量。

2. 水源選擇

農業灌溉用水之可使用雨水、河川水、地下水、井水、泉水、自來水…甚至是逆滲透水等，唯使用前需先經水質檢測及處理至合適範圍後才能運用。設施養液栽培常用原水有地下水、自來水及雨水，若以 EC 和 pH 衡量，雨水及自來水之水質較為穩定，而河川水及地下水之水質較差且含有病原菌的可能性較大 (Van Os et. al., 2019)( 表 3)。

雨水儲存的設計應能供應全年溫室用水，荷蘭溫室種植者有義務根據法律，雨水儲存能力至少為每公頃 500 立方米的水，大多數溫室存儲容量範圍為每公頃 500-1,000 $m^3$。臺灣雨量在冬季則相對乾燥，而夏季風能帶來很高的降雨量，應可收集並儲存以供利用，模擬結果顯示，一個具 800L 儲水量 /$m^2$ 溫室地板面積足以全年供灌溉與噴霧系統，唯在溫室營運的初期必須注意缺水問題 (Speetjens et al., 2012)。

## ( 二 ) 水質處理

原水水質不佳往往會造成肥料溶解度不佳或沉澱、灌溉管線阻塞及植株吸收營養不均衡等情形發生，又為求水資源有效應用養液循環再利用有其必要性，然設施無土栽培回收水甚至原水中常存有疫病菌 (Phytophthora spp.)、腐霉病菌 (Pythium spp.)、鐮胞菌 (Fusarium oxysporum)、立枯絲核菌 (Rhizoctonia solani) 等真菌及軟腐病 (Pectobacterium spp. and Dickeya spp.)、青枯病 (Ralstonia solanacearum) 等細菌，隨著養液系統傳播常造成大規模感染。

水質處理方法在化學性改善上包含曝氣氧化、過濾 (filtration)、酸鹼度調整、軟化 ( 陽離子交換 )、陰離子交換、去離子化 (deionization) 及逆滲透 (reverse osmosis) 等 (Pardossi et al., 2004)( 表 4)，在生物性則可透過過濾膜、逆滲透和殺菌 (disinfection)，常見殺菌方法則有熱、UV 紫外線、強氧化劑 ( 臭氧或含氯產品 ) 及化學藥劑添加，其中以 UV 照射和臭氧最為普遍 (Sarah et al., 2019)。

1. 氧化曝氣

原水若含有鐵錳含量較高，一般可採用曝氣氧化、沉澱、吸附過濾的方法處理。第一步驟為曝氣氧化，利用曝氣塔、曝氣池、打氣機等裝置或藥劑添加，將空氣中的氧氣或氧化劑充分的與水進行接觸，除可增加水中的溶氧量外，進而將可溶性的二價鐵離子 (Fe2+) 和二價錳 (Mn2+) 氧化反應成不易溶解、呈膠體或顆粒狀的三價鐵 (Fe3+) 或四價錳 (Mn4+) 化合物 ( 如 Fe(OH)3 和 MnO2)，後再進行催化過濾。

2. 過濾

從一般過濾 (1,000-10 μm)、微過濾 (10-0.1 μm)、超過濾 (0.1-0.005 μm)、奈米過濾 (0.05-0.001 μm) 到逆滲透 (0.005-0.0001 μm)，過濾孔徑越細，處理成本越來越高 ( 圖 3)。設施養液栽培水質處理多採一般過濾，以去除 10-1,000 μm 範圍的雜質，其類型有弧形篩 (bow screen)、鼓式過濾 (rotation drum filter)、沙濾 (sand filter)、平板過濾 (flat bed filter) 和篩網碟片過濾 (screen filter)，其中以沙濾和篩網碟片過濾在臺灣較為常見，如需要過除掉真菌和細菌，則需要使用到微米等級過濾裝置 ( 陳與張，2022)。

3. 陽離子交換 ( 軟化 )

離子交換樹脂可溶解在水中的各種陰陽離子，如陽離子交換樹脂利用 H+ 或 Na+ 進行交換，而陰離子交換樹脂則利用 OH– 或 Cl- 進行交換。臺灣地下水質 Ca2+、Mg2+ 過多而呈現硬水狀態，除 pH 較高將造成肥料溶解不易外，配製養液時若按原配方濃度，常會造成鈣、鎂的含量過高，原水需經由陽離子交換軟化處理 ( 陳與張，2022)。其中 Na 型強酸陽離子交換樹脂為軟化最常使用的處理方式，由陽離子交換樹脂吸收水中的 Ca2+、Mg2+ 等陽離子以軟化水質，交換選擇性依據離子交換基的種類或架橋度而異，大致上 Al3+>Ca2+>Mg2+、Cu2+、Mn2+>K+、NH4+>Na+>H+。

4. 殺菌

A. UV 紫外線照射

100-280 nm 短波 UV-C 具有較佳之殺菌效果，可破壞 DNA 及 RNA 鍵結、蛋白質結構，使微生物無法繁殖或死亡，其中最常使用之殺菌波長為 254nm。所使用的燈管分為高壓 (HD-UV，激發 200-280nm 波長較廣光譜範圍紫外線 ) 與低壓汞紫外殺菌燈 (LD-UV，激發約 254nm 波長之紫外線 )，目前以低壓燈管較常使用 ( 圖 4A)；殺菌效果取決於光強度和光照射時間的累計，照度 (mW.cm-2)× 照射時間 (s)= 累積光量 (mJ.cm-2)，照射時間可由水養液流速控制，100mJ.cm-2 用量對於真菌和細菌即有殺菌效果，160 MJ.cm-2 用量可殺死穿孔線蟲，若欲達完全殺菌 ( 包括線蟲和病毒 ) 則需增加至 250 mJ.cm-2( 楊與沈，1998)。

B. 氧化劑

利用氫氧自由基 (OH•)、自由基態氧 (O•)、次氯酸 (HClO) 等強氧化特性，破壞微生物細胞及病毒蛋白質結構，進一步破壞細胞核內 DNA 或 RNA，使其代謝受影響，達到抑制繁殖殺菌效果，常見水質處裡的氧化劑有臭氧、過氧化氫、二氧化氯及次氯酸鹽類等。臭氧處理可先經 50-80 μm 過濾之水以幫浦打進處理槽中，再將臭氧打入，同時亦加入硝酸調整 pH 至 4.0-4.5，每噸原水加入 10 g 臭氧處理一小時，若為使用過之循環水，則需加倍用量處理一小時 ( 圖 4B)；過氧化氫 H2O2 為較弱之氧化劑，5 ppm H2O2 可防治腐霉病菌、100 ppm 可殺死大部分真菌、500ppm 對病毒有效，若欲殺死穿孔線蟲需以 400 ppm 處理 24 小時以上，但濃度在 500 ppm 以上即對植物根部造成傷害。含氯化合物處理方便且成本低 ( 圖 4C)，原水可以 10 ppm Cl 處理，養液桶或灌溉管路則可以 2 ppm、每 1-2 個月進行一次殺菌，養液中 Cl 濃度超過 2.4ppm 則易造成植株受傷 (Raudales et al., 2014)。

隨著臭氧殺菌機的改良和效率提升，Wageningen UR 相關研究結果建議排放水可先以粗過濾雜質，再以 40 μm microflter 或 flatboard filter 過濾，而後用臭氧 (2.1 mg.L-1.min-1.ozone during 0.5 min at ORP-value at 600 mV) 殺菌，與雨水混合用於養液配置；若排放水之水質真的無法被再被利用，則先以臭氧 (2.1 mg.L-1.min-1.

ozone during 1 min at ORP-value at 700 mV)，後以 UV(300 mJ.cm-2 UV 254 nm) 殺菌並除去 PPPs 才能排出 (Beerling et al., 2017)。

5. 過濾膜

超過濾是薄膜處理中運用最廣的技術，除可過濾水中之懸浮物、膠質、有機質外，亦可移除真細菌與病毒 ( 圖 5)，但不會改變水溶液中之營養成份，具低能耗、水通量大、阻絕率高等特性，然此形態過濾膜常會黏塞致使效果不穩定。逆滲透去除灌溉水中之鹽類及 PPPs，可用於再循環利用水之消毒及排放前處理。Poseidon 為一有效淨化系統 ( 圖 6)，特別對於養液循環使用造成鈉離子累積過高會限制作物。該系統包含超過濾、鈉濾和活性炭技術，活性炭吸附有機物質如 PPPs，亦配備了下游逆滲透系統，可濃縮待排放的水，從而減少 80% 的水量。

( 三 ) 灌溉水量數據管理

1. 光輻射量應用

灌溉量及頻率會因光輻射量有所差異，以設施介質栽培番茄為例，依蒸散法則給水量應等於 2-3 ml.J-1( 在預設 30% 滲漏量情形下 )( 表 5)，2,000 J.cm-2.d-1 即應給予 4-6 L.m-2 灌溉水；頻率在光輻射量 200、400、600 及 800 W.m-2 時每一小時分別需灌溉 0-1、1-2、2-3 及 3-4 次 ( 表 6)。灌溉時間應從日出前 1-2 小時開始到日落後 1-2 小時，每日至少灌溉 10 次以上。

2. 用水量化模式

Van Tuyll 等人 (2022) 利用 Waterstreams 模型 (Voogt et al., 2012) 了解荷蘭番茄溫室用水情形 ( 圖 7)，其中溫度和降雨預設參數為年平均值。溫室可利用的外部水源有四種：雨水、地下水、自來水和地表水，模型計算這些來源的總年消耗量且取決於降雨量、輻射量 ( 影響蒸發散量 ) 以及儲水能力，因此每個水源的耗水量每年都會因地理位置和溫室規格而有所不同；該模型預設設置還包括回收 80% 屋頂冷凝水、30% 滲漏水再循環，被視為內部流動，經計算，上述四個水源消耗量分別為 683 L.m−2、128 L.m−2、43 L.m−2 和 0 L.m−2，年總計 854 L.m−2。使用其他來源的數據驗證了總耗水量 (Raaphorst and Benninga, 2019; van Woerden, 2005)，年用水

量範圍落在 750 至 950 L.m−2 之間。

( 四 ) 符合作物所需

1. 作物需水量

作物蒸發散量 (Evapotranspiration, ETcrop) 亦稱作物需水量，由作物生長期時期所需蒸散量及土壤介質蒸發量之和。露天環境下可利用水汽通量 (vapor flux) 系統由垂直風速及絕對濕度之互變異所計算之潛熱 (latent heat)，經單位換算即等於作物群落上方之蒸發散量 (Scott et al. 2003)，由作物實測蒸散量 ETC 和氣象資料所估算之潛勢能蒸散量 (ETo) 的比值求出作物係數 (crop coefficient, kc)，各種作物之作物係數應依據氣候條件建立估算值，因 kc 是直接受作物特性和所處環境所影響，由以此係數乘以栽植地之蒸發率，即可概略推估需水量。設施栽培中相同的概念也用於「FERTIGATION」模型，該模型基於對作物 ETc 的長時間計算，並包括了對營養需求的估算 (Voogt et al., 2000)，在菊花溫室生產中應用中能夠大幅減少水和肥料的使用量，並對產量或品質無影響 (Voogt et al.,2006)。然該模型的計算需要溫室的實際環境數據及控制參數，如輻射、溫度、供熱管道、使用屏風等，以及基本的土壤介質物理參數和作物生理以及溫室建設的數據。

2. 鹽類耐受性

營養液循環再利用除上述提到微生物感染問題外，由於植物對 Na 的吸收率較低，故在循環用水情況下 Na 離子累積是另一大克服點，當根系環境濃度高於吸收濃度時，Na+、Cl- 等殘留鹽類積累，導致 EC 值升高，透過滲透壓逆境和離子毒性限制植物生長影響光合作用及根系的水分吸收，對產量或品質產生負面影響 ( 表 7) (Kong et al., 2017)。此外，根表面過量的鈉離子會拮抗植物對其他營養吸收，由於 Na 和 K 離子的化學性質相似，對其吸收有較強的抑製作用，在 Na 脅迫下，植物有必要運行更具選擇性的高親和力 K 吸收系統，以維持充足的鉀營養 (Munns and Tester, 2008)。

Na 吸收濃度 (mmol.L-1) 定義為總 Na 吸收除以總水吸收，營養液中的 Na 與植物的吸收之間存在線性相關性 (Vooght and Van Os, 2010)。作物對 Na 吸收濃度可透

過一系列 Na 處理的封閉系統實驗得出，並確定養液濃度臨界濃度，玫瑰、菊花、及胡瓜對鈉敏感，番茄及彩椒則相對耐受 ( 表 8)，前人研究來看，番茄在 20 mmol.L-1 Na 範圍內番茄生長、產量及果實品量基本無顯著影響，然通常建議的設施栽養液原水鈉含量 <0.1 mmol.L-1，養液閾值濃度則低於 6 mmol.L-1，以防止植物受傷 (Beerling et al., 2017)。分根系統 (split-root System, SRS) 應用可克服該問題，利用兩個不同鹽分程度的栽培槽，正常槽以一般養液灌溉，殘留槽給予循環排放養液，番茄‘Livento' 栽培期間殘留槽養液 EC 值 5-6 mS.cm-1、Na 濃度介於 6-36 mmol.L-1，此 SRS 環境下 Na 投入含量為慣行的 5.5 倍，栽培之番茄 Na 吸收濃度亦較高，值為 4.48 mmol.L-1，較慣行 2.84 mmol.L-1 高出 1.6 倍 ( 陳與 Vooght, 2019；Barbagli et al., 2021)

( 五 ) 完善的水養液操作監測系統

綜和上述要件，為求高 WUE 之封閉式溫室水資源零排放種植，一套完整的水養液系統應包含雨水儲藏、滲漏液回收儲藏、廢水儲藏、水源混合、水質處理、養液配置等單位 ( 圖 8)，且為了準確控制根部區域水量和養分進入介質均一性且便於管理介質水分含量 WC 和 EC，以滴頭 dripper 為佳，以番茄和黃瓜為例，適用於容量為 3L.hr-1。並透過感測數據估算、監控及回饋進行施肥灌溉精準管理，目標為創造一個穩定的根區環境，從而實現零排放種植。

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**表1　灌溉用水等級的允許限值**

**Table 1　Permissible limits for classes of irrigation water.**

| Quality Level | EC (ms/cm) | TDS (mg/L) | SARz ( √ meg/l) | SAR (%) | B (ppm) |
|---|---|---|---|---|---|
| Excellent | <0.25 | <175 | 0~2 | ＜ 20 | ＜ 0.33 |
| Good | 0.25~0.5 | 175~525 | 2~10 | 20 ～ 40 | 0.33 ～ 0.67 |
| Permissible | 0.5~1.0 | 525~1400 | 10~18 | 40 ～ 60 | 0.67 ～ 1 |
| Poor | 1.0~1.5 | 1400~2100 | 18~26 | 60 ～ 80 | 1 ～ 1.25 |
| Unsuitable | >1.5 | >2100 | >26 | ＞ 80 | ＞ 1.25 |

SARz (√meg/l)計算公式= $\frac{[Na^{+}]}{\sqrt{\frac{[Ca^{2+}]+[Mg^{2+}]}{2}}} = \frac{\left[\frac{Na^{+}mg/L}{22.989}\right]}{\sqrt{\frac{\left(\left[\frac{Ca^{2+}mg/L}{20.04}\right]\right)+\left(\left[\frac{Mg^{2+}mg/L}{12.15}\right]\right)}{2}}}$ ;

SAR(%)＝[Na]/([Ca]＋[Mg])x100%

**表2　養液配置建議水質**

**Table 2　Recommended water quality for nutrient solution preparation.**

| Item | Standard value | Analytical sample value |
|---|---|---|
| EC | <0.5 mS/cm | 1.2~0.3 mS/cm |
| pH | 6~8 | 5.9~8.9 |
| Hardness | <150 CaCO3 | |
| Organic matter | <5 ppm | |
| Dissolved oxygen | >5 ppm | |
| NO-N 、NH-N | < 5 ppm | |
| CO32- | <10 ppm | |
| SO4-S 、PO4-P | <5 ppm | |
| Ca2+ | <40 ppm | 120~55 ppm |
| Na+ | <30 ppm | 20~50 ppm |
| Mg2+ | <20 ppm | 43~73 ppm |
| K+ ion | <5 ppm | |
| Fe3+ | <1 ppm | 3~12 ppm |
| Mn, Zn, Cu cation | <0.5 ppm | |
| B anions | <0.3 ppm | |

表 3　養液灌溉水源來源、風險及其品質

**Table 3　Water sources, risks, and their quality for fertigation.**

| Source | Pathogen | Nutrients | pH | EC(ms/cm) |
|---|---|---|---|---|
| Rainwater | + | -- | 3.5-7.8 | 0.05-0.4 |
| Tap water | -- | + | 6.4-7.4 | 0.2-0.4 |
| Surface water | ++ | ++ | 5.9-8.2 | 0.2-1.2 |
| Underground | ++ | ++ | 5-8 | 0.3-1.4 |
| Reverse osmosis | - | -- | | 0.00005-0.2 |
| Condensation water | - | -- | | |

表 4　水質處理方法及其用途

**Table 4　Water purification methods and their applications.**

| Method | Total dissaved solids | Bicarbonate and carbonate | Calcium and magnesium | Dissolved iron and manganese | Oxidized iron and manganese | Borate | Fluoride |
|---|---|---|---|---|---|---|---|
| Reverse osmosis | V | V | V | V | | V | V |
| Deionization | V | V | V | V | | V | V |
| Anion exchange | | V | | | | V | V |
| Water softening | | | V | V | | | |
| Activated carbon | | | | | | | V |
| Activated alumina | | | | | | | V |
| Oxidation/Filtration | | | | V | | | |
| Chelation | | | | V | | | |
| Filtration | | | | | V | | |
| Acid injection | | V | | | | | |

表 5　設施番茄計算蒸散量及需水量

**Table 5　Calculated transpiration and required water amount of substrate cultivated tomato under greenhouse.**

| Global radiation (J.cm-2) | 24h average temp (°C) | Calculated transpiration (L.m$^{-2}$) | Water required for 30% drainage |
|---|---|---|---|
| 300 | 17 | 0.53 | 0.76 L.m-2 2.5 ml.J-1 |
| 1000 | 18 | 2.14 | 3.05 L.m-22.5 ml.J-1 |
| 1200 | 21 | 3.56 | 5.09 L.m-22.5 ml.J-1 |

**表 6　設施番茄建議灌溉量**
**Table 6　Irrigation volumes and their frequency.**

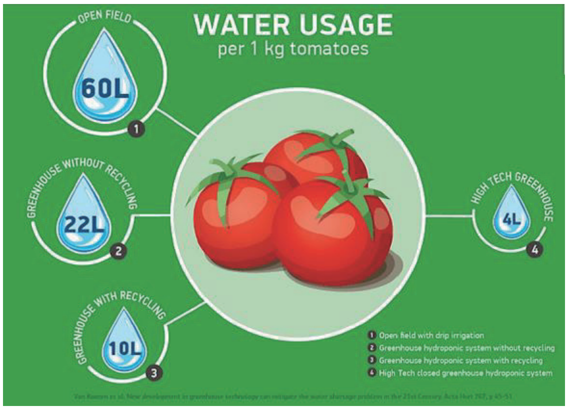
| Global radiation ($J.cm^{-2}$) | Global radiation ($J.cm^{-2}.h^{-1}$) | Irrigated water amount ($ml.m^{-2}$) | Irrigated frequency (/hour) | Water volume (ml/ irrigation) | Joules per irrigation |
|---|---|---|---|---|---|
| 200 | 72 | 216 | 0.5 | 400 | 135 |
| 400 | 144 | 432 | 1.1 | 380 | 128 |
| 600 | 216 | 648 | 1.9 | 340 | 113 |
| 800 | 288 | 864 | 3.0 | 290 | 98 |
| 1000 | 360 | 1080 | 4.1 | 260 | 84 |

**表 7　不同蔬菜作物對灌溉養液鹽分耐受性**
**Table 7　Irrigation nutrient salinity tolerances for different vegetable crops.**

| Crop | 0% Yield loss | 10% Yield loss | 25% Yield loss |
|---|---|---|---|
| | EC (ms.cm-1) | EC ( ms.cm-1) | EC (ms.cm-1) |
| Cantaloupe | 1.7 | 2.6 | 5.5 |
| Capsicum | 1.0 | 1.5 | 2.2 |
| Cucumber | 1.7 | 2.2 | 2.6 |
| Lettuce | 0.9 | 1.2 | 2.1 |
| Tomato | 0.5 | 2.3 | 4.4 |

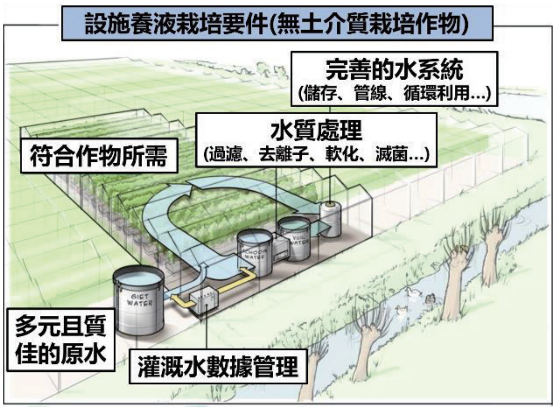
**表 8　不同作物對灌溉養液鈉含量耐受性**
**Table 8　Irrigation nutrient Na tolerances for different crops.**

| Crop | Limit Na (mmol.L-1) | Uptake Na (mmol.L-1) |
|---|---|---|
| Tomato | 10 → 20 | 1 |
| Cucumber | 8 | 1.2 |
| Sweet pepper – Vegetative | 8 →14 | 0.8 |
| Sweet pepper – Vegetative | 8 → 15 | 0.3 |
| Lettuce | 8 | 1.5 |
| Chrysanthemum | 6 | 0.3 |
| Gerbera | 10 | 0.4 |



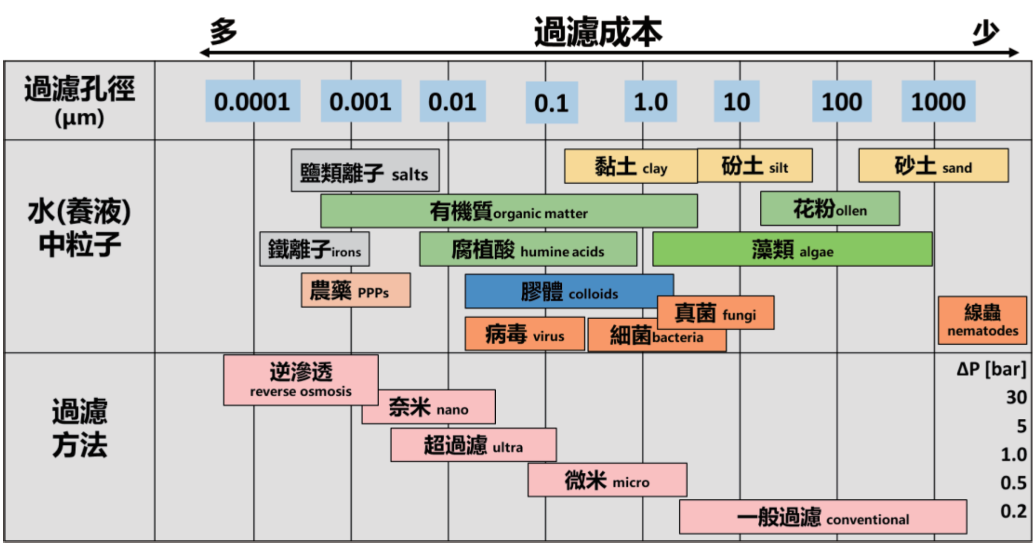

◄ 圖 1　不同栽培環境下番茄生產水分利用效率

Fig. 1　Water use efficiecny of tomato production under differernt cultivated condition.




◄ 圖 2　設施無土栽培水養液零滲漏策略

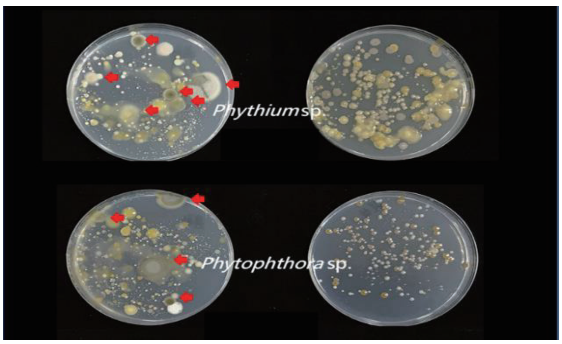
Fig. 2　Strategy for water zero emission under greenhouse cultivation.




▲ 圖 3　不同等級過濾所排除物質種類及其尺寸

Fig. 3　Types and sizes of substances excluded by different grades of filtration.

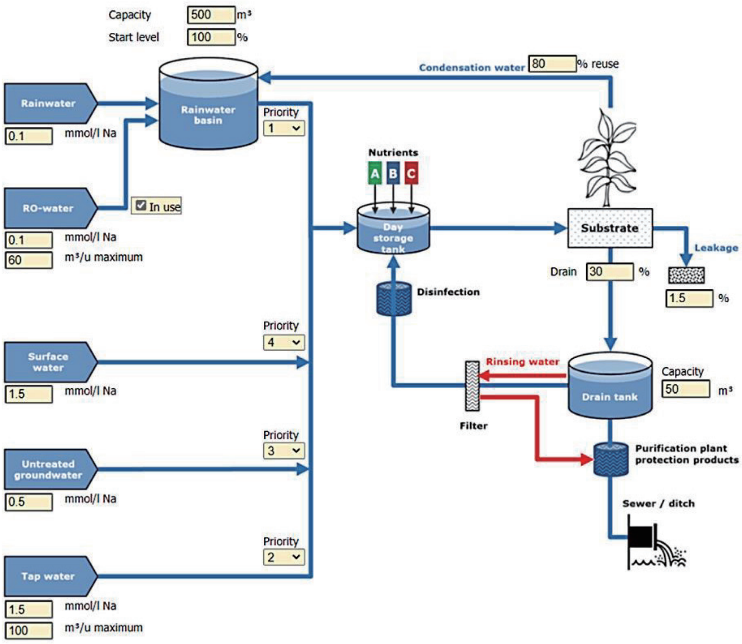

▲ 圖 4.　UV 殺菌機 (A)、臭氧產生器 (B) 及加氯器 (C)
Fig. 4　UV (A), oxidation (B), and chlorination (C) disinfection machine.



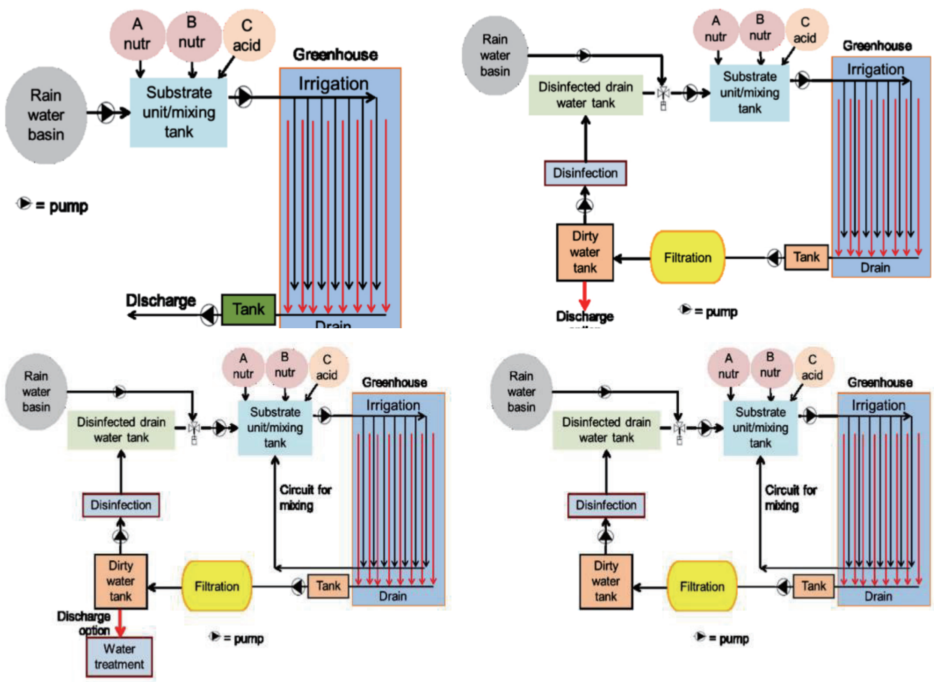

◄ 圖 5　水耕養液經超濾膜過濾後塗抹於 PDA 篩選培養基情形
Fig. 5　Hydroponic nutrient purified by ultrafiltration membrane then cultured in the PDA screening medium


◄ 圖 6　Poseidon 水質淨化系統
Fig. 6　Poseidon water purification system.

(照片來源 : https://www.vanderendegroup.com/)




◄ 圖 7　Waterstreams 模型用戶界面簡化圖
Fig. 7　A simplified diagram from the Waterstreams model's user interface.




▲圖 8　溫室開放式 (A)、半封閉式 (B)、帶有排水循環的半封閉式 (C) 和零排放 (D) 水系統的示意圖
Fig. 8　Schematic overview of an open (A), semi-closed (B), semi-closed with drainage circulation (C), and zero liquid discharge, ZLD (D) water system under greenhouse.

# Sustainable greenhouse production ~ strategy to efficient water utilization with zero emission

Wei-Ling Chen[1]*　Chang-Shen Chien[1]

## Abstract

Climate change and the environmentally sustainable issue have prompted producers to improve existing cultivation systems. Closed soilless greenhouse cultivation, in addition to having a high water use efficiency (WUE), also avoids the discharge of fertilizers and plant protection products through water. The management strategies for water zero-emission included the following: (1) Diverse and high-quality water sources with EC<0.25 ms.cm-1 and Na+<0.1 mmol.L-1, and making efficient use of rainwater and storing up to 800L. m-2 of greenhouse area; (2) Water treatment procedures for both source water and recycled nutrient solution, incorporating a serious of processes such as aeration oxidation, filtration, pH regulation, cation exchange, reverse osmosis, and sterilization; (3) Irrigated amount based on radiation and water-use models estimated; (4) Fertigation management in accordance with crop water and stress physiology then preventing sodium accumulation under circulating conditions; (5)Implementation of a comprehensive practicing and monitoring system for water-nutrient system. It aimed to create a stable root zone environment, thereby achieving zero-emission cultivation.

**Keyword:** Greenhouse cultivation, Evapotranspiration, Sodium accumulation, Water treatment, Water use efficiency, Zero-emission

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# 因應氣候變化下西南沿海農業區的耕作模式設計

江志峯 [1*]

## 摘要

設計新的耕作制度並實質進行大面積驗證，以 (1) 篩選合適作物或品種、耕種方法、耕犁方式等，並評估現有環境特性，調整目前的耕作制度，以因應暴雨、長乾旱、高熱出現頻繁的氣候，求得最適佈置及較高收益；(2) 推廣新的耕作制度，有效利用農業資源，提高此地區產業價值。2018-2021 年於中部沿海低生產力地區建構一年三季水旱輪作制度與最少使用化學資材的耕作制度，主要栽培作物的模式為春作不整地旱作 ( 玉米 )- 雨季直播水稻 - 秋作不整地旱作 ( 大豆 ) 的方式一年三作的節約資源型的耕作系統；配合本區域旱澇季明顯的氣候型態及作物的需水與耐旱特性，實施以二期作 ( 雨季 ) 直播水稻為主，每年輪換作物方式進行。作物栽培原則選擇以互補的可共享資源而不會導致後續作物的水與養分缺乏，提高水肥利用效率。需氮量高的作物可在固氮豆科作物之後 ( 例如：大豆 - 玉米 )。對需經耕犁的作物也應跟隨在不整地旱作物栽培後，強化深層土壤構造的保水力，可減少當季作物灌溉水量利於加深土壤有效供水深度 ( 玉米 - 水稻 )。當土壤肥力水平最低時，應在輪作結束時佈置土壤生產力低的作物，以利於繼承上季作物收穫後殘留的土壤水分 ( 水稻 - 大豆 )。現地進行結果顯示，保育耕犁春作玉米或毛豆 - 二期作直播水稻及不整地秋作大豆 - 食用玉米或小麥等作物的行播種植之新耕作模式，除可增加 30% 農田產能外，相對兩期作水稻季提高 51-121% 的總粗收益。

關鍵詞：輪作系統、作物型態、農地資源管理、作物接替

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# 前言

大氣中溫室氣體 (GHG) 的積累已明顯的影響氣候變化並受到國際社會的高度關注。自然災害也在迅速發生變化，前所未有的熱浪、熱帶氣旋、洪水、風暴、叢林大火和乾旱經常發生在世界各地，影響到世界糧食的穩定供應。前年與今年在台灣所謂的罕見事件 ( 百年大旱 ) 發生的頻率更高、強度更大，而且有些事件具有以前沒有見過或經歷過的特徵。這些變化已經對世界各地農村社區和其經濟體的生計和集體福祉產生負面影響。最近，科學家們開始將重點從遏制二氧化碳排放轉向適應二氧化碳排放。此等意味著有必要重新思考農業生態系統，現在經常用於農業的自然資源是不永續管理方法 (Brown et al., 2000；Tilman et al., 2002)。

台灣耕地有限，加上工商業經濟發展，農地流失嚴重；另存在勞力老化、人工短缺、工資昂貴的問題，使大部分的作物生產成本提高，而無法與其他國家產品競爭；又因氣候異常頻發，自然資源供應困頓且糧食自給率偏低的台灣，更因農產品貿易的國際化、自由化而備受壓力，市場價格受國際市場物價波動影響相當明顯，社會大眾對於農產品物價的變動幅度大頗有怨言。農業面臨著重大挑戰，既要滿足糧食生產的需求，又不能顯著增加種植面積 (Stevenson et al., 2013) 和造成環境退化 (Hobbs et al., 2008)。近年來，永續糧食生產面臨的挑戰一直存在，部分原因是氣候變化影響作物的生產 (Palm et al., 2013；Paudel et al., 2014a)。面對這種困境，農業生產必須以重點農產品的供需、國民營養及農民合理收入等觀念進行耕作制度的調整來考量。

為應對日益增長的糧食、飼料和能源需求以及氣候變化帶來的環境挑戰，農業部門擁有獨特的機會藉由創新和再生農業操作提高農業生產力、生態系統服務等達成聯合國設定的永續發展目標和人類福祉。改進的管理操作，包括：如減耕或免耕管理、作物殘留物添加、作物輪作和增加土壤有機碳 (SOC) 施用，以及平衡養分應用，以提高農業永續性 (Six et al., 2002；West and Post, 2002；Vanden Bygaart et al., 2003)。推動減耕或免耕的管理方式，配合農業資源再生的措施，可使土壤吸存碳和維持最佳的保水性，減少蒸發、逕流與沖蝕，為友善的耕作方式之一。

碳農業是常被提出的農業新制度，目的在緩解農業氣候變化的農場管理操作，包括：

土地和牲畜的管理、土壤、材料和植被中的所有碳庫，以及二氧化碳 ($CO_2$)、甲烷 ($CH_4$) 和氧化亞氮 ($N_2O$) 的通量。它包括碳去除 ( 碳在土壤和生物量中的封存和永久儲存 )、避免排放 ( 防止已經儲存的碳損失 ) 和減排 ( 即，將溫室氣體減少到當前農場排放水平以下 )。所有農業系統都可以緩解，儘管緩解潛力的水平因農場類型和不同地區而異。在衡量農業對永續性的影響及其改進貢獻的眾多可持續性指標中，我們重點關注農業部門的溫室氣體 (GHG) 排放，將其作為關鍵環境指標，從應用於農業的生命週期分析的角度評估幾種溫室氣體減排操作 (Kwon et al., 2021)。

## 一、過去耕作系統的研究

水稻是連作障礙最小的作物之一，若配合其他雜糧及園藝作物採輪作方式栽培，效果會更好，過去曾有許多解決嚴重的連作障礙的經驗。輪作水稻後不僅利於作物生產，對雜草防除及病蟲害管理亦有很好的效果，是最簡便的土壤管理方法。在雜草防除方面，水旱田輪作可改變雜草相，尤其是利用浸水控制旱田雜草，具有很好的雜草控制效果 ( 李，1999)。

複作制度為增加糧食產量的主要途徑之一，但須整體考慮影響作物生產的各種因素及相互之間的關係，及應用何種管理來配合環境，以達最高收益的生產，其中經濟性的評估至為重要。檢討作物產量與複作指數之變化趨勢，過去四十年土地使用頻度之大幅增加，並未抵銷技術所引進之作物增產，而隨後之複作指數降下，亦未導致單位面積產量之明顯提高 ( 蔡等人，1991)。

輪作是任何永續農業系統的重要組成部分。在正常生長季節，輪作作物的產量通常比單一栽培作物的產量高 10%，在乾旱生長季節高出 25%。三種或多種具有不同特性的作物輪作通常會導致土壤健康發生積極變化，從而促進作物生長 (Magdoff and van Es, 2021)。種植的作物類型、產量、產生的根的數量、收穫的作物部分以及田區管理作物殘留物的方式都會影響土壤有機質含量。大量的活性有機質 ( 為土壤生命提供食物 )、團聚體內部高含量的有機質 ( 幫助形成和穩定團聚體 ) 以及分解良好的土壤有機質或腐殖質 ( 以提供更多的陽離子交換能力 )。很少有實驗關注輪作對土壤生態的影響。農作物在田間留下的殘留物越多，土壤微生物的數量就越多。在俄勒岡州半乾旱地區進

行的實驗發現，兩年小麥休耕系統中的微生物總量僅為牧場下微生物總量的 25% 左右 (Magdoff and van Es, 2021)。

作物栽培之終極目標為單位面積作物生產標的的產值達最大，過去農民生產作物，一向追求在單位土地時間內獲得最高收益為目標，在進行適合的耕作制度的測試比較，往往以收益為指標。但農作物無論於國內或國際的市場價格變動大，此一指標並不容易應用於不同地區或時期，且適合的耕作制度或農業生產用地規劃，不但應能提高耕地及農業勞動力之生產效率，更應能維護長期的土壤生產力。

### 二、以雨季水稻爲基礎的旱作不整地栽培系統中增加土壤有機碳的挑戰和機會

土壤維持作物生產力是改善糧食安全和農業永續性的最大挑戰。以水稻栽培為主的生產系統被認為是最穩定的土壤有機碳 (SOC) 保存系統 (Lal, 2004b)。研究顯示減耕和免耕管理、作物殘留物添加和改進養分管理策略對提高 SOC 和作物產量的影響很大。在水稻的系統中土壤的交替乾濕環境使我們對水旱交替耕作、作物殘留和養分管理操作的理解，以及包括對土壤系統中的 SOC 的周轉率、儲存和損失的理解更加複雜。

農民根據市場需求改變種植方式，較少關注其保護效益。由於免耕和其他保護措施，在土壤剖面中積累 SOC 需要數年時間，並且在耕種後產生的收益很快就會消失 (Ghimire et al., 2014)。讓農民保持相同的作物輪作和管理操作可能是提高永續性的最大挑戰，尤其是在小農農業受試圃場的牽連影響很大。

## 材料與方法

### 田間試驗運作歷程及管理

2018 年起主要在苗栗通霄、臺中外埔、彰化和美、大城及雲林土庫試區等 5 區配合當地季節與水自然資源條件進行一年三作不整地食用玉米 - 直播水稻 - 不整地大豆的耕作模式運作與觀察。為期 4 年田間耕作制度，包括：兩種耕作方法、兩種耕作技術和四種作物設計之新耕作系統進行農田區穩定性的確證。參考當地的資源因素以複因子交互作用的試驗設計，如圖 1，現地實施以二期作雨季以直播水稻為中心，一年輪換作物

順序主要為春作不整地食用玉米 - 直播水稻 - 秋作不整地大豆之一年三作的耕作系統。並以地區性的耕作制度為對照。作物品種、施肥、灌溉等皆以當地農民慣用的模式選用配合進行。

以現地進行結果，保育耕犁春作玉米或毛豆 - 二期作直播水稻及不整地秋作大豆 - 食用玉米或小麥等作物的行播種植之新耕作模式，如圖 2，與兩期作水稻比較計算，以農糧署統計資料庫各縣市兩期作水稻收益資料參考。

## 結果與討論

本計畫投入的概念與操作技術包括：

### 一、田區地表平整度與水分管理

目前農田整平作業大抵在栽種水稻前浸水、犁田糊化作業時一併進行，但受一般機械平整設備自身缺陷和人工操作平整精度較低的限制，土地平整精度在達到一定程度後無法繼續提高。近 50 年來，新的平整機械設備不斷研發和改良，雷射光控制技術在土地整平上已廣為應用於提高土地平整作業的效率和精度，農地雷射整平技術是利用雷射光進行量測，精準度遠高於目前慣行以人工和機械操作。

農業試驗所農業化學組 20 年來曾致力於發展雷射整平水田節水技術，在評估水稻直播節水之效益已屬可行，可大幅度提高田間土地的平整精度。在嘉義溪口農場的表土土壤質地為坋質壤土 - 坋質粘壤土的水田區小田區 (0.60 ha) 水平高低差平均為 6 cm，全區 (1.5 ha) 水平高低差 12 cm；旱田全區 (2 ha) 水平高低差平均為 22 cm，以雷射整平機可以整平達到高低差 3 cm/200 m 以下，估計每灌一次水稻田即可減少 300 m3/ha 水量，全年可以減少 25-30% 的用水量 ( 農試所年報，2007)。旱田慣行整平後的高低差一般比水田更大。近年在西南沿海區導入雷射整平技術後，畦溝灌溉效率也可大幅提升 ( 江，2022)，減輕農民管理負擔，也大幅增加和產量。我國因為田區面積小而忽略此項雷射整平機在田間的利用，過去因需進行田區測量作業及機械組件與迴轉犁不同，同時犁具選配太小型造成整平工時偏高，不能普遍落實民間採用。2021 年農試所已建置全台

RTK 網絡，提昇農地精準整平的契機，選配具精準整平功能的掛在機組，應可以普及推展。

## 二、水旱耕作制度與兩期水稻作土壤性質的比較與現地實施要點

在水旱輪作系統中，土壤物理性狀在水旱兩季存在明顯差異。在水稻季，傳統的稻田耕作要在移栽水稻前進行帶水耕耙，將耕層土壤打漿使大土粒分散成為團粒或細小粘粒，多年的水耕後，粘粒在耕層下逐漸澱積而形成密實犁底層，這有助於減少農田滲漏，提高水分和養分的利用效率，同時控制雜草，利於插秧。然而，淹水種稻時土壤表層的漿狀結持力和多年形成的緊密犁底層，在由水田轉換為旱地時容易引起土壤板結，從而影響後季作物的生長發育，最終導致作物產量降低，這也被認為是水旱輪作條件下後季作物生長發育的主要障礙因子。由於過去機械不當耕犁，加上密集式的水稻栽培，使犁底層的出現深度高低不一，間接影響旱作的播種深度與根部的伸展發育，管理上需再進一步克服。水稻季推行改良耕犁以及剩餘生物質留田和其他有機質物料的施用，均能減輕耕層土壤粘密和旱季作物的土壤板結問題。

過去二十年，由於政策緣故，大多農民選擇鑿井灌溉的兩期水稻為主，近年來更由於政府推動雜糧的種植，使得部分農民選擇利潤較高的一些雜糧作物，如大豆、玉米與小麥。為探討作物制度的穩定性及對於當地資源利用的永續性，期能減少大量工業輔助能的投入。

## 三、COM(保育耕犁、有機質添加、敷蓋)一年三作複合式新耕作制度的現地實施

現代密集耕作模式有四個方面為人們所批評 ( 一 ) 過度依賴於添加的肥料、殺蟲劑和灌溉，加速了農業資源的枯竭，降低了農業的永續性。( 二 ) 過量使用持久性合成肥料和農藥過度污染地表水和含水層。( 三 ) 儘管其中一些可能是由於未能完全遵守保護措施，但過程中仍有太多的土壤侵蝕。( 四 ) 單作栽培的實踐，由於其低投入的有機質 (OM) 以及過度耕作和缺乏輪作，往往會耗盡土壤有機質 (SOM)，增加侵蝕和蟲害問題。人們普遍認為輪作可以改善土壤結構、滲透性、微生物活性、儲水能力、有機質含量和抗侵蝕能力，從而提高作物產量和生產系統的永續性 (Bullock, 1992；Karlen et al., 1994)。

## (一)春作不整地玉米栽培

栽培玉米所追求的目標是產量與品質。生育期長短又和作物的輪作、土地利用效率、管理時間長短及安全生育期間的長短有所關係。如安全時間太短，則風險增高，或氣候不適而勉強栽培，則產量不高。玉米對氣候尤其雨量有絕對性的影響。不整地栽培，顧名思義，是在田裡直接播種作物而不耕犁的作法，可讓土壤中原本存在的有機質不因耕犁而分解損失，並且穩定土壤的團粒結構，維持較佳的通氣性，面對突如其來的豪雨時，良好的土壤團粒結構可快速將多餘的水分排出，減少等待土壤乾燥期，而不耽誤農時 ( 江等人，2022)。試驗結果顯示，以慣行畦溝式栽培食用玉米，因春作播種期與成熟期降雨時間不長，試區食用玉米平均果穗鮮重為 5,000-6,500 kg/ha 為屬正常範圍，避免播種期雨量的危害，春作不整地玉米的栽培技術為開發的技術方向。

## (二)雨季直播水稻

水稻直播種植方式為新耕作制度中心作物季，主要解決育苗業者缺工導致秧苗價格高漲及機動的搶降水時水稻栽培的農時，5 個試區均可在雨季直播水稻，與同時間插秧種植方式比較則遭受不等病蟲草危害及鳥襲造成產量低或無收，其中土壤滲透性高的大城試區最為成效，稻穀產量最高達 7800 kg/ha，與插秧水稻的產量不相上下。未來實施時將朝 1. 田面整平，增加有效灌溉；2. 保育耕犁，深耕鬆犁底層方式；以及 3. 有機物質的添加，改善表底土壤構造，增加滲透力三方向改進。

## (三)秋作不整地大豆栽培

穀物豆類通常作為作物輪作或序列的組成部分來處理，而不是作為連續的單一栽培，因為它們與任何其他耕種物種一樣容易受到土傳病原體和害蟲的積累。 為了優化病蟲害、雜草和疾病的管理，並通過土壤剖面利用養分有效性，作物輪作或序列應納入具有不同生命週期、生長習性、根系結構和害蟲譜的物種 (Cook, 2013；Garrison et al., 2014；Reckling et al., 2016a)。

與穀物根部的細網絡相比，穀物豆類的主根結構和粗側根有助於水分滲透並形成後續作物根部所遵循的通道，但也可能影響浸出 (Dunbabin et al., 2003；Neumann et al., 2011)。本耕作模式春作不耕犁播種大豆，在不用雜草防治與肥料的前提下，發芽的大

豆無法與雜草競爭，但雨季水稻後的秋作在少耕犁播種大豆可以適度的控制雜草生長。5試區中以雲林土庫和嘉義朴子分別進行少耕犁和不耕犁的大豆栽培，其中少耕犁的栽培法大豆生長良好，同時不用除草劑防治雜草的管理方式，大豆對於資源的競爭高於雜草；土庫試區不耕犁的大豆栽培方式由於發芽其利用前季水稻殘留下的土壤水分足以供應其發芽，其發芽情形良好，同時也以遺留的稻草進行敷蓋，加上適當使用除草劑，雜草的生長也在控制範圍內，未來秋季灌溉水供應不足下，此作物制度與栽培技術具發展潛力。

## 四、COM的耕作制度與土壤有機質累積及養分循環利用

本耕作模式根據地區性光與降水的自然資源特性於試區佈置春作食用玉米 - 夏季直播水稻 - 秋作大豆的一年三作複合式耕作制度，管理上該制度包括保護性耕作的組合，主要提供改善的有機物質，表面留下大量的有機物質，提供了結合最好的有機和集約化農業的可能性，並承諾長期可持續，提供適當的栽培採用的方法使新系統切實可行。結果顯示，3 種作物目標收量鮮重產量分別為玉米果穗含苞葉為 19,500-21,500 kg/ha，水稻稻穀乾重為 4,500-7,800 kg/ha，毛豆含豆莢鮮重 1,700-5,700 kg/ha，大豆乾重產量為 1,800-4,160 kg/ha，結果也表明，3 季作物的產量均能可達到歷年作物的產量，原型作物制度的設計乃根據作物物候期配合地區性光與水的充分利用，主要原則為避開雨季種植玉米而栽種生長前期較不忌水的水稻，當季作物施氮量則是前季作物需氮量的多寡而定，例如玉米需氮量較大施用氮肥量多，夏季水稻便可減施氮肥，不但不會降低單位面積產量更能增加農田生產效能也能增加農民收益，如表 1，此項複合式作物生產耕作系統能提高光與水的利用效率，藉由田間試驗觀察其系統之穩定性，雖然試驗結果 3 季每項作物產量無法達地區單作最高產量，但已增加土地利用的效率，如圖 3，同時參照政策獎勵作物的品項，區域性一年三作耕作系統的參考作物形態模式，至於系統的耐受力的土壤管理因子，未來將進一步修正以達其產量的穩定性。

## 五、剩餘物與雜草管理

土地平整的耕作方法，選擇競爭性作物品種，機械除草、萌前和萌後除草劑的應用和相關的水管理作為控制雜草不可少的組成技術，也已成功建立水稻直播雜草管理的架框，需要更多的期作試驗驗證。

### (一)敷蓋

作物殘留物或堆肥可用作土壤表面的敷覆蓋物。這種情況在一些減少耕犁系統中經常發生，當時產生高殘留的作物或敷蓋作物殘留在地表上。敷蓋有許多好處，包括 1. 由於更好的滲入土壤和更少的土壤蒸發，提高作物的水分利用率；2. 土壤溫度變化不太劇烈；3. 雜草控制的問題。新耕作制度以機具將上季殘留物於當季作物播種同時進行敷蓋作業，對於種子發芽產生很好的效果，同時可防止入滲土壤的水分更少的蒸發，留待當季作物的利用。當用作覆蓋作物時，穀物豆類可以為後續作物提供氮，同時保護裸露的土壤，豆類與其他作物的混合物進一步降低了淋濾潛力 (Tosti et al., 2014)，其中野豌豆最具成本效益 (Büchi et al., 2015)。

### (二)作物根留存

一些研究顯示，植物根及堆肥對土壤有機碳的存留高於秸稈的碳，根部的碳比地上部的碳對土壤有機碳的衝擊較大也較穩定。根部已經分佈良好並與土壤密切接觸，因此往往貢獻更大比例的耐分解的有機物，而不像是地上殘留物。此外，與地上植物部分相比，許多作物根部含有大量分解相對較慢的物質，例如木質素。 一項用燕麥進行的實驗發現，一年後只剩下三分之一的表面殘留物，而 42% 的根部有機物仍留在土壤中，是顆粒有機物的主要貢獻者。

## 六、生物質增匯抵碳的負碳效益

豆科植物通過一系列“間斷作物 ( 本研究為水稻及玉米 )”、“氮”和“豆科植物特異性”效應影響後續作物 (Chalk, 1998；Peoples et al., 2009)。當缺乏多樣性的種植序列 ( 例如歐洲大部分地區典型的小粒穀物 ( 小麥和大麥 ) 的連續生產 ) 被闊葉作物或麥田“破壞”時，就會出現間斷作物效應 (Robson et al., 2002)。其效果最重要的部分是減少穀物土傳病害 (Kirkegaard et al., 2008)，而其他部分包括清除其他害蟲宿主以及使用替代方法和農用化學品來減少害蟲、病原體和雜草的機會 (Prew and Dyke, 1979；Stevenson and van Kessel, 1997) 以及土壤結構的改善 (Chan and Heenan, 1996)。

計算大豆季後的不整地玉米氮平衡量除通霄試區玉米為正值，顯示系統獲得額外氮源，而土庫與霧峰 2 試區為負值，說明玉米收穫後剩餘物遺留田間，如表 2，利於後二

期直播水稻對於土壤剩餘的氮養分的使用，不同土壤管理組類型所繼承的氮源不同，低地石灰性粗質地排水不完全沖積土的土庫試區以礦質態氮為主，而低台地淺層排水良好沖積土的霧峰試區則以有機氮為主，如表 3。另外，3 季作物根的留存量較兩期作水稻根留存，可增加每年儲存在土壤的生物質量，具有高碳吸存的潛在效益，如表 4。氮效應是指從豆類殘留物中釋放出生物固定的氮，其釋放速率受到其相對較低的碳氮比的影響，並且對後續作物的影響在砂質土壤中比壤質土壤中更明顯 (Jensen et al., 2004)。

## 結論

新耕作制度在單期田供水區既可滿足糧食生產的需求，也有負碳效益，減緩環境退化的潛力，未來推展目標：(1) 依不同稻田土壤性質當診斷指標，完成不同土壤質地於雨季直播水稻栽種與部分管理技術改良，提高更多面積田區稻種苗立率與管理技術，建立適合我國直播水稻的操作標準作業模式，作為擴大推廣規模的基礎。直播水稻可避開灌溉水不足的乾旱風險，穩定水稻的生產達到一般的平均產量水準；(2) 加強利用現代農機具進行水稻直播與旱作不整地播種的兩項栽培技術實施於主要農業生產區進行推展，持續利用區域性農地資源不斷地調整農業生態操作區域性的耕作制度來適應當地的農業生物多樣性，以應對未來氣候變化的威脅。

稻田產生的溫室氣體，如 CH4 和 N2O，具有更大的暖化潛勢，可能會抵消 SOC 儲存和減緩 CO2 排放帶來的好處。瞭解不同耕作方式下的溫室氣體通量、殘留物和養分管理以及它們的碳當量和淨碳儲存等等對於擬定政策舉措和減緩氣候變化很重要。未來更需要更多的研究應該集中在一般具體的水稻田、旱作輪作的生產系統上，以提高我們對受耕犁、殘留物和養分管理操作影響的溫室氣體排放和 SOC 吸存的理解。碳農業具有緩解氣候變化和帶來其他好處的巨大潛力；促進農業氣候減緩的大規模實施應該是我國的全民負碳工程優先事項。碳農業帶來社會協同效益 ( 包括生物多樣性、土壤健康、水質等 )。低碳農業減緩必須是永久性的，低碳農業實施不當可能會對其他社會目標產生負面影響。需要進一步開發低碳農業監測方法，增加操作經驗，改進對低碳農業潛力的評估，以增加知識並減少低碳農業知識吸收的障礙。

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**表 1　各種輪作方式三年的平均總收益及其標準偏差 ( 萬元 / 公頃 )**
**Table 1　Average yearly revenue of different crop rotation systems from 2018 to 2020.**

| | 輪作物制度分類 * | 彰化 | 雲林 |
|---|---|---|---|
| 2018 至 2020 年 3 年全國稻穀生產成本調查報告 #* | 水稻 - 水稻 | 37.2±1.7 | 37.2±1.2 |
| 2018 至 2020 年 3 年試驗輪作物制度 * | 食用玉米 - 水稻 - 大豆 | | 64.7±12.1 |
| | 食用玉米 - 水稻 - 食用玉米 | 82.1±10.3 | |
| | 大豆 ( 毛豆 )- 水稻 - 小麥 | 56.3±14.3 | |

#:2018-2020 年農糧署統計資料庫各縣市兩期作水稻收益資料
*: 食用玉米 20 元 /kg; 水稻 25 元 /kg; 毛豆豆莢 30 元 /kg; 小麥 25 元 /kg

**表 2　不整地春作不同品種玉米栽培施氮量 140 kg N/ha 在不同前作物下之產量及氮平衡**
**Table 2　Yield and nitrogen balance of different previous crops under the nitrogen application rate of 140 kg N/ha in spring cropping with conservation tillage for different varieties of corn.**

| 試區 | 土壤管理組 | 品種 | 前作物 | 產量 #(t/ha) | 地上部累積氮量 (kg/ha/) | 土壤氮差額 (kg/ha) | 氮平衡量 *(kg/ha) | 耕犁方法 / 種植方式 |
|---|---|---|---|---|---|---|---|---|
| 苗栗通霄 | A5b | 台農 5 號糯 | 玉米 | **10.5** | **137** | **-24.2** | **20.8** | 畦溝 / 苗栽 |
| 雲林土庫 | L4b | 美粒甜 | 大豆 | **17.6** | **67** | **-13.4** | **-59.2** | 不整地 / 播種 |
| 台中霧峰 | T5a | 802 糯 | 大豆 | **19.7** | **120** | **45.7** | **-65.4** | 不整地 / 播種 |

#: 含苞葉鮮果穗重
*: 氮平衡量 = 收穫植體地上部氮量 - 施氮量 - 土壤氮差額 ( 種植前後根域土壤礦質氮相差量 )

**表 3　2021 年春作玉米試區種植前後土壤有機質差異**
**Table 3　Differences in soil organic matter before and after planting in the 2021 spring**

| | 土壤 | 苗栗通霄 | 雲林土庫 | 臺中霧峰 |
|---|---|---|---|---|
| | 深度 | | g/kg | |
| 種植前 | 0-15 | 13.0 | 18.5 | 9.3 |
| | 15-30 | 8.4 | 12.6 | 7.6 |
| 種植後 | 0-15 | 13. 2 | 18.4 | 14.1 |
| | 15-30 | 9.8 | 15.0 | 9.8 |

crop corn test plot.

**表 4　作物最大生物質產量的碳量 , kg C/ha/yr**
**Table 4　Carbon amount for maximum crop biomass production, kg C/ha/yr.**

| | 穀粒 | 葉 | 莖 | 根 | 葉 + 莖 + 根 |
|---|---|---|---|---|---|
| 玉米 # | 4123.6 | 2267.9 | 2267.9 | 1649.4 | 6185.2 |
| 大豆 # | 1229.2 | 772.6 | 772.6 | 702.4 | 2247.7 |
| 水稻 * | 3750 | 1675.5 | 1675.5 | 877.7 | 4228.7 |
| Total(A) | | | | 3229.5 | 12661.6 |
| 兩期作水稻 * | 7500 | 3351 | 3351 | 1755.4 | 8457.4 |
| Total(B) | | | | 1755.4 | 8457.4 |
| A-B | | | | 1474.1 | 4204.2 |

#: 資料來自 DNDC 作物生長模型作物參數
*: 資料來自 江 , 2012


圖 1　2018 年 5 處試區以二期作濕田直播水稻為中心的作物複作制度
Fig. 1　5 test areas centered on the second-phase wet field direct-seeding rice cropping system in 2018.

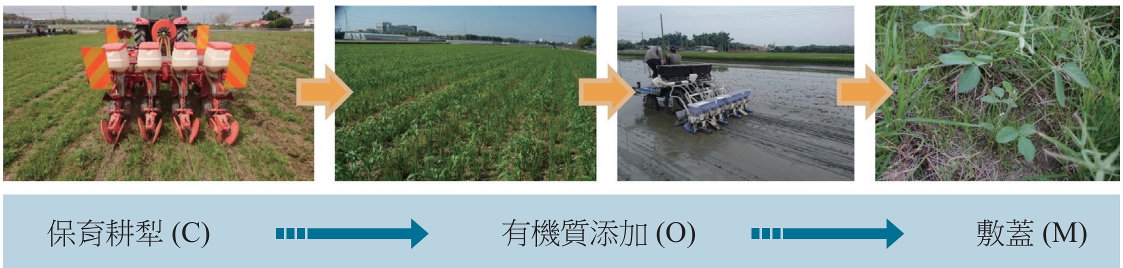


圖 2　COM 複合式耕作制度的管理
Fig. 2　COM complex multi cropping management.


圖 3　彰雲作物複作制度增加土地利用的效率
Fig. 3　The cropping system increases the efficiency of land use in Chang-Yun area.

# Cropping pattern design in southwestern coastal agricultural areas in response to climate change

Chih-Feng Chiang (1)*

## Abstract

A land stability validation of a new cultivation system designed for single-phase field water supply area is conducted to promote new cropping model upgrading production value by efficient use of agro-ecological resources and better selection of crops, cultivars, cultivation methods and tillage for the design of new cropping system with best income (compared to existing system). During 2018-2021, a rotation system of three-crops per year (spring non - tillage fresh use corn - direct seeded rice - autumn non - tillage soybean) combined with less chemical material input are introduced in Southwestern coastal agricultural areas of poor productivity. The benefits observed from rotation among mutual complementary (paddy-upland) crops are co-sharing resources greatly enhance water/nutrient use and avoid water/nutrient efficiency of neighboring or subsequent next crop. The cropping order arranged for high N requirement crop can be after previous N-fixing legumes (soybean-corn), and that of tillage requiring crop can be after previous non-tillage upland crop (corn-paddy), which would strengthen water retention capacity of deep layer soil structure, reducing irrigation demand of current crop and hence, increasing soil available (supplying) water depth (corn-paddy). After a rotation cycle, when soil fertility at least level. Low fertility required crop should be select to plant for inheriting uptake of remaining residue soil moisture of last crops. The new cultivation models of conservation tillage of spring corn or soybean—2nd direct seeded rice and autumn non-tillage soybean-- fresh use corn/wheat (row planting) have resulted in not only increasing field productivity potential up to 30% but upgrade gross income 51~121% of two crops of rice.

**Keyword:** Rotation system, Cropping pattern, Agricultural resources management, Crop succession

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# 花蓮地區有機雜糧耕作模式介紹

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## 摘要

花蓮是國內有機農業發展最興盛的縣市，近年由於「綠色環境給付」及「大糧倉計畫」的政策推動，縣內有機雜糧種植面積急劇上升。其中以有機大豆種植面積最大、蕎麥種植面積上升最快。此外，由於轄內原住民族占比高，樹豆也為其中最普遍栽培且具特色的雜糧；然而，這些作物的生產皆面臨人力不足、生產成本高昂，及田間管理不易等問題。為此本場投入研發，於有機大豆生產中開發低成本專用省工農業機械及智慧化管理系統，於蕎麥生產導入不整地無人機撒播技術，更研發樹豆機械化生產技術，反轉過往全人工栽培的生產模式。希望藉由這些技術的研發來強化農友生產經營的穩定度，更盼此類技術的應用，能讓農友更有信心擴大有機栽培面積，協助更多農友投入於永續生產的實踐。

**關鍵詞：**有機農業、大豆、蕎麥、樹豆、機械化

1 農業部花蓮區農業改良場
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# 前言

農業生產提供人類生存所需的食物以及活動所需的其他資源，是維持人類生活最基本也最重要的產業；然而，受氣候變遷影響、生物多樣性降低、土壤劣化及流失、水資能源的逐漸枯竭，以及生產成本上升，種種不利因素漸漸威脅著農業滿足人類需求的能力 ( 楊，2007；楊與蕭，2022)。「永續農業」相關概念也因而陸續被提出；然而，目前尚未有一致且明確的定義規範永續農業是如何操作 (Velten et al., 2015)。根據美國法典的定義，永續農業是一個動植物的綜合生產系統，且能在長期目標上達成滿足人類食品和纖維需求、提升環境品質、有效利用非再生資源和農場資源，並整合適當的自然生物循環和控制、保持農場經營的經濟可行性，以及提升農民和整個社會的生活品質 (U.S. Congress, 1990)。而有機農業在狹義範圍下也被認為是實踐永續農業的一種辦法 ( 謝，1993；林，2005；朱等人，2018)。

近年我國政府為響應國際倡議加大減碳力道，亦開始追求 2050 淨零轉型的目標，各部門紛紛動員研議階段性減碳目標與策略，其中農業部門更肩負經濟發展、生態保護與糧食安全等任務 ( 施等人，2021)。2018 年我國溫室氣體總排放量，雖然農業部門僅占全國排放量 2%，但仍有努力空間，而其中非燃料燃燒排放就占農業部門的 47%，之中又以農業土壤占比最大為 45.9%，其次便是水稻種植產生的排放占 22.7%，故在維持糧食安全前提下，減少水稻生產面積便是首要減少碳排放的策略之一，因此農政單位也已經推動相關行動計畫包括綠色補貼、大糧倉計畫、配合水情計畫下的大輪作系統規劃、循環農業與農機補助等政策 ( 施等人，2021；精緻農業高峰論壇，2022)。

自農業部動調整耕作制度活化農地、大糧倉計畫－推動國產雜糧產業發展等政策後，讓國產雜糧產業方興未艾，原本就是國內有機農業大本營的花蓮縣，從 105 年到 112 年 6 月間有機雜糧 / 特用作物種植面積也急速成長快 10 倍，從 99 公頃增加至 983 公頃，此類作物占縣內有機耕作土地面積更從 7% 提升至 31%( 行政院農委會農糧署，2016；行政院農委會農糧署，2023)；然而，在有機耕作面積快速成長的同時，從農人口高齡化、農業缺工、有機生產成本高昂，以及本縣地形南北狹長，耕地分散不易形成代耕制度等限制，皆讓有機農友在維持作物永續生產道路上面臨挑戰，也因此機械化與智

慧化生產技術導入是有其必要，故本場透過低成本的農機及技術研發，提高農友作業效率並減輕農事辛勞及成本，並依產業發展規模推升產業邁向機械化，甚至智慧化生產。

## 有機大豆智慧化生產省工又減碳

在消費市場日漸重視食品安全的世界潮流下，宜蘭花蓮一直是有機農業的大本營，即使在台灣加入 WTO 後，國產雜糧面積持續下降的大環境下，有機大豆仍是花蓮地區雜糧主力栽培作物之一。花蓮地區於民國 100 年有機大豆種植面積不到 10 公頃；然至今已遽增至 300 多公頃，成長幅度逾 30 倍以上，且成長趨勢未歇，顯示有機大豆極具開發潛力。

然而，國內已達超高齡社會，東部地區除人口高齡之外，亦有人口外流嚴重之問題，除此之外，經盤點在花蓮的有機大豆生產困難更集中於播種、雜草管理、採收、乾燥、選別、分級等農事操作耗費太多人力，以及氣候變遷衝擊下的田間管理操作模式變化。由於宜蘭花蓮地形南北狹長，生產者型態又以小農居多，在土地多非自有且大多呈現零星分布的情況下，農友常須四處奔波，致難以集中管理，因此，如何在人力有限之前提下提高人力使用效率，對於宜蘭花蓮地區農友而言是一大考驗。

鑑於宜花有機大豆產業發展面臨的種種挑戰，為此本場研究團隊投入有機大豆專用省工農業機械研發，讓小農能以低成本購入農機設備滿足生產需求，同時規劃推動有機大豆生產管理邁向智慧化，建置有機大豆智慧化管理系統平台，藉由導入感測器及攝影機等 IOT 科技設備 ( 圖 1)，蒐集各田區實景影像、田區氣象及土壤監測數據，如氣溫、光照、雨量、風速、土壤溫度、含水量、電導度等，再藉由系統中有機大豆生長模型演算分析，估算各田區作物生長階段，最後智慧化管理系統更能進一步針對各田區生育階段提供對應的農務操作建議，如播種期建議、除草時機建議、施肥、病蟲害管理及採收等，以及未來一周農務操作天氣風險警示，來協助轄區內農友改善並擬定適合的生產排程策略。

目前省工農業機械研發已有成效，本場針對有機農友之經濟需求開發一系列符合

生產規模的農機，包括播種機、除草機、選別機、分級機等，可減少傳統人力栽培成本 90%，創造每年 3,500 萬之市場效益 ( 張等人，2019)；而有機大豆智慧化管理系統平台導入後，線上掌握田區生產情形更能降低農友於田區間的移動次數，減少交通所耗費的大量能源，使有機大豆生產永續節能再升級，符合全球節能減碳之產業趨勢，另外，透過此平台協助農友將田區資訊如作物生長階段、未來天氣預報、田區氣象資訊等因素綜合整理後，提出相關農事操作建議及風險評估，將增加人力調配之彈性及使用效率、提升對災害風險的調適能力，以利農友進一步優化經營版圖。此平台的導入已由實例證實讓農友避開因天災導致超過減產 30% 的風險。

在過去，多數有機大豆田區只能採取非常粗放的管理方式，造成相對減產的困境。本場進一步導入科技，以數據支持方式輔助農友進行大田作物生產，與過去耕作方式有所區別。目前以轄區產業快速發展的有機大豆作為初步開發對象，期望本技術未來能普及於露天大面積栽培作物，提高農友對於每塊田區的掌握度和精確度，讓農友能更即時掌握田間訊息，有效進行田區生產管理，也減少農業生產碳足跡。

## 有機樹豆邁向機械化永續又減災

樹豆為原鄉重要傳統作物，富含蛋白質及礦物質，近年消費者對於健康意識 抬頭，促使產業逐漸復甦。然而，傳統樹豆栽培主要在畸零地或較無水源的坡地栽培，種植後管理較為粗放，慣行樹豆多於 2-4 月間採播種或移植幼苗方式種植，植株因具光週期敏感影響，約於 10-11 月開花，並於次年 1-3 月採收，如此長的生長週期提高生產風險，此外，由於樹豆開花期長，有豆莢成熟期不一致的問題，因此不論何種種植方式最後皆是由人工進行採收，另亦伴隨農業缺工及原鄉人口流失、人工成本大幅增加之問題，使生產成本高昂，如此不僅壓縮產品利潤，也使產品相對高價難以走入一般消費市場，如此更加不利生產者栽培面積擴張 ( 蔡等人，2021)。再者，人力不足的問題也常導致農友錯過最佳播種及收穫期，田間收穫產量因此降低，產品品質也較參差不齊，無法穩定建立加工市場。

為解決部落面臨的困境，勢必得在傳統栽培方式之外走出不一樣的路，讓樹豆產

業除了在部落生根，更能增加面積，使原鄉特色作物能經濟化地規模永續生產。解決人力短缺的問題最有效方式就是機械化；但以慣行方式採較大的行株距栽培，到隔年樹豆收穫適期，植株株高可超過 2 公尺，主莖直徑最粗甚至可超過 8 公分，並不適合機械採收。因此，本場從 110 年便以「應用雜糧產業現有農械設備輔助樹豆生產機械化」為目標，持續於「找回原力－原鄉生態永續新農業核心技術研發與擴散」執行計畫研究解決方法，開始嘗試利用大豆產業既有設備，如真空播種機進行樹豆播種，並透過改變播種期及栽培密度來調整樹豆的植株型態，以利後續由雜糧聯合收穫機收穫，在最後的樹豆分級篩選工作，本場亦導入自行研發之「豆豆跑步機」，讓樹豆產業全程機械化。

經本場初步試驗發現於 7 月中旬後，以產業現有播種機械採平畦栽培，行距在 60 公分，株距設定在 12 公分 -24 公分種植較為合適，如此栽培密度下至 8 成豆莢成熟轉色收穫適期時，樹豆植株型態有明顯變矮小現象，其株高不超過 2 公尺，主莖直徑平均不超過 2.5 公分 ( 圖 2)。本栽培技術突破傳統栽培方式下植株生長型態的限制，因而得以利用現有的雜糧聯合收穫機進行機械採收 ( 圖 3)；然而，若以產業現有播種機械採作畦栽培，株距設定不論是 12 公分或是 24 公分，樹豆植株會因為畦上有雙行的機械設定，導致畦上行距較近而有過度密植情形，影響了植株生長及降低產量，後續需要針對此部分再進一步研究。

傳統樹豆採收是以人力收穫，一般農友會於樹豆成熟時期分批進行成熟豆莢採收，採收效率上 1 人每天僅能收穫 0.02 公頃；而雜糧聯合收穫機採收的作業效率 1 人就可達每天 1.2 公頃的收穫量，單就採收而言，田間作業效率上提高了 60 倍。此外，雜糧聯合收穫機出料時已是脫粒好之樹豆；傳統人力採收豆莢後，尚需經人工以小型脫粒機進行脫粒作業。就採收時間上來看，傳統樹豆人工採收每公頃需 6 名工人以 7-10 天採收，再加上 2 名工人 2 天的脫粒作業時間；然而，機械化採收每公頃採收及脫粒 1 天便可完成，減少了大量人力成本，每公頃淨收益也增加近 1 萬元。作物生產週期部分，透過機械化生產及栽培期調整至 7 月中旬，收穫時期上亦與傳統栽培差異不大 ( 陳，2019)，相較之下整體生產時間減少 3-4 個月，不僅省工、省時、省成本，又能大幅降低農友生產管理上面臨的天氣風險。

初步建立樹豆機械化栽培技術後，花蓮場將持續完善樹豆產業，一方面透過栽培技

術提升樹豆機械化栽培的單位產量；另一方面因為目前國內樹豆品種並不是以機械收穫為目的選拔，品種仍有生育期不一致與株型較大的問題，生育期不一致可能造成機械收穫後的樹豆成熟度不一，而有發霉或未熟粒，品質較差，株型較大可能使栽培密度的降低造成減產，因此，本場也將透過品種選育，補足適合機械收穫樹豆品種的缺口 ( 詹等人，2022；黃等人，2023)。

## 有機蕎麥從天空降落省時又減碳

蕎麥近年在花蓮栽培面積急速成長已達 655 公頃，主要產區集中於花蓮玉里。一般當地蕎麥種植是與水稻輪作，在水稻收穫完成整地後才播種，播種方式是以人工方式背負裝滿種子的肥料桶進行撒播。然而，由於水稻生產鏈已相當完善，從播種整地到收穫多是由代耕業者協助完成，也因此在農忙時期農友得等待代耕業者完成水稻收穫整地後，方才能接續蕎麥撒播工作，農務時間調配上並無彈性，也可能因此錯失播種適期，使得蕎麥播種因發芽不均且生育期短使得植株低矮，造成單位產量偏低現象。

此外，由於當地從農人口年齡分布普遍偏高，以人工方式背負約 30 公斤的裝備進行 1 小時的播種工作，讓農友身體負擔相當大，也讓不少農友因此遭受職業病而被迫提早退休。為呼應「以農業科技解決產業問題」及「解決缺工及自動化」的政策目標，本場積極投入省工機械以及無人機應用研究，於玉里與農友合作，於水稻收穫前後著手測試蕎麥不耕犁播種的減碳耕作模式，建立蕎麥省工無人機撒播技術。

試驗利用無人機撒播蕎麥‘台中二號’種子，處理分為割稻前不整地施追肥、割稻後不整地施追肥、割稻後整地施追肥、割稻後整地不施追肥、並以割稻後整地後人工撒播不施追肥方式作為對照。播種種子含水率為 12-15%，每公頃撒播 60 公斤，追肥時間為播種後 28 天。無人機機型為擎壤 EG316，以每秒 3.5-5 公尺的飛行速度在 3.5-4 公尺的飛行高度及寬幅下航行，並使用 360°撒播器，設定轉盤轉速約 1,450-1,650 rpm，撒播器開啟 20% 出料口的參數下，以每公斤蕎麥種子撒播約需 12 秒的速率進行播種 ( 圖 4)。

初步試驗蕎麥應用無人機撒播的產量表現，在割稻前不整地追肥處理下每公頃可收穫 1,800 公斤，顯著高於一般割稻整地後人工撒播不施追肥的生產模式下每公頃只能收

穫 1,274 公斤。此外，在播種作業效率上，無人機撒播每公頃作業時間約 10-15 分鐘，較一般以人力播種需 50-60 分鐘提高作業效率至少 5 倍以上。同時，應用無人機撒播可在前期作水稻未收穫前即進行撒播，並在水稻採收後再將稻稈切碎覆蓋在蕎麥種子上，不但能達到敷蓋效果而避免雜草生長及種子被鳥類啄食，更能少去整地工作，達到不耕犁栽培的減碳效果 ( 何，2022)，也因此節省每公頃 6,000 元的翻耕整地成本。由於此播種方式不用等待前期作收割機及曳引機打田的代耕排程，在農務時間調配上更具彈性。

## 結論

農業要永續，國家才會永續。要讓農業永續，除要有土地、陽光、水，更重要的是要有農民去耕作與生產 ( 陳與葉，2023)。永續農業的實踐，需先達到農民經濟收入與生活的穩定，方能追求達成最終目標「與自然環境共處地和諧生產」。國內有機農業大本營的花蓮縣，近年有機雜糧種植面積急速上升，呼應政策走向，解決轄內產業問題，並致力推動及輔導有機農業發展是本場的任務。要協助大糧倉計畫目標「擴大雜糧耕作面積」順利達成，首要階段就得先改善農友面臨的生產栽培困境，重拾農友從事雜糧生產的信心。本場從轄區內面積最大的雜糧作物大豆、面積急劇飆升的蕎麥，以及傳統部落種植的永續作物樹豆進行生產耕作模式的研發改進，在各自生產模式中紛紛導入機械化，甚至是智慧化，來強化農友生產經營的穩定度，更盼望以此類技術的開發應用，能讓農友在生產技術端更加放心，使其投入更多心力於永續生產的實踐。

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◄ 圖 1　有機大豆大田生產導入田間監測設備
Fig. 9　A multi-sensor system in organic soybean production

▲ 圖 2 樹豆密植技術導入後，主莖直徑明顯降低
Fig. 10　The diameter of the main stem has been significantly reduced after the introduction of the dense planting technology of pigeon peas by the HDARES.

▲ 圖 3　雜糧聯合收穫機進行樹豆機械化採收
Fig. 11　Harvesting pigeon peas with a combine harvester.

▲圖 4　無人機撒播蕎麥示意圖
Fig. 12　Illustration of buckwheat sowing by the drone.

# Introduction to organic cultivation of upland crops in Hualien

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## Abstract

Hualien is the county with the most prosperous organic agriculture development in Taiwan. In recent years, the policies such as "Green Environment Payment Policy" and the "Big Granary Program" have led to a sharp increase in the cultivation area of organic upland crops in the county. Among them, organic soybean has the largest planting area, and buckwheat has shown the fastest growth in cultivation area. Additionally, due to a high proportion of indigenous peoples residing in the region, pigeon pea is also a commonly cultivated and distinctive upland crop. However, the production of these crops faces challenges such as labor shortages, high production costs, and difficulties in field management. To address these issues, we have developed low-cost specialized agricultural machinery and an intelligent management system for organic soybean production, introduced drone-based sowing technology in buckwheat production, and developed mechanized production techniques for pigeon peas, aiming to transform the traditional labor-intensive cultivation mode. We hope that the application of such technologies will instill confidence in farmers to expand their organic cultivation areas and encourage more of them to engage in sustainable production.

**Keyword:** Organic farming, Soybean, Buckwheat, Pigeon pea, Mechanization

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# 2023作物永續栽培體系國際研討會總結

氣候變遷對農業的衝擊非常顯著，包括氣溫與水資源的變化，提高農業生產的風險，然而，**京都大學縄田栄治教授** 指出近30年來，全球三大穀物(玉米、稻米、小麥)的產量都呈現成長趨勢，且在熱帶地區(尤其是東南亞地區)的增產幅度最為明顯，原因在於栽培技術(品種、施肥、機械等)的明顯進步，然而，若氣候變遷的趨勢持續下去，依然將對農業生產造成明顯的負面影響，需要持續的新技術導入，因此，熱帶地區的農業研發(包括臺灣)，對未來全球糧食供應占有極重要的地位。

在氣候變遷下的永續農業策略，FAO的氣候智慧型農業提出「調適(Adaptation)」與「減輕(Mitigation)」，前者是增強作物在氣候變遷下的韌性，維持正常生長，包括面對缺水、缺肥等逆境下，提升作物生長活性，促進水分利用效率與氮素利用效率。**臺大農藝系劉力瑜教授** 指出，可利用作物模式，評估水稻不同生長發育階段受缺水的衝擊，並可結合品種、土質、降雨時機、植株需水關鍵期來綜合擬定灌溉策略。而設施栽培方面，**臺中場陳葦玲博士** 提出可應用水養液的循環系統，達到零滲漏的目標，以降低水資源的耗用與精準栽培生產。**興大植病系黃姿碧教授** 提出微生物，例如芽孢桿菌(Bacillus)，在促進作物生長及漁業畜產應用之潛力，**臺大園藝系盧炯敏助理教授** 則提出一些共生微生物的導入，可以藉由刺激作物ABA的調控，在水分與氮素受限的狀況下，維持光合作用與最終產量。此外，輪作制度的應用也是非常重要的策略，**加拿大農部馬保羅博士** 提到，將玉米或油菜與豆科作物輪作，有助作物在低氮肥投入下，進一步提升產量，可以節約肥料的施用，間接降低肥料的碳排，且產量不減反增之下，更有利於單位產量的碳足跡。**農試所江志峯助理研究員** 也提到，臺灣西南沿海的水旱輪作(玉米-水稻-大豆)制度，應用不整地栽培與水稻直播技術，並配合季節降雨，可達到最佳水分利用與氮素營養管理，在環境親和的前提下增加農田生產力與經濟收益。至於水旱輪作過去可能遭遇的雜糧作物種植問題，**花蓮場陳緯宸助理研究員** 則說明近年臺灣雜糧機械化與智慧化技術的研發，提升有機大豆、蕎麥、樹豆的栽培，並強化生產穩定度。

除了調適策略之外，「減輕」更是作物永續的最重要策略，也就是全球目前最熱議的淨零碳排議題，需要完整且精準的系統來量化、監測、驗證與模擬預測農業生產過程中溫室氣體排放，**臺大生農學院林裕彬院長** 指出，結合區塊鏈技術，以水稻為例，可將水稻在生產過程中的碳排進行精準、詳細、連續性的監測，並可作為未來碳排認證的重要工具，是日後碳權、碳交易、碳抵換之類的主要依據；而作物生產過程中，田間階段是碳排的最重要熱點，**農試所陳柱中副研究員** 團隊，則正在進行 DNDC 模式的田間碳排驗證與評估，作為未來田間碳排的快速且準確估算的重要工具，提供田間減碳的策略擬定依據。而要達到農作物淨零生產包含許多策略，例如 **臺中場吳以健博士** 以稻米生產為例，說明間歇灌溉、合理化施肥、稻殼烘乾機、在地生產等方式，多管齊下的減碳效益。而 **興大土環系高培慈助理教授** 提到，將農業副產物再利用，包括以燃料、肥料或生物炭等方式，營造循環農業體系，能提升作物的生產力，也降低資材投入，達到低碳的功效。

本研討會從氣候變遷對於作物生產的影響切入，再以臺灣農作物生產過程中溫室氣體排放量最高的水稻產業為例，分享碳監測與與追蹤技術，擴展到作物模式與水稻灌溉及減碳生產技術，進一步延伸到作物輪作體系及土壤、微生物與水資源等農業生產重要支柱，提出諸多提升作物韌性層面，以及減碳循環層面的作物永續策略，以提供農產業更多的技術支援。

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