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Department of Geography

Algae Growth under different Fertilizer Regimes in Swiss Rice Paddies

GEO 511 Master's Thesis

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Abstract

As rice cultivation expands into temperate regions such as Switzerland, understanding ecological dynamics within rice paddies becomes crucial for sustainable agricultural practices. This thesis explores the interactions between macroscopic green algae and rice cultivation, focusing on algal composition of Swiss rice paddies, influence of fertilizer on algae growth, and crop performance under algae presence. Through an integrative approach, the study was divided into three sub-projects: field monitoring of Swiss rice paddies (1), fertilizer experiment in the paddy of La Sauge (2), and a greenhouse experiment (3).

In sub-project 1, field observations across multiple sites in the canton of Aargau identified *Chara spp.* and *Hydrodictyon spp.* as the dominant algal genera. Algal presence varied between sites, influenced by factors such as paddy age, water depth, nutrient inputs, and shading from rice or floating plants. While some paddies showed high algal coverage early in the season, none exhibited viable algal communities when rice was maturing, suggesting a natural die-off due to shading, nutrient limitations, or initiated drying of the paddy.

Sub-project 2 focused on the impact of varying fertilizer regimes on algae. Despite high initial algal coverage across all treatments, no significant effect of fertilizer amount or timing on algal biomass was observed. Algal decline over time was attributed to rice canopy shading. Water chemistry only varied slightly across treatments, with pH and temperature decreasing, and conductivity increasing over the growing season.

Sub-project 3 provided insights into causal relationships between algae, fertilization, and rice performance. Here, algae flourished in unfertilized and organically fertilized conditions but declined under mineral fertilization, likely due to nutrient imbalances or competitive exclusion by fast-growing rice. Algae altered water parameters, particularly in unfertilized systems, by raising pH and temperature, while reducing conductivity. Interestingly, algae increased rice biomass in nutrient-poor conditions but had negligible or slightly negative effects under high fertilization (110 kg N ha^{-1}). Algal presence also affected nitrogen dynamics by reducing Nitrogen Uptake Efficiency of rice plants in fertilized treatments. Further, contributing to ammonia volatilization, thus reducing nitrogen availability.

Collectively, this study demonstrates that macroscopic green algae have a measurable influence on nutrient dynamics and rice quality in Swiss paddies. These findings highlight the importance of considering algal dynamics in the management of temperate rice paddies, to optimize nutrient efficiency, and promote sustainable cultivation practices.

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Chapter 1

Introduction

1.1 Rice cultivation in Switzerland

Rice cultivation, traditionally associated with the vast and humid plains of Asia, has found a foothold in unexpected regions of Europe, including Switzerland. While rice has been cultivated in the canton of Ticino south of the alps since 1997 (Lob 2009), warmer conditions have also allowed pilot projects in northern Switzerland (north of the Alps) since 2017. These initiatives aim to make sustainable use of periodically waterlogged agricultural land while enhancing biodiversity (Fabian et al. 2022a, Gramlich et al. 2023).

In the canton of Aargau, rice cultivation has been successfully implemented, largely due to favorable microclimatic conditions, the interest of farmers in high-value niche products and abundant water availability. Major rivers such as the Aare and Reuss provide reliable water supplies necessary to maintain flooded paddy fields.

Rice cultivation in Switzerland offers several ecological and agricultural benefits. Flooded rice paddies create wetland-like habitats beneficial to various species such as amphibians, insects, and birds. Observations have documented increased populations of rare species, including certain frogs and dragonflies, which benefit from these newly created habitats (Fabian et al. 2022a). Furthermore, rice paddies represent an efficient use of land that would otherwise be difficult to farm due to waterlogging. A lot of the drainage systems in Switzerland need to be renovated to maintain its effectiveness (Fabian et al. 2022b). Rice paddies therefore offer an alternative and sustainable solution for periodically inundated fields (Fabian et al. 2022b). Incorporating rice into traditional crop rotations may also improve soil structure and fertility, and contribute to integrated pest management, thereby enhancing the resilience of local agroecosystems (He et al. 2021).

However, rice cultivation also presents several environmental and logistical challenges. The management of water in rice paddies can lead to environmental concerns, particularly water pollution. Flooded fields can become sources of nutrient runoff, organic matter, and trace pollutants, potentially affecting adjacent water bodies (Xu & Su 2020, Varol & Tokatı 2021). The anaerobic conditions in waterlogged soils also facilitate methane production, a potent greenhouse gas (Leifeld et al. 2019). In addition, rice cultivation is labor-intensive and, in Switzerland, may not always be economically viable due to factors such as unfavorable weather conditions or high weed pressure (Fabian et al. 2022a).

These environmental and economic considerations highlight the importance of optimizing productivity in each rice paddy to ensure efficient resource use and therefore reducing the ecological footprint of rice farming in temperate regions.

1.2 Algae in rice paddies

A noteworthy aspect of rice paddies is the presence of algae, which thrive in these aquatic environments. In rice fields, the algal community mostly consists of green algae and cyanobacteria (blue-green algae) species (Imran 2024). Their composition varies highly with the pH of the water, the temperature and nutrient-level (Ismail et al. 2022).

Algae play a dual role in rice cultivation, with their impact depending on various factors. Cyanobacteria, have been shown to benefit rice growth by fixing atmospheric nitrogen, thus enriching the water and soil with essential nutrients (Dineshkumar et al. 2018, Pabbi 2015, Paudel et al. 2012). Algae further support microbial communities and contribute to oxygen production, which can enhance the overall ecological balance of the paddies (Wang et al. 2022, Chen et al. 2022).

However, algal communities can also have negative impacts on rice cultivation. When proliferating excessively, they can compete with rice plants for essential nutrients, such as nitrogen and phosphorus, potentially inhibiting rice growth (Imran 2024). Furthermore, the decay of green algae can release organic acids and other byproducts, altering the water's pH and potentially impacting rice plant health (Roger & Watanabe 1984).

Given the general biological principle that larger organisms often have higher nutrient demands, it can be inferred that macroalgae – due to their greater biomass and surface area – may exert a more pronounced competitive pressure on nutrient availability than smaller microalgae. This could lead to disproportionately greater effects on rice plants when macroalgal species dominate the algal community. Moreover, the physical presence of dense macroalgal mats can reduce light penetration and oxygen diffusion in the water, further stressing rice plants and potentially exacerbating negative impacts on crop health and productivity (Imran 2024).

This study focuses on macroscopic green algae which are a large algal group and consist of charophytes and chlorophytes (Arora & Sahoo 2015). Macroalgae – particularly green algae – are an integral component of paddy ecosystems, including those found in Aargau. In other paddies in the temperate region, high abundances of filamentous algae and chara spp. have been found (Pinke et al. 2014). However, their role in rice cultivation remains insufficiently explored in current research. Martínez-Eixarch et al. (2017) reported that increased presence of weeds and macrophytes in rice paddies can significantly reduce rice yield. As green algae are classified within the macrophyte group, they may contribute to this yield reduction.

1.3 Nitrogen cycle in rice paddies

In flooded rice paddies, nitrogen cycling is a complex process influenced heavily by alternating aerobic and anaerobic conditions (Fig. 1.1).

Upon application of mineral fertilizers, such as urea, nitrogen rapidly undergoes hydrolysis, forming ammonium (NH_4^+), the dominant nitrogen species under flooded conditions (Panda et al. 2019, Gu & Yang 2022). Organic fertilizers, including animal manure, compost, or green manure, also contribute nitrogen through microbial mineralization, releasing ammonium into the soil solution (Keeney & Sahrawat 1986).

Rice plants predominantly take up nitrogen as ammonium in anaerobic (flooded) conditions, effectively utilizing available nutrients from mineral and organic fertilizers (Gu & Yang 2022).

The efficiency of nitrogen uptake within paddies significantly influences crop yield and environmental sustainability and is influenced by fertilizer management practices (Mikkelsen 1987). Additionally, green algae present in flooded rice paddies also preferentially utilize ammonium as their primary nitrogen source due to its ease of assimilation compared to nitrate (NO_3^-) (Vermeer et al. 2003, Starý et al. 1987, Ramli et al. 2020). Thus, optimizing fertilizer types, application rates, and timing can enhance nitrogen use efficiency while mitigating adverse environmental impacts.

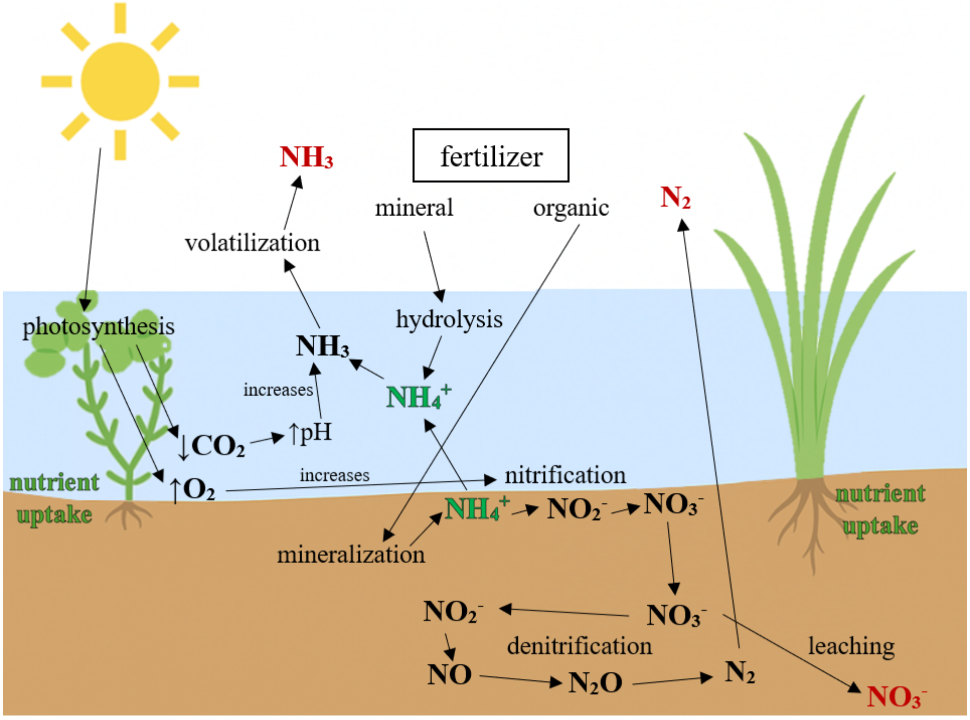

Figure 1.1 Summary of the nitrogen cycle in a paddy with rice plants (on the right) and macroscopic green algae (on the right). NH_4^+ (in green) is the preferred nitrogen form for rice plants and algae to take up. Nitrogen losses are indicated in red. Schematics adapted from Mikkelsen (1987), Ishii et al. (2011), Gu & Yang (2022).

Ammonium losses primarily occur through nitrification/denitrification and ammonia volatilization. Nitrification – the microbial oxidation of ammonium via nitrite (NO_2^-) to nitrate – is generally limited under anaerobic conditions due to restricted oxygen availability (Keeney & Sahrawat 1986, Ishii et al. 2011). However, this process can still occur in thin aerobic soil layers at the water-soil interface (Keeney & Sahrawat 1986, Panda et al. 2019). Nitrate produced can then undergo denitrification, where anaerobic microorganisms convert nitrate into nitrogen gas (N_2) or nitrous oxide (N_2O) (Ishii et al. 2011). This removes nitrogen from the system and potentially causes environmental pollution through greenhouse gas emissions (Ishii et al. 2011).

Ammonia volatilization is another significant pathway of nitrogen loss in flooded rice paddies. High water pH, common under flooded conditions, promotes the conversion of ammonium ions (NH_4^+) to ammonia gas (NH_3), leading to direct atmospheric nitrogen losses (Canatoy et al. 2024, Purwono et al. 2017).

Nitrogen losses through diverse processes, including uptake through algae, can lead to deficiencies in rice plants and affect photosynthesis, growth, yield and quality of the rice (Shrestha et al. 2022). A low nitrogen content can decrease the quality of rice grains in terms of their filling, size and protein content (Leesawatwong et al. 2005, Zhou et al. 2018, Shrestha et al. 2022).

A thorough investigation of the nitrogen cycle, along with key physical parameters of paddy water in the presence of algae, is essential for understanding nutrient dynamics and their availability to rice plants. Algal activity can influence processes such as nitrogen transformation, oxygen levels, and pH, all of which play a critical role in determining the efficiency of nutrient uptake and overall rice productivity.

1.4 Research objectives

In Switzerland, where rice farming remains a developing practice, the role of algae in paddies is an underexplored, yet critical area of research. Understanding the nuanced influence of algae, particularly macroscopic green algae, on rice growth is essential for optimizing yields and promoting sustainability. Therefore, this study investigates the connection between the presence of algae and nitrogen levels as well as physical parameters of the paddy water in a field study and a greenhouse experiment.

To structure this investigation, three key research questions and hypotheses have been formulated to guide the study:

1. What type of macroscopic green algae are common in Swiss rice paddies?

H1: The macroscopic green algae found in Swiss rice paddies are expected to be similar to those observed in other temperate rice-growing regions. This similarity is likely due to shared environmental conditions, such as moderate climate, comparable photo periods, and possibly similar cultivation strategies regarding nutrient input.

2. How does the amount and type (mineral vs. organic) of fertilizer influence macroscopic green algae growth?

H2: The growth of macroscopic green algae in rice paddies is expected to be positively correlated with nutrient availability, regardless of fertilizer type. However, the type of fertilizer may influence the rate and extent of algal growth due to differences in nutrient release dynamics and bioavailability. Mineral fertilizers typically provide readily available forms of nutrients(Panda et al. 2019), potentially supporting rapid algal blooms shortly after application. In contrast, organic fertilizers often release nutrients more gradually (Keeney & Sahrawat 1986), possibly leading to more sustained but less intense algal growth.

3. How do macroscopic green algae influence rice in terms of rice biomass, rice quality and nutrient availability?

H3: The presence of macroscopic green algae in rice paddies is hypothesized to negatively affect rice growth and productivity, primarily through competition for essential nutrients, primarily nitrogen in the form of ammonium (Gu & Yang 2022, Vermeer et al. 2003, Starý et al. 1987). This competition may reduce the availability of these nutrients to rice plants, leading to decreased biomass accumulation and potentially lower grain yield and quality (Shrestha et al. 2022).

These research questions and hypotheses aim to provide a comprehensive understanding of the interactions between algae and rice in Swiss paddy fields, with the goal of identifying optimal management strategies for macroscopic green algae to enhance rice yield.

Chapter 2

Material and Methods

This work is divided into three sub-projects, each addressing distinct research questions. Firstly, rice paddies in four locations in Switzerland were monitored to assess common algae types and gain insights into the Swiss farmers' practices. Secondly, an ongoing fertilizer project in a rice paddy in La Sauge (FR) was accompanied by studying their algae distribution under different fertilizer applications. Thirdly, a greenhouse experiment was conducted to examine how the presence of algae influences rice growth and, conversely, how fertilizer application impacts algal development.

2.1 Swiss paddy rice sites and sampling design for the different sub-projects

The sites and sampling designs varied among the three sub-projects.

2.1.1 Sub-project 1: Monitoring of Swiss rice paddies

At the beginning of 2024, ten farmers in Switzerland were cultivating rice on paddy fields (Fig. 2.1).

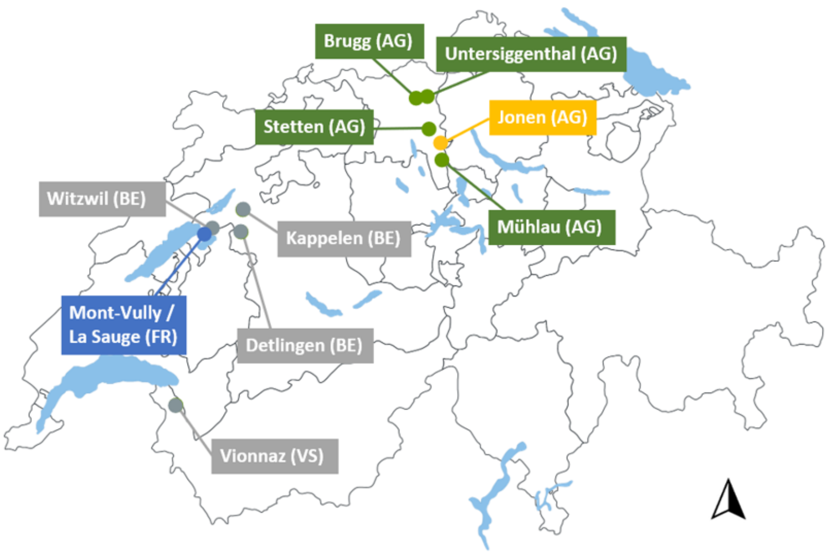

Figure 2.1 Rice paddies in Switzerland 2024. Green = investigated paddies in this sub-project; blue = paddy investigated in sub-project 2; grey = other active rice paddies; orange = terminated paddy early in the season. Data: Agroscope (n.d.).

Several of these farmers managed multiple paddies, with one farmer having up to eight fields. Half of the farmers were located in the canton of Aargau, near the Reuss, Limmat, and Aare rivers. For this sub-project, the focus was on rice paddies in the canton of Aargau.

Each rice paddy site was visited twice during the rice growing period (Table 2.1).

Table 2.1 Investigated paddies in Switzerland: their location, number of paddies and date of investigation.

Location	Number of paddies investigated	1st visit	2nd visit
Stetten	2	22.07.2024	03.09.2024
Mühlau	1	22.07.2024	03.09.2024
Brugg	2	23.07.2024	04.09.2024
Untersiggenthal	1	23.07.2024	04.09.2024

During these visits, water and rice measurements as well as algae cover estimations were conducted (see section 2.2 & 2.3). Measurements were taken at five designated locations within each field (Fig. 2.2), which varied between the first and second visits to ensure representation across the field.

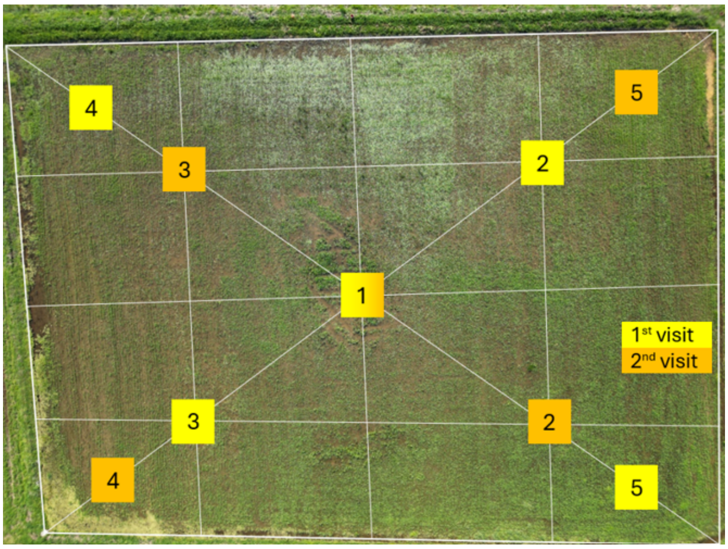

Figure 2.2 Sampling design for sub-project 1. Yellow represents the water, algae and rice measurements during the first visit (22 and 23 July); orange represents these measurements on the second visit (3 and 4 September).

In Stetten 1 and Untersiggenthal, no measurements were taken at the second visit due to the lack of water. Furthermore, a measurement device failure caused missing values of orthophosphate in Stetten 1.

Farmer survey

Furthermore, as part of the Paddy Rice Project initiated by Agroscope, a comprehensive survey was conducted to gather insights into the practices and experiences of Swiss rice farmers. The survey covered a range of topics essential to understanding rice cultivation in Switzerland, including water management strategies, fertilization approaches, weed control methods, and crop yields. For the first time, this year's survey also included questions specifically focused on algae management:

(1) What type of (visible) algae did you encounter in your paddy?

(2) What do you do with the algae?

The survey aimed to provide a comprehensive overview of farming practices and to identify challenges and opportunities specific to rice cultivation in Switzerland. It was conducted with all Swiss farmers that were active in the year 2024. In cases where farmers had discontinued rice cultivation before or during the 2024 growing season, the survey was still conducted when appropriate, focusing on their reasons for discontinuation. However, this sub-project focuses exclusively on farmers located in the canton of Aargau.

2.1.2 Sub-project 2: Fertilizer experiment in the paddy of La Sauge

In La Sauge, an ongoing research project was conducted by Agroscope (Metzger et al. unpublished). This project investigates the effects of varying fertilizer concentrations and application timings on rice yield and nitrogen export. The primary objective is to determine the optimal nitrogen fertilization approach for rice and whether nitrogen fertilization remains a limiting factor for regions where low yields are expected. Additionally, the study explores the potential of proximal sensing methods – such as SPAD meters and VIS-NIR leaf spectrometers – to estimate optimal fertilization timing and dosage.

This fertilizer project was conducted in one of the rice paddies in La Sauge (FR) (Fig. 2.1) on an area of 1300 m^2. The area was divided into four treatments in four replicates (= 16 different plots, each 9 x 9 m) (Fig. 2.3).

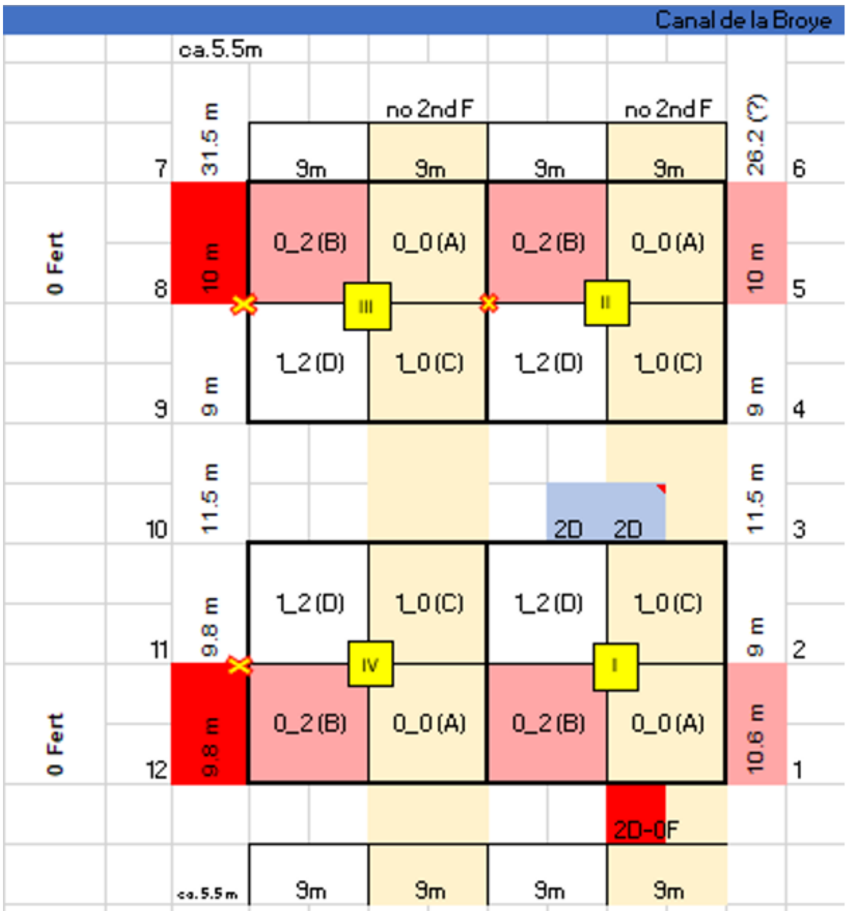

Figure 2.3 Experimental design of the fertilizer experiment in La Sauge with different treatments (A, B, C, D). Red indicates no first fertilization; yellow indicates no second fertilization.

Four treatments were applied, consisting of no N fertilizer (A), only applying half of the allocated fertilizer amount during transplantation (C), only applying half of the allocated fertilizer amount before panicle initiation (B) and full fertilization (D) (Table 2.2). The first fertilization occurred at the time of transplanting (23 May 2024) using ammonium sulfate, providing 42 kg N ha^{-1}. The second fertilization was applied just prior to panicle initiation (2 July 2024) using urea, delivering 39 kg N ha^{-1}. Each treatment was replicated four times.

Table 2.2 Explanation of the applied treatments.

Treatment	
A(0_0)	No fertilization
B(0_2)	Only second fertilization
C(1_0)	Only first fertilization
D(1_2)	First and second fertilization

To complement this research, algal assessments (section 2.3) and water measurements (section 2.2) were carried out at La Sauge. Therefore, one sampling/measurement spot in each of the 16 plots was chosen, approximately in the middle of the plot, resulting in four samples and measurements per treatment. These measurements were conducted twice over the growing period of rice in 2024, the first time on 1st of July and the second time on 28th of August.

2.1.3 Sub-project 3: Greenhouse experiment

The third study was conducted in a controlled greenhouse environment to simulate conditions typical of rice paddies in Switzerland. In the experiment, *Loto*, a risotto variety from Italy, was cultivated under a regimented schedule in the greenhouse, where temperatures ranged between 25 °C and 28 °C, with supplemental lighting during the day to ensure consistent growth conditions.

Prior to the experiment, rice plants were pre-cultivated for 23 days in compost soil and watered every second or third day. On August 28, 2024, plants were transplanted into 9 cm x 9 cm x 20 cm containers, with one rice plant per container. The containers were filled with approximately 7 cm of mixed soil (34 % sand, 42 % silt, 24 % clay), followed by 8 to 10 cm of water. The waterline was marked. Air pumps were installed in each container for air supply, replicating the dynamics of natural rice paddies. The experimental treatments combined three fertilizer regimes – none, organic, and mineral – and two levels of algae inoculation (0 g and 5 g wet biomass), resulting in six treatment combinations (Table 2.3). Each treatment was replicated five times. Therefore, the experiment included 30 containers, which were randomly distributed within the greenhouse to mitigate spatial bias.

Table 2.3 Treatment clarification with treatments varying in algae inoculation, fertilizer type and rate.

Treatment	Algae	Fertilizer type	Nitrogen application rate [kg N ha^{-1}]	Replicates
1	no	none	0	5
2	no	organic	110	5
3	no	mineral	110	5
4	yes	none	0	5
5	yes	organic	110	5
6	yes	mineral	110	5

A combination of green algae *Chara spp.* and *Hydrodictyon spp.*, collected from a paddy field in Mühlau (AG), were inoculated into the containers of Treatments 4-6, the day after the flooding

(29 August 2024), simultaneously with the fertilizer application (Table 2.4). Fertilization rates corresponded to 110 kg N ha^{-1}, applied as either organic or mineral fertilizer. Both fertilizers were from the label "Hauert", with the organic fertilizer "Biorga Quick" containing 12 % N and the mineral fertilizer "Harnstoff Geprillt" containing 46 % N.

Measurements of water and plant parameters were taken over eight weeks, from August 30 to October 21, at nine time points (T1 to T9) (Table 2.4). The time periods between the measurements were increased gradually by one day due to the assumption that the chemical dynamics fluctuate more at the beginning of the experiment and therefore need to be investigated more frequently.

The end of the experiment was marked as the day when the biomass of the rice and algae was collected, on October 22.

Table 2.4 Schedule of the experiment

		Day of the experiment
Flooding of rice		-2
Algae inoculation & fertilizer application		-1
Measurement timepoint	T1	1
	T2	4
	T3	8
	T4	13
	T5	19
	T6	26
	T7	34
	T8	43
	T9	53
Biomass collection of algae and rice		54

2.2 Water parameters

Water parameters were analyzed to monitor nutrient dynamics and environmental conditions. Parameters included concentrations of Total Ammonia Nitrogen (TAN), orthophosphate (PO_4^{3-}), nitrate-nitrogen (NO_3^--N), nitrite-nitrogen (NO_2^--N), as well as pH, temperature, and conductivity.

To measure the pH, the temperature and the conductivity of the water, the HQ4300 portable meter of the Hach Company was used. Thus, two probes were installed and put into the investigated water.

To measure TAN, orthophosphate and nitrite-nitrogen, the SL1000 portable parallel analyzer of the Hach Company was used. This device uses Chemkey reagents to measure different parameters in the water.

For the nitrate-nitrogen measurements, samples were sent to the laboratory to be analyzed. For that, 20 ml of the water sample was filtered with a 0.2 μm filter and frozen until it was analyzed.

The results of TAN were converted to ammonia-nitrogen (NH_3-N) and ammonium-nitrogen (NH_4^+-N) by making use of their equilibrium which is determined by the pH value and the temperature of the water. The following equations were used (Purwono et al. 2017):

$$NH_3 - N = \frac{TAN \times 10^{pH}}{e^{\frac{6344}{273+°C}} + 10^{pH}} \tag{2.1}$$

where:
NH_3-N = ammonia-nitrogen (mg NH_3-N L^{-1})
TAN = Total Ammonia Nitrogen (mg L^{-1})
pH = pH value
°C = temperature

Based on the NH_3-N concentrations of the formula (2.1), ammonium-nitrogen concentrations were calculated as follows:

$$(NH_4^+ - N) = TAN - (NH_3 - N) \tag{2.2}$$

where:
NH_4^+- N = ammonium-nitrogen (mg NH_4^+- N L^{-1})
NH_3-N = ammonia-nitrogen (mg NH_3-N L^{-1})
TAN = Total Ammonia Nitrogen (mg L^{-1})

2.2.1 Sub-project 1: Monitoring of Swiss rice paddies

For this project, the following water parameters were monitored: TAN, PO_4^{3-}, NO_3^--N, pH, temperature, and conductivity. Additionally, the water height was monitored to assess the different water management strategies of the farmers. PH, conductivity, temperature and water height were measured at 5 locations within one field. For the nutrient analyses, 5 samples, taken from these same five locations were mixed together and measured, resulting in one measurement per field.

A measurement device failure caused a missing value of PO_4^{3-} in Stetten 1.

2.2.2 Sub-project 2: Fertilizer experiment in the paddy of La Sauge

PH, conductivity and temperature were measured in La Sauge at 16 locations. Furthermore, at the second fertilization time, NH_4^+-N and NO_3^--N concentrations were monitored for 7 days after the second fertilization at one location where the second fertilization was applied and one where it was not. One measurement was taken before the application of the fertilizer (0h), and then after the application as follows: + 6h, + 1d, + 3d, + 4d, + 5d, + 7d. The first fertilizer application was not monitored as the fertilizer was put into the soil during transplantation, and eventual fertilizer leakages into the water would be distributed evenly due to the water flow induced by the flooding that followed the transplantation.

A measurement device failure caused missing pH values at the second visit.

2.2.3 Sub-project 3: Greenhouse experiment

In the greenhouse project, all water measurements were carried out at each measurement day in each container individually. Except for Nitrate-Nitrogen which was only measured one time at T4.

Additionally, evaporation was measured manually at each time point in the greenhouse, as well as four additional times during longer time periods between measurements (between T5 & T6, T6 & T7, T7 & T8, T8 & T9). To compensate for evaporation losses, water was filled up each time to the same water level, as marked at the beginning of the experiment.

2.3 Rice plant and algae examination

2.3.1 Sub-project 1: Monitoring of Swiss rice paddies

In this project, rice shoot height was monitored manually by randomly selecting one rice plant at each sampling location. Algal cover was visually estimated as a percentage by assessing the water surface at each sampling spot.

Five algae samples were collected in each paddy using a 10 cm diameter tube. Excess water was removed, and the biomass was transferred into sealed plastic bags. To reduce decomposition, samples were stored overnight in a cooler. Subsequently, algal samples were examined microscopically for taxonomic identification. Identification was carried out using the Algae Identification Lab Guide (Serediak & Huynh 2011) alongside the Characean key provided by Boissezon & Auderset (2023) and Hoesch (2003).

This study focused solely on macroscopic green algae (chlorophytes & charophytes) observable to the naked eye. While various algal types were identified, species-level determination was not possible due to morphological characteristics that could correspond to multiple species. Consequently, only the genus could be confidently assigned.

After identification, the wet biomass of each sample was weighed. The samples were then dried at 60 °C for 48 hours, and subsequently the dry biomass was recorded with a fine scale.

2.3.2 Sub-project 2: Fertilizer experiment in the paddy of La Sauge

The assessments of rice and algae in La Sauge were conducted using the same methodology as described in sub-project 1.

2.3.3 Sub-project 3: Greenhouse experiment

In the greenhouse experiment, rice shoot height was measured in each container at every timepoint.

At the conclusion of the greenhouse experiment, both algae and rice plants were harvested for biomass analysis. Wet and dry biomass measurements were conducted for rice shoots, panicles, and algae (procedure as in sub-project 1). Additionally, the carbon and nitrogen concentration of both rice plants and algae were determined using elemental analysis. In preparation for the elemental analysis, the samples were milled and weighed into tin capsules.

To obtain the total nitrogen and carbon content, the concentration was multiplied by the respective plant or algae mass.

To assess the efficiency of the nitrogen used in the rice plant, the following formulas were used (Good et al. 2004):

Nitrogen Use Efficiency (NUE):

$$NUE = \frac{Sw}{N} \tag{2.3}$$

where:
Sw = dry shoot weight [mg]
N = nitrogen content in shoots [mg]

Nitrogen Uptake Efficiency (NUpE):

$$NUpE = \frac{Nt}{Ns} \tag{2.4}$$

where:

Nt = total nitrogen in plant [g]
Ns = nitrogen supply per plant [g] (applied N in fertilizer, per container)

2.4 Statistical analyses

All statistical analyses were conducted in R (version 4.4.2, R Core Team 2024), using the packages *readxl* (Wickham & Girlich 2023), *car* (Fox & Weisberg 2019), *dplyr* (Wickham et al. 2023), *rstatix* (Kassambra 2023), *effsize* (Torchiano 2020) and *ggplot2* (Wickham 2016) for visualizations.

2.4.1 Sub-project 1: Monitoring of Swiss rice paddies

No statistical analyses were made for this sub-project due to the small sample size of only 6 rice paddies monitored (only 4 twice) and a challenging comparability due to different management practices of the farmers.

2.4.2 Sub-project 2: Fertilizer experiment in the paddy of La Sauge

To assess differences in dry algal biomass and water parameters (pH, temperature, conductivity) among treatments, separate one-way analyses of variance (ANOVA) were conducted for each sampling date (1 July and 28 August) (Table B.5). For the first sampling date, treatments were grouped into two categories (A & B vs. C & D) due to identical fertilizer application schemes. For the second sampling date, all four treatments were analyzed individually.

Prior to conducting ANOVA, two key assumptions were evaluated:

- *Normality:*
  The normality of the residuals from each ANOVA model was examined using the Shapiro-Wilk test (Shapiro & Wilk 1965). Assumption of normality was met if Shapiro-Wilk test was insignificant ($p > 0.05$).

- *Homogeneity of Variances:*
  Equality of variances across treatment groups was tested using Levene's test (Levene 1960), with the median as the center measure. Assumption of homogeneous variances was met if Levene's test was insignificant ($p > 0.05$).

If both assumptions were met, a one-way ANOVA was conducted to compare the treatment means. If either assumption was violated, the complementary non-parametric Kruskal–Wallis rank-sum test was performed to assess group differences in a variance-robust manner (Kruskal & Wallis 1952).

Effect sizes were reported based on the chosen test: $\eta 2$ for ANOVA and $\varepsilon 2$ for Kruskal-Wallis rank sum test (Cohen, 1988).

Significance codes were assigned as follows: p '***' < 0.001 '**' < 0.01 '*' < 0.05 '.' < 0.1. For values above the marginal significance of < 0.1, 'ns' was assigned, for no significance, in figures.

2.4.3 Sub-project 3: Greenhouse experiment

The primary objective of the analysis was to assess the effects of algae presence on a range of physicochemical and biological parameters (Table B.8) by comparing Treatment pairs 1 vs. 4 (no fertilizer), 2 vs. 5 (organic fertilizer), and 3 vs. 6 (mineral fertilizer), which were designed to represent algae-free versus algae-influenced conditions under otherwise comparable experimental settings.

One sample (in Treatment 4) was excluded from the statistical analyses due to unexplained plant death. As the rice plant in this sample died prematurely for unknown reasons, it was not possible to obtain reliable measurements, and therefore the sample was omitted to avoid potential bias in the results.

Prior to selecting the appropriate statistical tests, the assumptions of normality and homogeneity of variance were evaluated with the same procedure as in section 2.4.2.

For each parameter, the following decision framework was applied to each pairwise comparison:

- If both groups were normally distributed ($p > 0.05$) and exhibited equal variance ($p > 0.05$), a two-sample Student's t-test was performed (Student 1908).
- If either assumption was violated, a non-parametric Wilcoxon rank-sum test was used instead (Wilcoxon 1945).

All tests were two-tailed and performed at a significance level of $\alpha = 0.05$. The same significance codes as in sub-project 2 were assigned.

To quantify the magnitude of observed differences between treatment groups, effect sizes were calculated based on the chosen test: Cohen's d for ANOVA (Cohen 1988) and r for the Wilcoxon rank-sum test (Rosenthal 1991). Effect sizes were positive if the mean of the treatment with algae was bigger than the mean of the treatment without algae.

Differences between treatments were calculated using the mean values of each treatment. The same significance codes as in sub-project 2 were used.

Chapter 3

Results

3.1 Sub-project 1: Monitoring of Swiss rice paddies

3.1.1 Common algea in Swiss rice paddies

Two primary genera were identified: *Chara spp.* and *Hydrodictyon spp.* (Fig. 3.1). Potential species within the *Chara* genus include *Chara globularis aggr. sp.*, *Chara tenuispina sp.*, *Chara contraria sp.*, and *Chara vulgaris sp.* For *Hydrodictyon spp.*, commonly referred to as the water net, species identification was further narrowed due to the rarity of most candidates, leaving *Hydrodictyon reticulatum (Linnaeus)* as the most probable species.

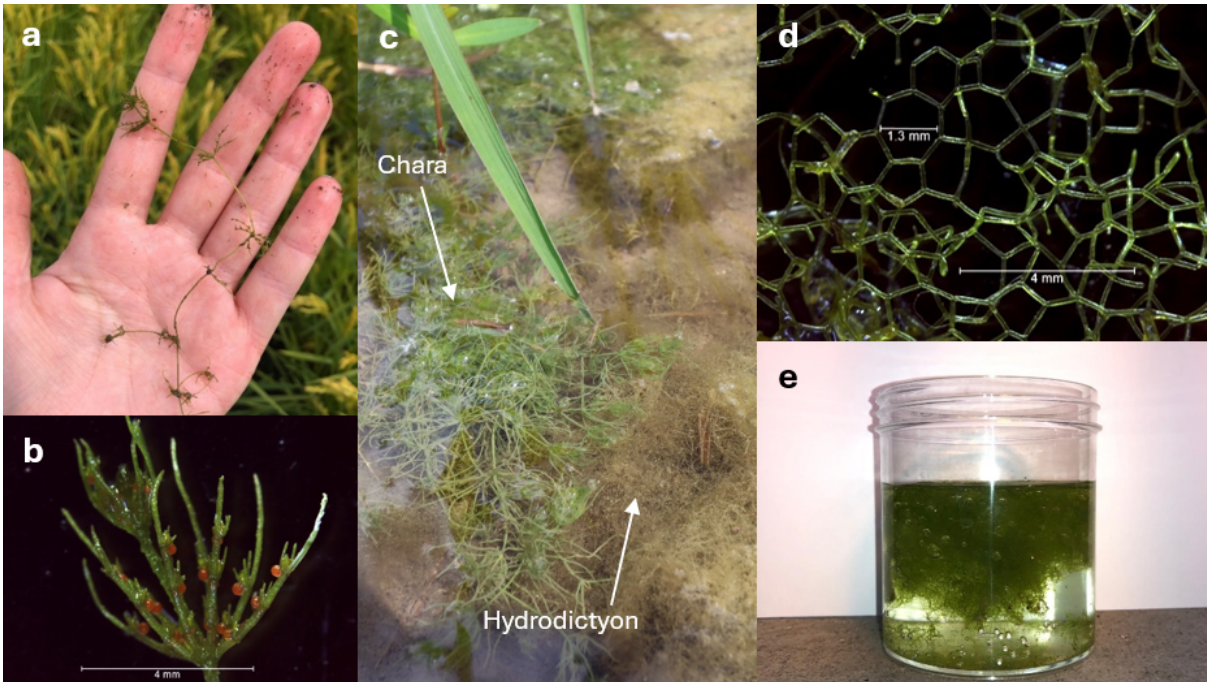

Figure 3.1 Pictures of *Chara spp.* (a, b, c) and *Hydrodictyon spp.* (c, d, e).

Furthermore, the genera *Zygnema spp.* and *Spirogyra spp.* (Fig. 3.2), from the order *Zygnematales*, were identified in the rice paddies, though they were less abundant compared to *Chara spp.* and *Hydrodictyon spp.* Despite their lower prevalence, these genera are commonly found in freshwater environments and are known for their filamentous growth and characteristic chloroplast arrangements (Joska & Bolton 1995).

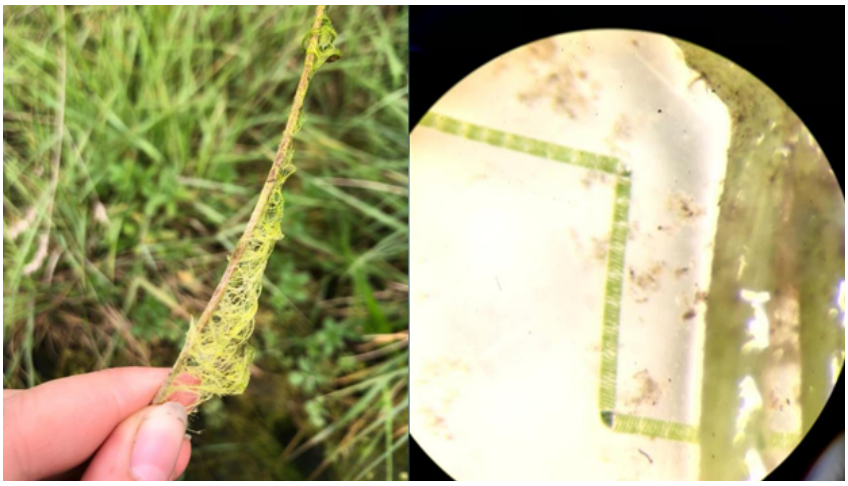

Figure 3.2 Picture of *Zygnema spp.* (left) and *Spirogyra spp.* (right).

The composition of algal communities varied across different locations. In Stetten, one field (Stetten 1) contained exclusively *Hydrodictyon spp.*, whereas the other paddy (Stetten 2) exhibited no detectable algal presence from the surface, likely due to the high abundance of *Lemna sp.* (Fig. 3.3), a floating aquatic plant. In Mühlau, *Hydrodictyon spp.* was the predominant algae, followed by *Chara spp.* and a minor presence of *Spirogyra spp.* In Untersiggenthal, *Chara spp.* was the most common genus, with additional occurrences of *Spirogyra spp.* and *Zygnema spp.* Both paddies surveyed in Brugg lacked visible algal growth entirely (Fig. 3.3).

Figure 3.3 View of Stetten 2 (left) showing dense *Lemna sp.* coverage, and Brugg (right) lacking visible algae growth.

3.1.2 Algae abundance

The mean surface cover of algae exhibited variability both between different locations and among paddies within the same site (Fig. 3.4). While no algal growth was detected in Brugg and Stetten 2, Untersiggenthal and Stetten 1 displayed high mean algal coverage during the first visit (85 %, sd = 14.6; 58 %, sd = 39.5), with Untersiggenthal showing a relatively homogenous distribution. Other paddies demonstrated substantial variation in algal coverage within the same field, as seen in Stetten 1, where surface cover ranged from 0 % to 95 %.

The relationship between algal surface coverage and dry algal biomass was not always consistent. For example, Mühlau exhibited a higher mean dry algal biomass than Stetten 1, despite Stetten

1 having greater mean algal surface coverage. Additionally, Stetten 2 contained detectable algal biomass, yet no visible algal surface coverage, likely due to a dense *Lemna* layer obstructing the sight to the algae beneath.

By the second visit, all paddies exhibited no vital algal presence. In Stetten 1 and Untersiggenthal no algae could be examined due to the drying of the paddy.

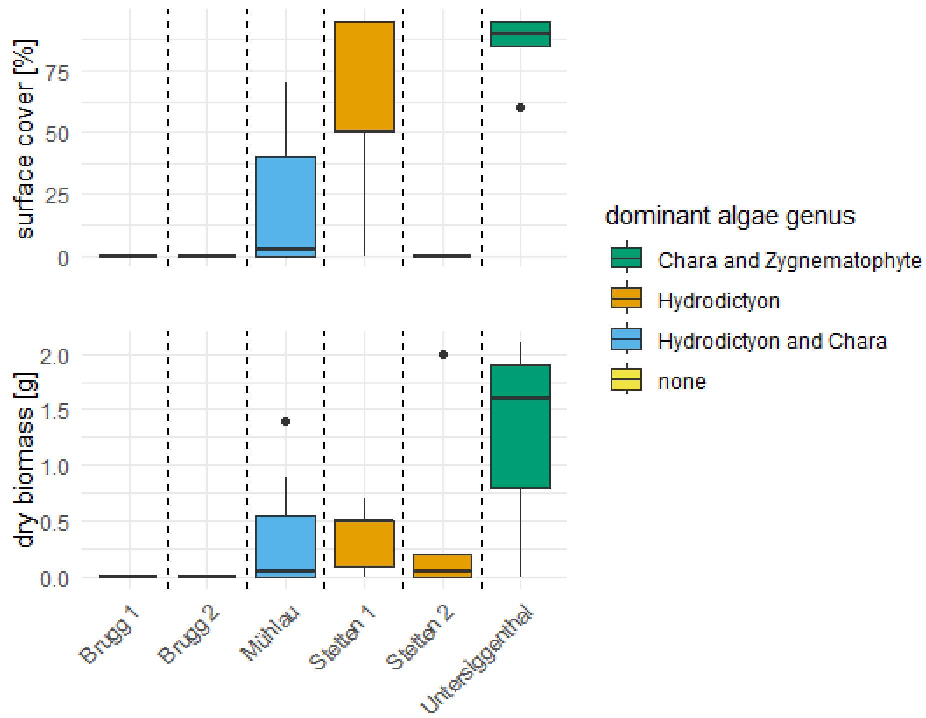

Figure 3.4 Boxplots of the algal surface cover and its corresponding dry biomass of the first visit across all investigated paddies. Coloring corresponds to their dominant algae genera found in these paddies.

3.1.3 Water quality

The chemical analysis of the water quality revealed a mean TAN concentration of 0.09 mg L^{-1} (sd = 0.06) on the first visit which decreased to 0.05 mg L^{-1} (sd = 0.05) on the second visit (Table 3.1). Orthophosphate levels on the other hand increased from 0.39 (sd = 0.63) to 0.78 mg L^{-1} (sd = 1.23). Nitrate-nitrogen was barely detectable during the first visit and was entirely absent by the second visit.

Stetten 2 exhibited a notably higher TAN concentration (0.2 mg L^{-1}) than the other sites, along with a pronounced increase in the orthophosphate level from 1.7 to 2.86 mg L^{-1} between visits. The orthophosphate concentration also increased in Brugg 1, rising from 0.04 to 0.2 mg L^{-1} over time. In contrast, the remaining paddies showed a general decline in nutrient levels. Overall, concentrations remained relatively low, occasionally approaching the detection limits of the measurement device for TAN and orthophosphate.

Table 3.1 Total Ammonia Nitrogen(TAN), orthophosphate (PO_4^{3-}) and nitrate-nitrogen (NO_3^--N) concentration of the different paddies at the first and second visit. Mean ± sd.

	Total Ammonia Nitrogen (TAN) [mg L^{-1}]		Orthophosphate [mg L^{-1}]		Nitrate-Nitrogen [mg L^{-1}]	
Visit	1	2	1	2	1	2
MEAN	0.09 ± 0.06	0.05 ± 0.05	0.39 ± 0.63	0.78 ± 1.23	0.01 ± 0.01	0 ± 0
Stetten 1	0.13	-	-	-	0	-
Stetten 2	0.2	0.12	1.7	2.86	0	0
Mühlau	0.02	0.05	0.11	0	0	0
Brugg 1	0.1	0	0.04	0.2	0.03	0
Brugg 2	0.04	0.01	0.08	0.07	0	0
Untersiggenthal	0.04	-	0.01	-	0.01	-

Overall, pH values ranged from 7.04 (Stetten 2) to 9.4 (Untersiggenthal), indicating a generally neutral to alkaline water condition (Fig. 3.5). The mean pH recorded during the first visit was 7.92 (sd = 0.65), which minimally decreased to 7.69 (sd = 0.4) by the second visit. Within-field variability remained low. While Brugg, Mühlau, and Stetten 2 exhibited similar pH values (mean = 7.51, sd = 0.16), Stetten 1 and Untersiggenthal had notably higher pH levels (mean = 8.7, sd = 0.45). Between the two sampling periods, pH remained relatively stable, with a slight increase observed in the two Brugg paddies and a slight decrease in Stetten 2. In two paddies – Stetten 1 and Untersiggenthal – pH measurements were only available from the first visit due to field drying.

Conductivity ranged from 103.5 (Untersiggenthal) to 325 μS cm^{-1} (Brugg 2), with a mean of 231.9 μS cm^{-1} (sd = 60.56) on the first visit, increasing to 239.4 μS cm^{-1} (sd = 26.59) on the second visit. Within-field variability was generally low, except in Stetten 1, where values ranged from 174.5 to 285 μS cm^{-1}.

Water temperatures ranged from 21 °C (Brugg 2) to 30 °C (Untersiggenthal), with a mean of 25 °C (sd = 2.1) on the first visit, decreasing to 22 °C (sd = 1.3) on the second visit. A temperature decline over time was observed in all paddies except Stetten 2, where a slight increase was recorded. Within-field temperature variability was generally low.

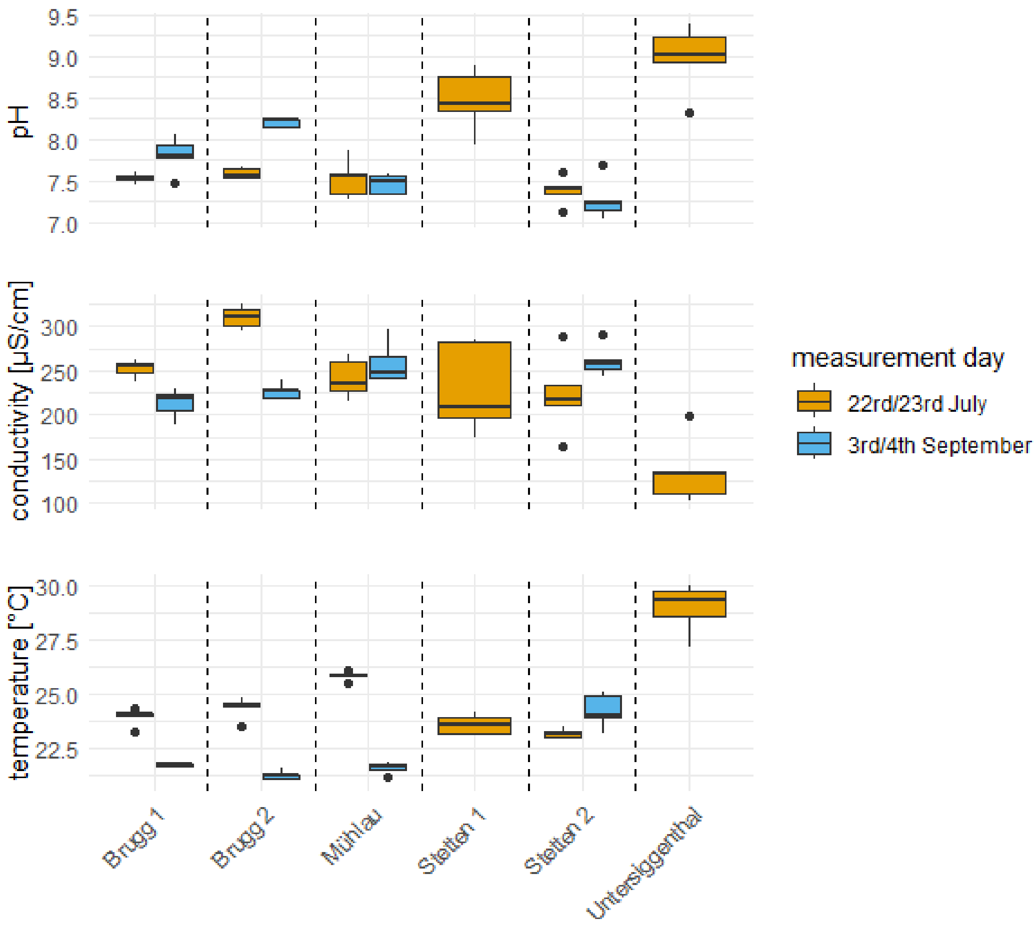

Figure 3.5 Boxplots of the pH, conductivity and temperature of the different paddies at the first and second visit. Water parameters of Stetten 1 and Untersiggenthal were not measured at the second visit due to no available water.

3.1.4 Farmer survey

The survey responses highlighted the existing variations in cultivation strategies among farmers, particularly in the timing of key agronomic practices (Table 3.2).

While most farmers initiated flooding at the end of May, Stetten delayed flooding until the end of June, whereas Mühlau began flooding as early as the beginning of May. In general, rice planting occurred shortly after flooding, with the exception of Untersiggenthal, where planting was conducted one day prior to field inundation.

Fertilization strategies also varied considerably. One farmer applied fertilizer twice (Untersiggenthal), while others applied it only once. Fertilizer types differed substantially: only the farmer in Stetten used exclusively organic fertilizer, whereas the others applied various mineral fertilizers, including urea, ammonium sulfate, and Geistlich N. Additionally, the farmer in Untersiggenthal applied cattle manure as a base fertilization earlier in the season. The farmer in Stetten furthermore makes use of the nutrient rich water of his fishpond located next to the paddies.

The applied nitrogen amounts ranged widely, from minimal applications of cattle manure (0.195 kg N ha^{-1}) to a higher application of mineral fertilizer (Geistlich N) in Brugg (80.4 kg N ha^{-1}).

Most farmers reported applying between 20 and 36 kg N ha^{-1}. All fertilization rates were below the regulation of the Swiss government regarding fertilizer, which is 110 kg N ha^{-1} (Richner & Sinaj 2017).

All respondents indicated that water input was ceased and field drying initiated in August, with harvesting occurring between September and November.

All interviewed farmers reported that they do not actively manage or remove algae in their rice paddies and expressed no particular concern about its presence. Their primary focus was on weed control, which they identified as a more pressing issue. In fact, weed pressure was cited as one of the main reasons for the discontinuation of rice cultivation in one paddy located in Mühlau.

Table 3.2 Summary of the survey results of famers included in this sub-project regarding general paddy specifics, schedule of cultivation practices, fertilization strategies and algae type and usage. a = fertilizer was applied twice; b = all farmers stated that they didn't do anything with the present algae.

Location	Brugg	Mühlau	Untersiggenthal	Stetten	
				1	2
Paddy specifics					
Area [a]	130	50	80	25	45
First established in [year]	2024	2020	2019	2024	2021
Fields investigated / total fields	2/2	1/2	1/1	2/3	
Dates in 2024					
Flooding	20.5.	8.5.	30.5.	20.6.	
Planting	28.5.	10.5. & 15.5.	29.5.	20.6.	
Fertilization	17.5.	15.7.	mid-March / mid-July[a]	15.6.	
Drying	14.8.	28.8.	20.8.	10.8.	
Harvest	24.10.	5.11.	24.10.	1.10. & 23.10.	23.10.
Fertilization					
Type	Geistlich N	urea	cattle manure & urea / Ammonium sulfate[a]	Hauert Biorga Quick	
Amount [kg/ha]	670	50	50 / 100	300	
N [%]	12	46	0.39 / 21	12	
N [kg ha-1]	80.4	23	0.195 / 21	36	
Algae					
Genus (spp.)	-	*Chara, Hydrodictyon*	*Chara, Zygnematophyte*	*Hydrodictyon*	-
Usage[b]	-	-	-	-	

3.2 Sub-project 2: Fertilizer experiment in the paddy of La Sauge

Grain and straw yield were significantly higher ($p < 0.05$) in Treatment D which received both fertilizations (Metzger et al. unpublished). The experiment further showed that fertilization timing influenced tiller and grain production. Fertilizing at transplantation led to more biomass (tillers) and fertilizing before panicle initiation led to better grain filling (Metzger et al. unpublished).

3.2.1 Algae type and distribution

In La Sauge, the only genus of algae found, was *Chara spp.* At the first visit, its distribution within all 16 plots was unanimously the same with a surface coverage of 90 %. On the second visit, the mean algal coverage decreased to 80.3 % (sd = 11.76).

No significant differences in dry algal biomass were detected among the treatments during either the first ($\varepsilon^2 = 0.04$ ns) or second ($\eta^2 = 0.08$ ns) visit (Table B.5). However, greater variability in algal biomass was observed in treatments C and D during the first visit compared to the other treatments (Fig. 3.6). Additionally, from the first to the second visit, algal biomass appeared to decrease in treatments C and D, while showing a slight increase in treatments A and B.

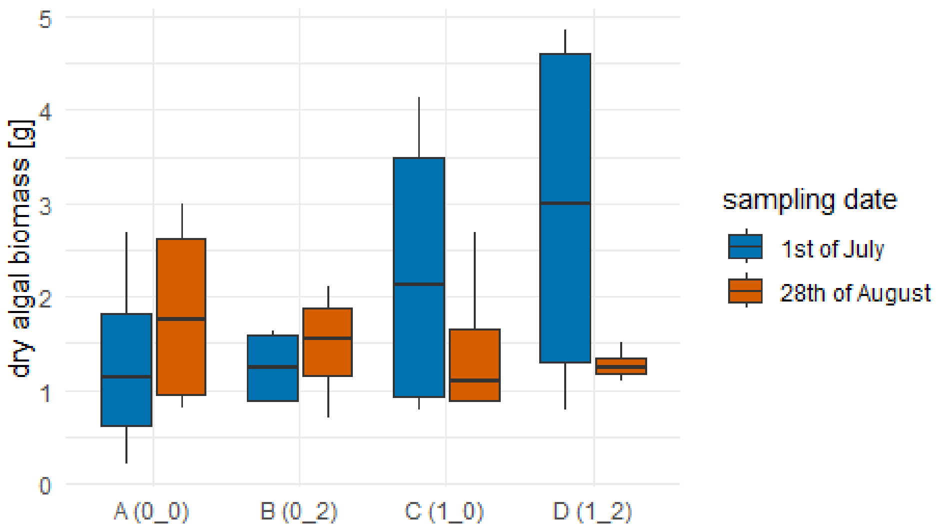

Figure 3.6 Dry algal biomass by treatment and sampling date.

3.2.2 Water parameters and nutrients

During the first visit, the mean water pH was 9.9 (sd = 0.4), which decreased to 8 (sd = 0.2) by the second visit (Fig. 3.7). In contrast, conductivity increased from 106.5 (sd = 3.9) to 247 μS cm^{-1} (sd = 17.8) over the same period. Mean water temperature declined from 26.7 °C (sd = 2.2) to 19.5 °C (sd = 1.5), and the mean water depth decreased from 16.9 (sd = 1.1) to 6.4 cm (sd = 2.5). On 1st of July, pH was significantly lower in the fertilized plots (C & D) (mean = 9.75, sd = 0.49) than in the unfertilized (A & B) (mean = 10.06, sd = 0.11) ($\varepsilon^2 = 0.25$ *) (Table B.5). No other significant differences were observed between the treatment groups at each visit, and within-treatment variability remained low throughout the sampling period.

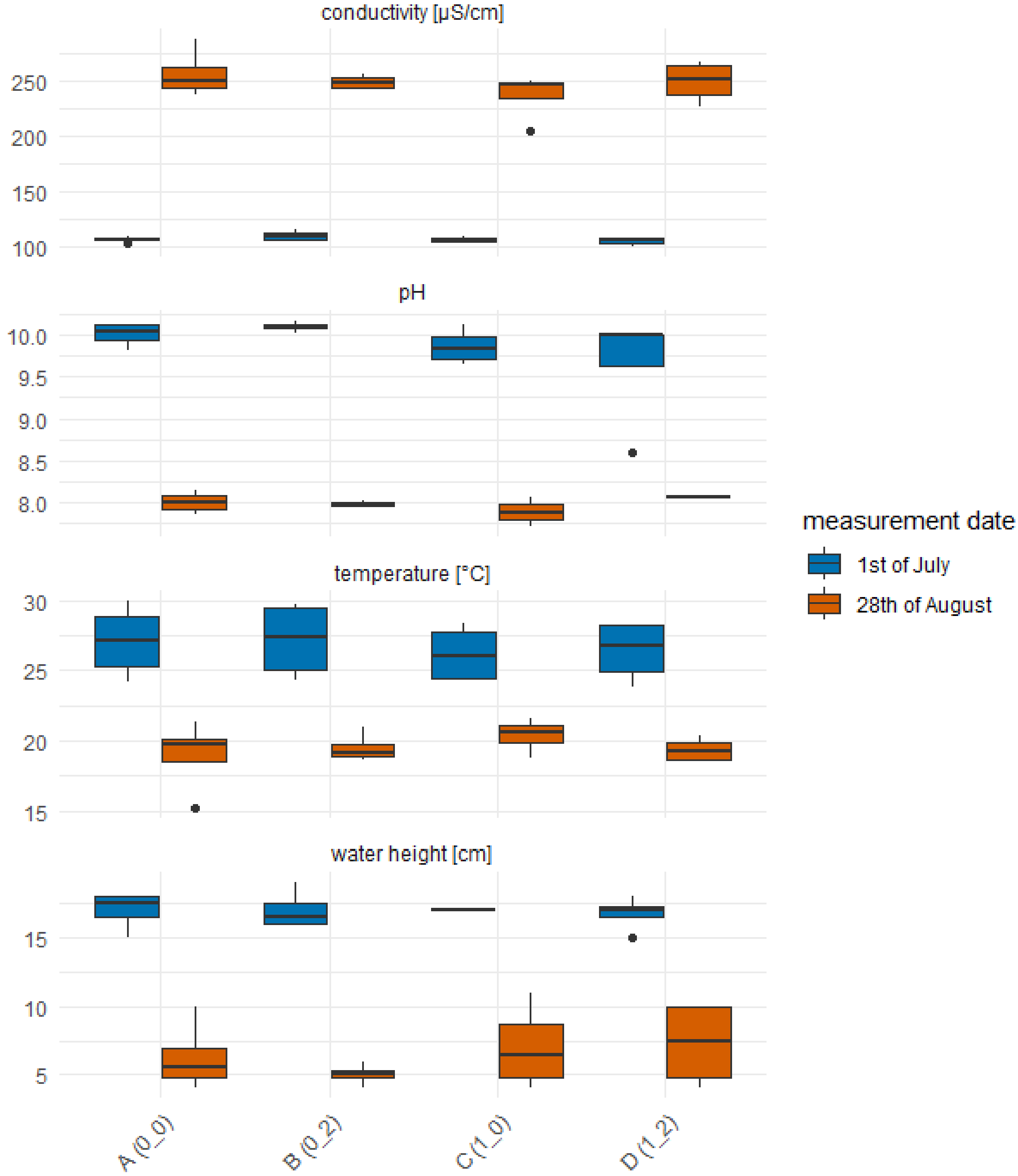

Figure 3.7 Conductivity, pH, temperature and water height by treatment and measurement date.

The ammonium-nitrogen level was non-detectable (< 0.07 mg L^{-1}) in the unfertilized plot after the second fertilization (Metzger et al. unpublished). In the fertilized plot, the value increased from initially 0.393 mg L^{-1} (6h after fertilization) to 2.82 mg L^{-1} (1d after fertilization). Afterwards it decreased again to 0.213 mg L^{-1} (3d after fertilization) and wasn't detectable (< 0.07 mg L^{-1}) on day 4 and 5. On day 7, the value increased again to 0.095 mg L^{-1}. Nitrate-nitrogen on the other hand wasn't detectable (< 0.06 mg L^{-1}) in both plots over the whole measurement period.

3.3 Sub-project 3: Greenhouse experiment

3.3.1 Nutrient availability and water parameters under algal presence

Nitrate-nitrogen (NO_3^--N) concentrations were measured at T4 as a single-time observation (Fig. 3.8). The results indicated distinct higher NO_3^--N levels in the mineral fertilizer treatment compared to both the organic and unfertilized treatments. In the mineral fertilizer treatment, the mean NO_3^--N concentration was higher in the absence of algae (mean = 138.45 mg L^{-1}, sd = 9.96) than in its presence (mean = 77.83 mg L^{-1}, sd = 19.07), showing a negative impact of algae (d = -3.99 ***) (Table 3.3). The organic fertilizer treatments exhibited the lowest NO_3^--N concentrations, with values approaching zero. Unfertilized treatments displayed slightly higher NO_3^--N levels, which were significantly smaller in the presence of algae (mean = 0.41 mg L^{-1}, sd = 0.12) compared to treatments without algae (mean = 20.66 mg L^{-1}, sd = 1.68) (r = -0.82 *).

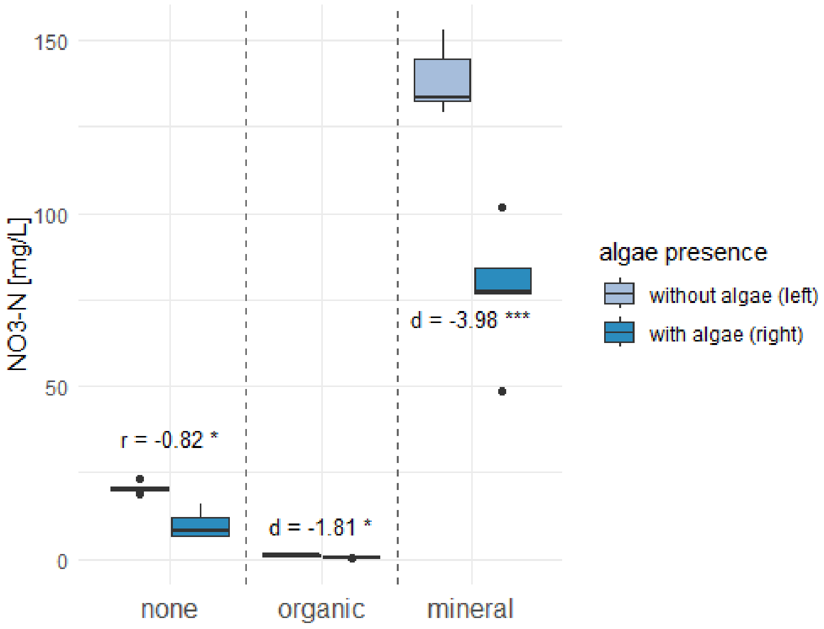

Figure 3.8 Nitrate-nitrogen (NO_3^--N) concentration in treatments varying in fertilizer type and algae presence. Measured at T4.

Table 3.3 Nutrients and physical water parameters in treatments with and without algae. Diff = mean of treatment with algae – mean of treatment without algae. ES = effect size. Significant differences in bold ($p < 0.05$).

Fertilizer	none			organic			mineral		
	diff	ES		*diff*	ES		*diff*	ES	
Nutrients [mg L^{-1}]									
NH_4^+-N	-0.002	r	-0.08	**-0.22**	d	-2.01*	-0.06	r	-0.03
NH_3-N	**0.05**	d	3.14 **	0.07	d	1.26 .	**0.06**	r	-0.76 *
NH_4^+: NH_3	**-4.11**	d	-2.32 *	-2.28	r	-0.43	-2.29	d	-1.37 .
NO_3^--N	**-10.57**	r	-0.82 *	**-0.63**	d	-1.81 *	**-60.63**	d	-3.99 ***
NO_2^--N	0.02	r	-0.49	**-0.06**	d	-0.73 *	0.03	r	0.59
Water parameters									
pH	**0.62**	d	3.18 **	0.19	d	1.13	0.16	r	-0.56 .
Conductivity [μS cm^{-1}]	**-67.9**	d	-4.51 ***	-34.24	d	-1.41 .	**-62.62**	d	-2.06 *
Temperature [°C]	**0.49**	d	2.51 **	-0.23	d	-0.74	0.17	d	0.48

Ammonium-nitrogen concentrations (NH_4^+-N) remained near or below detection limits for both unfertilized treatments, irrespective of algae presence, throughout the entire sampling period (T1–T9) (Fig. 3.9). In contrast, all fertilized treatments displayed a pronounced spike in NH_4^+-N levels shortly after fertilizer application (T1–T4). The mineral fertilizer treatments – both with and without algae – reached the highest concentrations, peaking at a mean of approximately 1.5 mg L^{-1} (without algae) and 1.3 mg NH_4^+-N L^{-1} (with algae). The organic fertilizer treatments also exhibited elevated NH_4^+-N levels and peaked at similar values without algae (approx. 1.5 mg L^{-1}) but did not rise as high with algae as in the mineral fertilizer treatment (peak values: 1.2 mg L^{-1}).

After reaching maximum concentrations, NH_4^+-N declined rapidly in all fertilized treatments, returning to near-baseline levels by T5 or T6 and remaining low through T9. The presence of algae tended to slightly reduce the concentration of NH_4^+-N as well as hasten the decline of NH_4^+-N in both the mineral and organic fertilizer treatments, although the magnitude of this effect varied among replicates. Nevertheless, only in treatments with organic fertilizer, pots with algae had a significant lower NH_4^+-N level (mean = 0.47 mg L^{-1}, sd = 0.56) then in pots without algae (mean = 0.69 mg L^{-1}, sd = 0.72) (d = -2.01 *) (Table 3.3). Overall, fertilized treatments initially showed increases in NH_4^+-N concentration that dissipated within a few sampling intervals, whereas unfertilized controls, regardless of algae presence, maintained consistently low NH_4^+-N levels.

NH_3-N concentration was mostly higher in the presence of algae (Fig. 3.10) indicated by a pronounced peak in the treatments with algae in comparison with the ones without. In both, unfertilized and minerally fertilized treatments, these effects were statistically significant ($p < 0.05$) with a large effect in unfertilized treatments (d = 3.14 **) (Table 3.3). Notably, the concentration of NH_3-N in the non-fertilized treatments is nearly zero in the absence of algae but reaches values of 0.29 mg L^{-1} in the presence of algae. Although this difference in organically fertilized treatments was only marginally significant ($p < 0.1$), the effect size was large (d = 1.26 .), suggesting a potentially meaningful difference that may not have reached significance due to limited sample size.

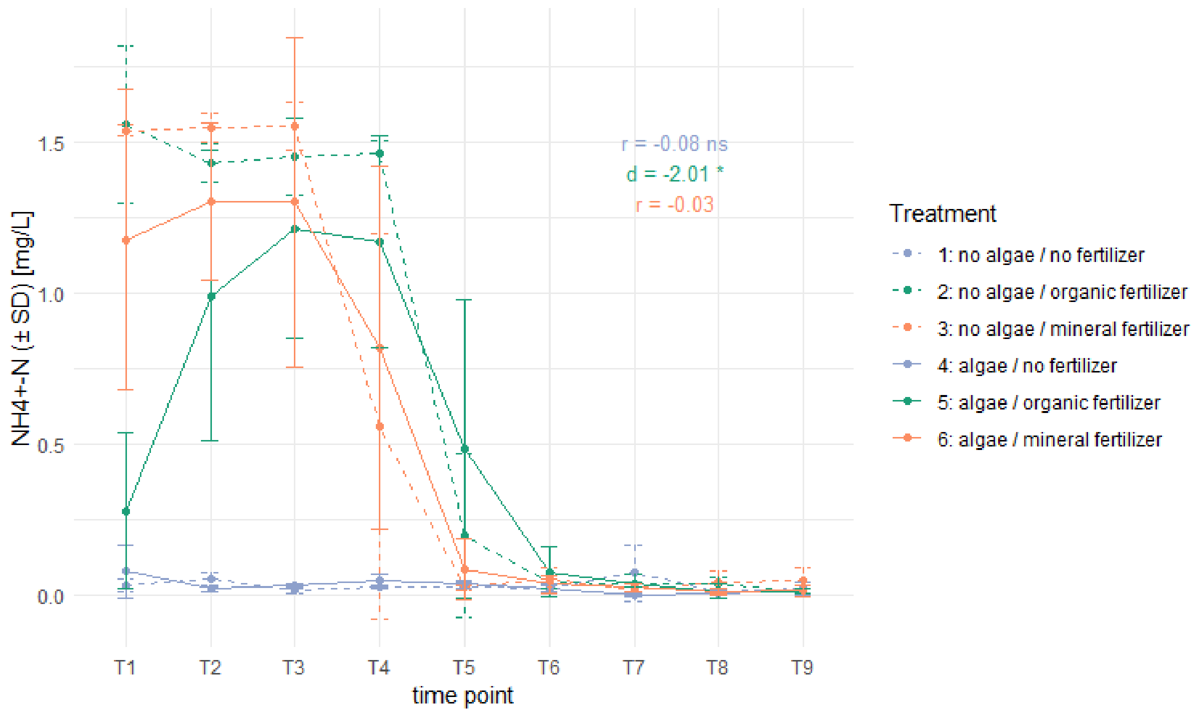

Figure 3.9 Ammonium-nitrogen (NH_4^+-N) concentration over time by treatment.

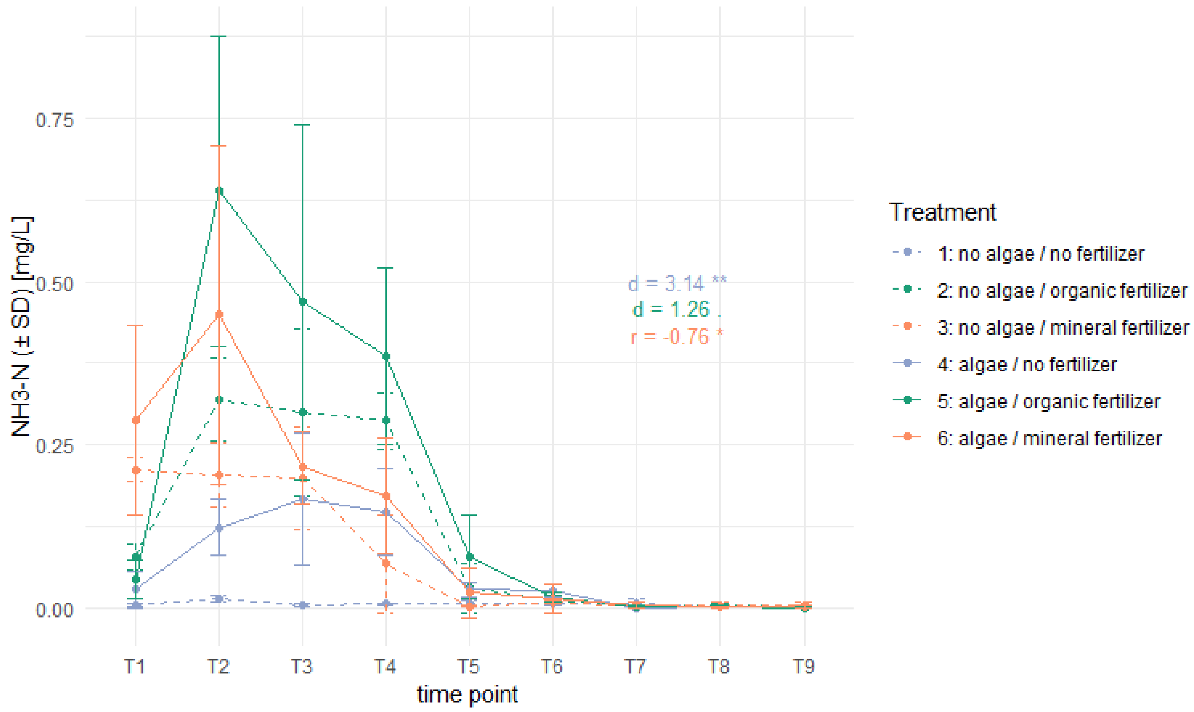

Figure 3.10 Ammonia-nitrogen (NH_3-N) concentration over time by treatment.

The ratio of NH_4^+:NH_3 initiated in all treatments, values in favor of NH_4^+, with an approximate mean ratio of 7:1 (Fig. 3.11). This ratio varied over the sampling period with mostly increasing values over time (Fig. A.1). Across all treatments, the NH_4^+:NH_3 ratios tended to be lower in the presence of algae and the differences between with and without algae declined over time. For the unfertilized treatments, this ratio overall was significantly lower in the presence of algae (mean = 3.61, sd = 5.09) than in its absence (mean = 8.58, sd = 4.21) (d = 2.32 *) (Table 3.3).

Also, the minerally fertilized treatments had a lower ratio with algae (mean = 7.88, sd = 4.17) than without (mean = 10.52, sd = 3.01), although only marginally significant but with a large effect size (d = -1.37 .).

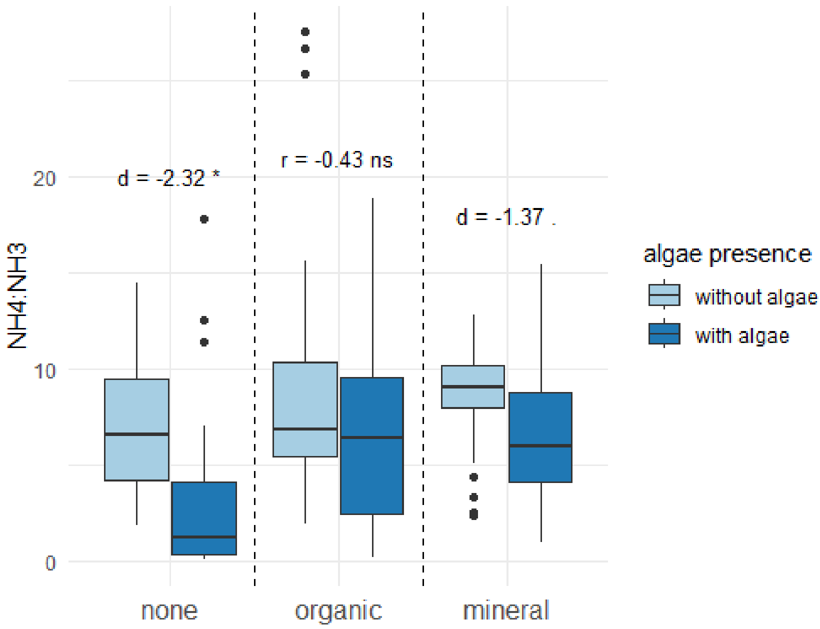

Figure 3.11 Mean ammonium:ammonia ($NH_4{}^+$:NH_3) ratio in treatments varying in fertilizer type and algae presence.

In the unfertilized treatments, the mean pH values were higher in the presence of algae (mean = 9.09, sd = 0.67) than in its absence (mean = 8.46, sd = 0.23) (d = 3.18 **) (Table 3.3).

The unfertilized treatment with algae consistently exhibited more alkaline pH values throughout the experiment – especially between T2 and T6 – while all other treatments remained in the neutral to slightly alkaline range (Fig. 3.12). Towards the end of the experiment, pH also dropped for the unfertilized treatment with algae. Algal presence also enhanced pH in organically fertilized treatments, though not statistically significant, the effect size was large (d = 1.13 ns) (Table 7). Overall pH was slightly higher in the presence of algae in all fertilizer regimes.

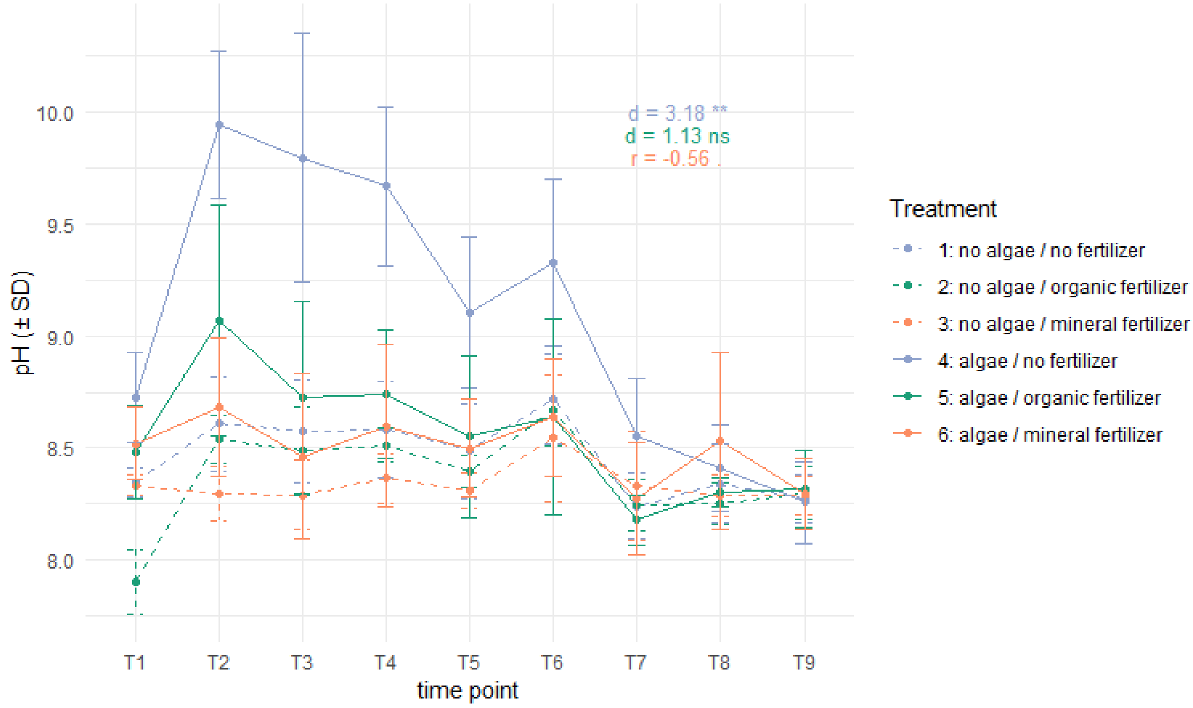

Figure 3.12 The pH over time by treatment.

Conductivity decreased significantly in the presence of algae in the unfertilized (diff = -67.896 μS cm^{-1}, d = -4.51 ***) and minerally fertilized (diff = -67.896 μS cm^{-1}, d = -2.06 *) treatments (Table 3.3). It also decreased in the organic treatment (diff = -34.24 μS cm^{-1}) with marginal significance ($p < 0.1$) but with a large effect size (d = -1.41 .). Overall algae seemed to decrease the conductivity in all fertilizer regimes, especially through T2 to T7 (Fig. A.2).

Temperature was significantly higher in the unfertilized treatment in the absence of algae (mean = 25.66, sd = 0.89) than in the presence of algae (mean = 26.15, sd = 0.94) (d = 2.51 **) (Table 3.3). In the fertilized treatments, no significant differences in temperature between algae presence were detected. All treatments followed similar diurnal trends over time (Fig. A.3).

3.3.2 Rice and algal growth

Biomass measurements at the end of the experiment revealed a significant increase of total biomass and panicle weight in the unfertilized treatments in the presence of algae (diff = 0.47 g, d = 1.62 *; diff = 0.4 g, d = 1.96 *) (Table 3.4). In organic treatments biomass decreased in the presence of algae (diff = -0.5 g, d = -0.83 ns), while in mineral treatments the effects of algae remained small (diff = 0.3 g, d = 0.35 ns).

Table 3.4 Rice biomass in treatments with and without algae. Diff = mean of treatment with algae – mean of treatment without algae. ES = effect size. Significant differences in bold ($p < 0.05$).

fertilizer	none			organic			mineral		
	diff	ES		*diff*	ES		*diff*	ES	
rice biomass [g]									
total	**0.47**	d	1.62 *	-0.5	d	-0.83	0.3	d	0.35
panicles	**0.4**	d	1.96 *	-0.14	d	-0.94	0.02	d	0.09
leaves	0.25	d	1.19	-0.36	d	-0.72	0.28	d	0.4

In the presence of algae, the highest mean rice biomass is recorded in the mineral fertilizer treatment (mean = 2.58 g, sd = 0.85) followed by the organic fertilizer treatment (mean = 2.28 g, sd = 0.46), with the lowest biomass observed in the unfertilized treatment (mean = 1.73 g, sd = 0.35) (Fig. 3.13).

In the absence of algae, a similar trend is maintained for minerally fertilized (mean = 2.28 g, sd = 0.89) and unfertilized treatments (mean = 1.26 g, sd = 0.23). Whereas, in the organic fertilizer treatment, rice biomass is the highest (mean = 2.78 g, sd = 0.72), surpassing values observed in the mineral fertilizer treatment with algae.

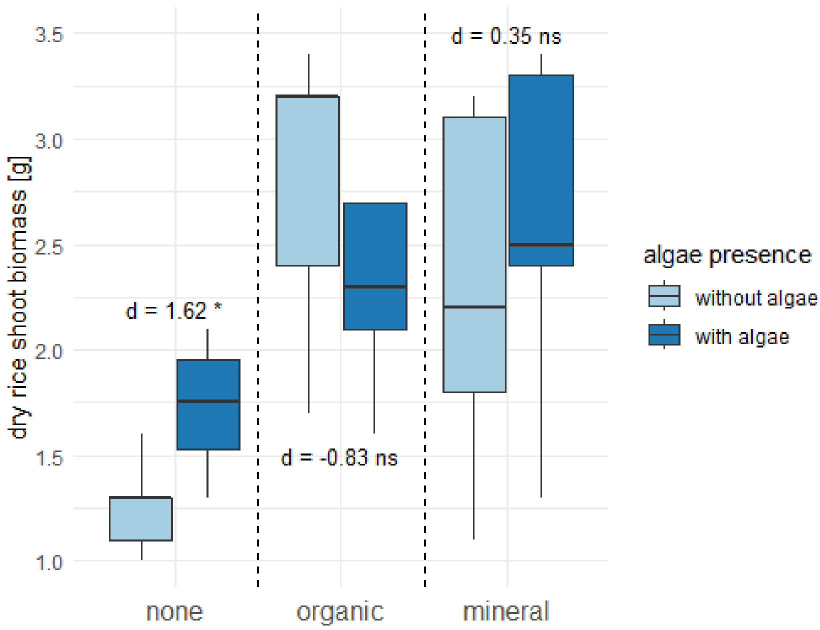

Figure 3.13 Dry rice shoot biomass in treatments varying in fertilizer type and algae presence. Measured at the end of the experiment.

Algal biomass increased in both the unfertilized and organically fertilized treatments, whereas it significantly declined in the mineral fertilizer treatment compared to the initially inoculated amount (Fig. 3.14).

The highest algal growth occurred in the unfertilized treatment, where wet algal biomass reached a maximum of 10.1 g, with a corresponding dry biomass of 1 g. The mean algal growth in this treatment was 3.38 g (sd = 1.69), with all samples exhibiting positive growth. In contrast, the organically fertilized treatment demonstrated a lower mean algal growth of 1.78 g (sd = 2.59), with one sample showing a decline in biomass. Additionally, an outlier with a wet biomass of 11.1 g was observed in this treatment. In the mineral fertilizer treatment, algal biomass declined to zero in all but one sample, which retained 3 g of wet algal biomass at the end of the experiment.

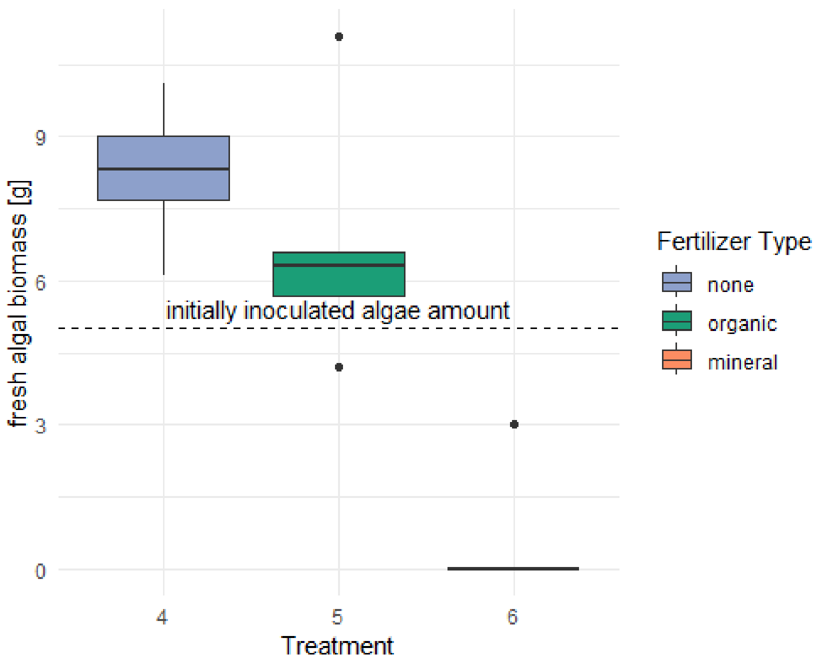

Figure 3.14 Wet algae biomass in treatments varying in fertilizer type. Comparison to the initially inoculated algae amount (5 g). Measured at the end of the experiment.

3.3.3 Carbon and nitrogen in rice shoot and algae

Nitrogen and carbon content and concentration were influenced by both fertilizer type and the presence or absence of algae (Fig. 3.15).

In the absence of algae, plants treated with mineral fertilizer exhibited the highest nitrogen content (mean = 43.64 mg, sd = 9.47), followed closely by those treated with organic fertilizer (mean = 36.44 mg, sd = 7.09). Whereas the unfertilized treatment group showed distinct lower nitrogen content (mean = 18.12 mg, sd = 2.7). A similar trend was observed in the presence of algae, although overall nitrogen content was slightly lower in the fertilized treatments compared to without algae. The mineral fertilizer treatment remained the highest nitrogen content across both algae conditions. There were no significant differences between algal presence and absence in all fertilizer regimes (Table 3.5).

Nitrogen concentration followed a comparable pattern. Without algae, the mineral treatment resulted in the highest N % (mean = 2.06 %, sd = 0.53), whereas the unfertilized (mean = 1.45 %, sd = 0.17) and organic (mean = 1.36 %, sd = 0.31) treatments had lower but comparable concentrations. With algae, nitrogen concentration declined in mineral (mean = 1.39 %, sd = 0.57, d = -1.23 .) and unfertilized (mean = 1.23 %, sd = 0.09, d = -1.55 .) treatments, whereas it stayed the same for organic treatments (mean = 1.35 %, sd = 0.27, d = -0.03 ns) (Table 3.5).

Carbon content was higher in the fertilized treatments compared to the unfertilized treatment, irrespective of algae presence. However, algae presence appeared to slightly reduce carbon content in the organic treatment (diff = -193.97 mg, d = -0.78 ns), whereas the mineral treatment maintained similar levels across both algae conditions (Table 3.5). In unfertilized treatments, the carbon content was higher with algae (mean = 727.65 mg, sd = 152.91) than without (mean = 478.91 mg, sd = 94.36) (d = 2.02 *).

Carbon concentration showed less variability among treatments compared to absolute carbon content. In the absence of algae, the unfertilized treatment had the lowest C % (mean = 37.94 %, sd = 0.94), while the mineral treatment showed the highest (mean = 41.72 %, sd = 1.02). With algae, carbon concentrations increased significantly in the unfertilized treatment (mean = 42.13 %, sd = 0.65, d = 5.04 ***) and decreased in the mineral treatment (mean = 39.79 %, sd = 0.83, d = -2.08 *) (Table 3.5).

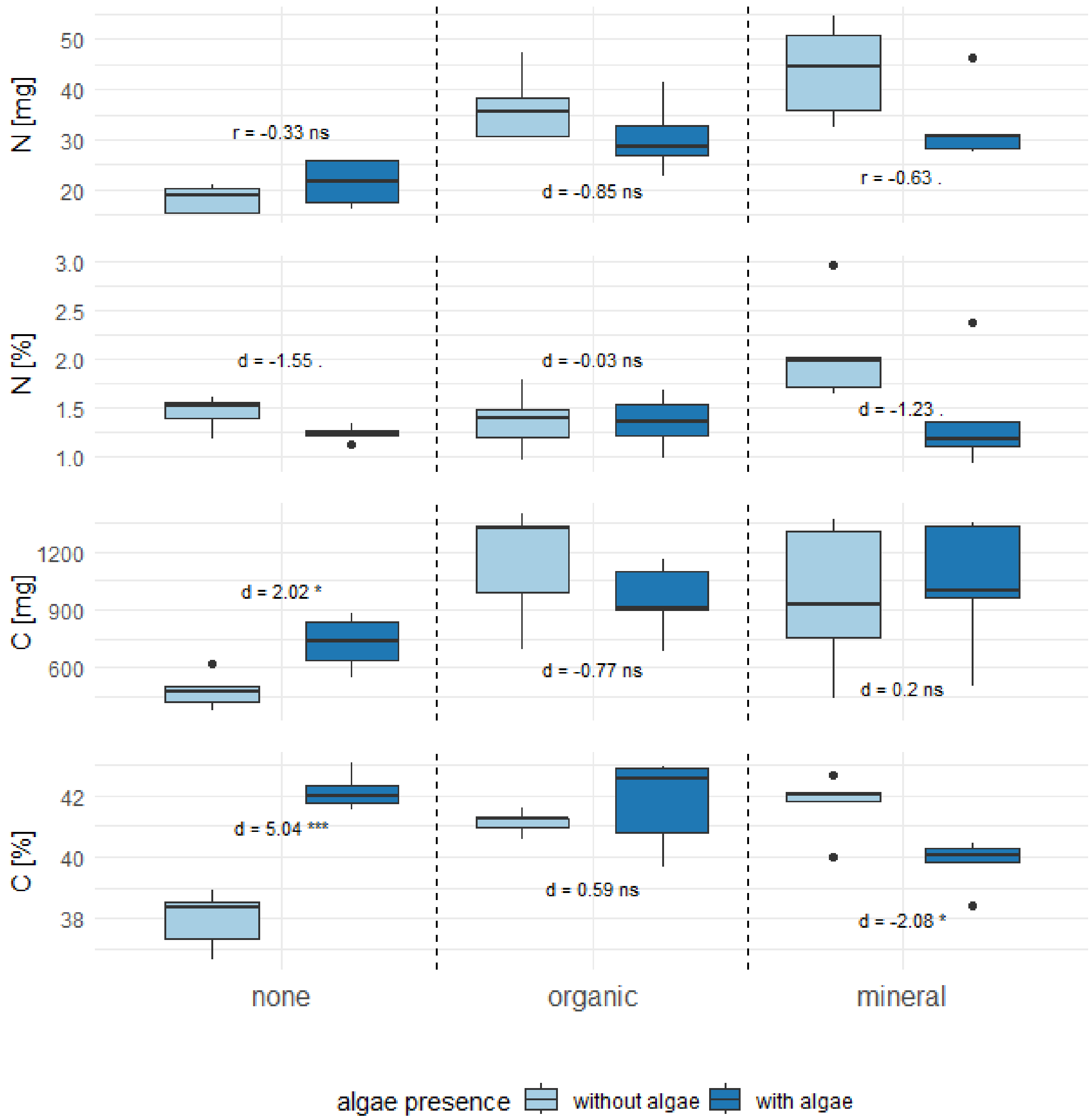

Figure 3.15 Nitrogen and carbon content and concentration in rice shoots in treatment varying in fertilizer type and algae presence. Measured at the end of the experiment.

Table 3.5 Carbon and nitrogen in rice shoots in treatments with and without algae. Diff = mean of treatment with algae − mean of treatment without algae. ES = effect size. NUE = Nitrogen Use Efficiency; NUpE = Nitrogen Uptake Efficiency. Significant differences in bold ($p < 0.05$).

fertilizer	none			organic			mineral		
	diff	ES		*diff*	ES		*diff*	ES	
Concentration									
N [%]	-0.22	d	-1.55 .	-0.01	d	-0.03	-0.67	d	-1.23 .
C [%]	**4.19**	d	5.04 ***	0.64	d	0.59	**-1.93**	d	-2.08 *
CN ratio	**7.83**	d	2.37 **	0.21	d	0.03	10.91	d	1.37 .
Content									
N [mg]	3.22	r	-0.33	-6.03	d	-0.85	-10.88	r	-0.63 .
C [mg]	**248.74**	d	2.02 *	-193.97	d	-0.78	73.44	d	0.2
N Use and Uptake Efficiency									
NUE	11.81	d	1.49 .	-0.13	d	-0.007	**28.96**	d	1.55 *
NUpE	-		-	-6.77	d	-0.85	-12.22	r	-0.63 .

Nitrogen content in algal tissue was highest in organically fertilized treatments and lowest in minerally fertilized treatments (Table 3.6). Carbon content followed the same trend. C:N ratio was highest in the unfertilized treatment followed by mineral, and lowest in the organic treatment.

Table 3.6 Mean carbon and nitrogen in algae by fertilizer type and sample size ± sd. In Treatment 4, one sample was excluded from all analyses; in Treatment 6, only one sample contained algae.

Fertilizer	# samples	N %	N mg	C %	C mg	C:N
None (4)	4	1.38 ± 0.26	6.95 ± 2.88	29.46 ± 4.47	143.3 ± 58.5	21.58 ± 1.92
Organic (5)	5	1.54 ± 0.43	9.61 ± 3.4	25.63 ± 4.09	161.18 ± 40.82	17.1 ± 2.1
Mineral (6)	1	1.56	4.67	28.78	86.35	18.49

Combining the results of the CN analysis for rice shoot and algae, mean total nitrogen content in the containers was highest in the minerally fertilized treatment without algae (mean = 43.64 mg, sd = 9.47) (Table 3.7). In the same fertilizer regime but with algae present, the total nitrogen content decreased (mean = 33.7 mg, sd = 7.63). In contrast, in the unfertilized and the organically fertilized treatment, the total nitrogen content increased in the presence of algae.

Table 3.7 Mean nitrogen content in rice shoot and algae tissue per container ± sd.

	Without algae			With algae		
Fertilizer	none	organic	mineral	none	organic	mineral
Nitrogen [mg]						
rice shoot	18.12 ± 2.7	36.44 ± 7.09	43.64 ± 9.47	21.34 ± 5.12	30.41 ± 7.15	32.76 ± 7.64
algae	0.13 ± 0.3	0.57 ± 1.27	-	6.95 ± 2.88	9.61 ± 3.4	0.93 ± 2.09
total	18.25 ± 2.77	37.01 ± 6.56	43.64 ± 9.47	28.29 ± 5.47	40.03 ± 4.94	33.7 ± 7.63

3.3.4 Nitrogen Uptake Efficiency (NUpE) and Nitrogen Use Efficiency (NUE) of rice

In the absence of algae, plants receiving mineral fertilizer showed the highest NUpE (mean = 48.98 %, sd = 10.62), whereas organic fertilizer resulted in a lower NUpE (mean = 40.9 %, sd = 7.95) (Fig. 3.16).

The presence of algae led to a notable reduction in NUpE for both fertilizer types, yet not statistically significant (organic: d = -0.85 ns, mineral: r = -0.63 .) (Table 3.5). Organic fertilizer treatments showed a broader range of NUpE values but with a lower mean (34.13 %, sd = 8.02) compared to treatments without algae. Mineral fertilizer treatments also exhibited reduced NUpE under algae presence (mean = 36.77 %, sd = 8.58).

Overall, the highest Nitrogen Uptake Efficiency was observed in mineral fertilizer treatments without algae, whereas all treatments with algae exhibited reduced efficiency, indicating a potentially inhibitory effect of algae on nitrogen uptake.

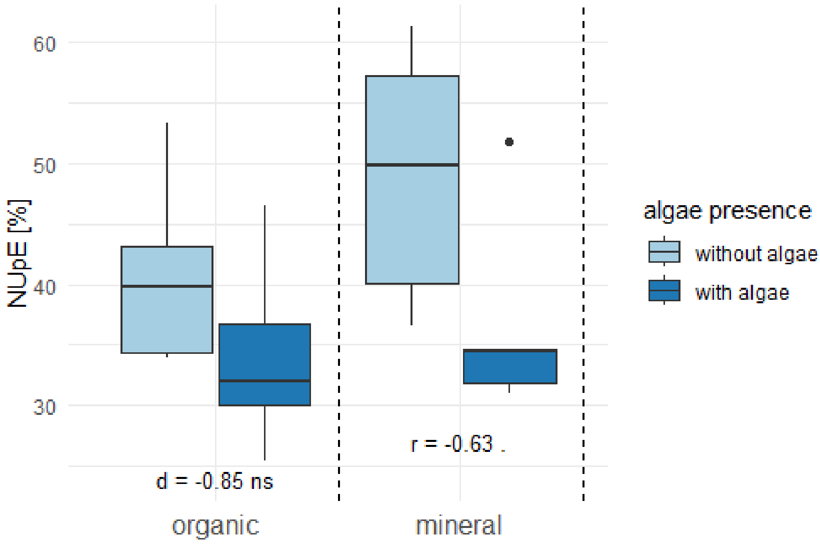

Figure 3.16 Nitrogen Uptake Efficiency of rice shoots in treatments varying in fertilizer type and algae presence.

Nitrogen Use Efficiency (NUE) was influenced by both fertilizer type and the presence of algae (Fig. 3.17).

In the absence of algae, plants treated with organic fertilizer exhibited the highest variability in NUE (mean = 76.68, sd = 18.4). The unfertilized treatment had a more consistent NUE (mean = 69.17, sd = 8.95). The mineral fertilizer treatment had the lowest NUE (mean = 50.64, sd = 10.66).

The presence of algae led to a distinct shift in NUE patterns. The mineral fertilizer treatment, which previously had the lowest NUE, now showed a marked increase (mean = 79.59, sd = 24.12, d = 1.55 *) (Table 3.5). Organic fertilizer had a similar mean NUE as without algae (mean = 76.55, sd = 16.48). The unfertilized treatment showed an increase in mean NUE and a reduced variability in the presence of algae (mean = 81.52, sd = 6.29, d = 1.49 .) (Table 3.5).

Overall, algae presence appeared to enhance NUE, particularly in the mineral fertilizer treatment, suggesting an interactive effect that may improve Nitrogen Use Efficiency under certain conditions.

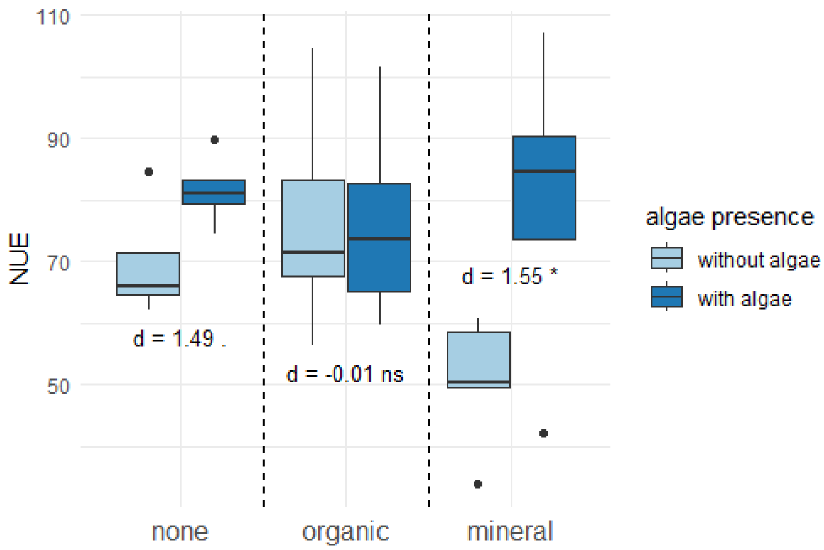

Figure 3.17 Nitrogen Use Efficiency of rice shoots in treatments varying in fertilizer type and algae presence.

Chapter 4

Discussion

4.1 Sub-project 1: Monitoring of Swiss rice paddies

4.1.1 Algal composition and distribution

The identification of macroscopic green algae in Swiss rice paddies – specifically the genera *Chara spp.*, *Hydrodictyon spp.*, *Zygnema spp.*, and *Spirogyra spp.* – aligns with ecological expectations for such environments. These genera are commonly found in freshwater habitats where environmental variables such as nutrient availability, light penetration, and water flow influence their distribution (Volodina & Gerb 2013, Stancheva & Sheath 2012). The algal community was dominated by *Chara spp.* and *Hydrodictyon spp.*, with their distribution varying by location: *Chara spp.* was particularly abundant in Untersiggenthal, while *Hydrodictyon spp.* dominated in Stetten and Mühlau. The presence of *Zygnema spp.* and *Spirogyra spp.*, though less frequent, suggests localized environmental fluctuations that support a more diverse algal community.

Differences in algae amount between paddies and over time

Algal biomass and surface coverage varied markedly between sites. Both Brugg paddies lacked algae, possibly due to their recent establishment in 2024. Newly established fields often have lower organic matter content, which can inhibit algal colonization (Roger & Watanabe 1984). Additionally, the absence of a well-established weed and algal spore bank may have limited algal growth (Mahé et al. 2020). Conversely, Stetten 1 – also established in 2024 – exhibited considerable algal biomass, likely due to its hydrological connectivity with older paddies, facilitating the transport of algal spores.

In Stetten 2, algae were not visible on the surface despite little detectable biomass, indicating that *Lemna spp.* likely formed a light-blocking canopy, inhibiting algal photosynthesis below the water surface. This shading effect likely contributed to algal die-off over time. On the second visit, no viable algae were observed in any paddy, coinciding with the advanced growth of rice plants that created dense shading (Guha 1995). In Stetten 1 and Untersiggenthal, complete field drying further contributed to algal mortality.

Algae characteristics

Chara spp. are known for their ability to calcify and stabilize sediments, favoring freshwater conditions with moderate nutrients, alkaline pH, and low turbidity (Blindow et al. 2014). Their presence in Untersiggenthal and Mühlau suggests that these paddies support calcium-rich, alkaline, and low-flow conditions. Untersiggenthal exhibited the highest pH values (approx. 9), supporting this association, whereas Mühlau maintained more moderate but still basic pH (approx. 7.6).

Chara spp. preferentially absorb ammonium (NH_4^+) over nitrate (NO_3^-) (Vermeer et al. 2003), which may lead to competition with rice plants for nitrogen. They also improve water quality by binding phosphorus and reducing turbidity (Blindow et al. 2014, Kufel & Kufel 2002), traits consistent with conditions observed in Untersiggenthal and Mühlau.

The presence of *Hydrodictyon spp.* (water net) is notable due to its preference for nutrient-rich (eutrophic) waters, where it forms large net-like structures (Volodina & Gerb 2013). Its dominance in Stetten and Mühlau suggests higher nutrient inputs at these sites. In Stetten, organic fertilizer (300 kg ha^{-1}, 12 % N = 36 kg N ha^{-1}) was applied, and the use of nutrient-rich fishpond water may have further enriched the system. In Mühlau, however, only 23 kg N ha^{-1} from mineral fertilizer was applied, which challenges the assumption that *Hydrodictyon spp.* requires high nutrient levels. Like *Chara spp.*, *Hydrodictyon spp.* also prefers NH_4^+ uptake, implying potential nitrogen competition with rice (Starý et al. 1987).

Zygnematophyceae, including *Zygnema spp.* and *Spirogyra spp.*, typically inhabit still and fresh water environments (Hall & McCourt 2015) but were also found in running waters with neutral to alkaline pH (Stancheva & Sheath 2012). *Spirogyra spp.*, or "water silk," often thrives in conductive, moderate to fast flowing waters and may serve as bioindicators for both pollution and good water quality, depending on species (Joska & Bolton 1995). *Zygnema spp.*, by contrast, prefer clean conditions (Joska & Bolton 1995).

Geographical comparisons in algal types

Compared to rice paddies around the world, particularly in tropical and subtropical regions, the green algal composition of Swiss paddies shows both similarities and distinct differences. In Southeast Asia and other tropical regions, rice paddies often feature green algae such as *Cladophora spp.*, *Oedogonium spp.*, *Chlamydomonas spp.* and *Ulothrix spp.*, which thrive in warmer, nutrient-rich conditions (Lee et al. 1992, Kumar & Annadurai 2021). These genera were not found in the Swiss paddies. But *Hydrodictyon spp.* is also commonly found in Asian paddy systems, as reported by Wells et al. (1999) and Lee et al. (1992) along with members of the genus *Chara* (Wood & Imahori, 1959). Species-level differences are likely, but conclusive comparisons require more detailed taxonomic work.

Comparative studies from European rice paddies such as those in Spain or Hungary, similarly report the presence of *Chara spp.*, *Hydrodictyon spp.*, and *Spirogyra spp.*, affirming that Swiss paddies follow patterns observed in other temperate rice ecosystems (Rodrigo & Alonso-Guillén 2016, Carretero 1988, Pinke et al. 2014).

4.1.2 Conditions of Swiss rice paddies

The fieldwork findings provide a comprehensive snapshot of environmental conditions in Swiss rice paddies, particularly with respect to water quality and algal dynamics. Observed variations between paddies were largely shaped by location-specific factors such as irrigation practices, fertilization regimes, and landscape context.

Therefore, the results from individual paddies should not be directly compared, as measurements were conducted on a single date, while fertilizer applications differed in type, timing, and amount. The temporal gap between fertilization and sampling likely affected nutrient concentrations, as nutrients may have been rapidly assimilated or transformed. For more accurate comparisons, future sampling should occur at standardized intervals following fertilization. Nevertheless, factors such as tillage, soil, weather, and crop management practices would still influence nutrient dynamics and comparability.

Water quality and nutrient availability

Despite these limitations, the measured parameters – pH, conductivity, temperature, and nutrient levels – provide valuable insights into nutrient cycling and ecosystem health. The observed decline in Total Ammonia Nitrogen (TAN) between visits suggests nitrogen was taken up by algae or rice plants, or underwent microbial transformation via nitrification (Ishii et al. 2011).

In contrast, orthophosphate levels increased in some paddies, particularly Stetten 2, which also had a dense cover of *Lemna spp.* and a very shallow water depth (approx. 3 cm). This made clean sampling difficult, potentially skewing nutrient values. The rise in orthophosphate may also be due to sediment release, fertilizer input, or decomposition of organic matter (Roger 1996), especially as most algae were no longer viable at the second visit.

Nitrate-nitrogen (NO_3^--N) was almost entirely undetectable, likely due to rapid plant uptake or loss via denitrification, which is common in flooded systems (Bharathi et al. 2021).

PH values remained mostly within the ideal range for rice cultivation (6.5 – 8.5) (Espino et al. 2023), but Untersiggenthal and Stetten 1 exceeded this with values above 9 and above 8.5 respectively. These high pH values were potentially influenced by intense algal photosynthesis, which removes CO_2 and raises pH (Lelková & Poulíčková 2004, Sand-Jensen et al. 2018). Both paddies showed high surface cover of algae, which support this hypothesis. Calcification by *Chara spp.* may also contribute to these elevated values in Untersiggenthal (Blindow et al. 2014).

Conductivity remained within acceptable irrigation limits (Fipps 2003), with most values classed as excellent to good ($< 750\ \mu S\ cm^{-1}$). Generally, conductivity values did not vary a lot between the observed paddies, except for Untersiggenthal, which showed notably low conductivity (103.5 $\mu S\ cm^{-1}$), potentially indicating lower nutrient inputs.

Farmer's success and challenges in 2024

Most farmers reported satisfactory yields and increasing consumer interest in Swiss-grown rice. However, Mühlau and Untersiggenthal experienced severe weed infestations, requiring substantial manual labor. One paddy in Mühlau was even discontinued due to uncontrollable weed pressure.

Importantly, algae were not perceived as problematic by any farmers. None reported active management of algal growth, suggesting that algae are currently considered ecologically neutral or even beneficial in these systems.

4.2 Sub-project 2: Fertilizer experiment in the paddy of La Sauge

The La Sauge paddy was exclusively colonized by *Chara spp.*, with no other macroalgae observed. The initially high pH (approx. 9.9) may indicate *Chara*-driven calcification and photosynthesis, consistent with prior findings (Blindow et al. 2014, Sand-Jensen et al. 2018).

Despite different fertilization treatments, algal biomass and coverage did not vary significantly. This is likely because the first fertilization was put into the soil. The fraction of fertilizer that got into the water after flooding was then evenly distributed, leading to homogeneous conditions of the water across treatments (Metzger et al. unpublished). This explains the lack of variation observed during the first visit. Even though the water conditions were the same across treatments, rice growth differed due to the fertilizer in the soil, leading to higher biomasses in fertilized treatments (C & D) (Metzger et al. unpublished). But rice biomass seemed to not have an influence on its surrounding algae growth either.

Even after the second fertilization, no significant treatment effects emerged, suggesting that fertilizer had minimal influence on algal growth under these conditions. However, it is important to note that algal measurements were taken 52 days after fertilization, when shading from mature rice plants may have already begun limiting light availability. Therefore, fertilizer may have initially benefited algae but then led to increased rice growth resulting in more shading and less nutrients for algae. This highlights a need for closer synchronization between fertilization events and algal monitoring, especially during advanced crop growth stages.

A similar limitation applies to the measurements of water parameters – pH, conductivity and temperature – which also showed minimal variation among treatment groups. These measurements may have reflected homogenized conditions resulting from delayed sampling rather than true treatment effects.

Only pH was significantly lower in fertilized plots than in unfertilized plots after the first fertilization. This effect could be due to the fertilization with ammonium sulfate which is rather acidic (Wang et al. 2020).

4.3 Sub-project 3: Greenhouse experiment

The statistical results of the greenhouse experiment should be interpreted with caution due to the small sample size ($N = 5$ per group; 10 total per comparison), which may have limited the statistical power to detect significant differences (Cohen 1988). As a result, some comparisons yielded non-significant p-values despite medium to large effect sizes. These larger effect sizes, however, may still indicate meaningful biological or ecological differences between groups, suggesting trends that could become statistically significant with larger sample sizes or in further experiments.

4.3.1 Algal growth and health under different fertilizer regimes

In the greenhouse experiment, algal growth varied considerably by fertilizer type. In unfertilized and organically fertilized systems, algae exhibited positive growth, while in minerally fertilized systems, algae declined sharply, likely due to an unfavorable nutrient balance or inhibitory effects from high nitrogen concentrations (Bharathi et al. 2021). Ohadi et al. (2021) also reported a decrease in algal biomass with more than 60 kg N ha^{-1} of applied mineral fertilizer, but none of their treatments resulted in the complete dying of algae as in this study.

Interestingly, algal biomass was higher in unfertilized treatments than in organically fertilized ones. This, combined with the decline in mineral fertilizer treatments, suggests that the 110 kg N ha^{-1} application rate may inhibit algal growth, either directly or through enhanced shading from fast growing rice plants. In comparison with the fertilizer rates of Swiss farmers in the canton of Aargau and in La Sauge, this fertilizer rate was notably higher. Most farmers applied between 20 and 42 kg N ha^{-1} and not more than 80 kg N ha^{-1}.

These results suggest that algae only tolerate lower nutrient levels and are reduced by too high nutrient levels. Algae therefore were able to grow primarily through photosynthesis. However, biomass alone does not fully reflect algal health.

The C:N ratio is a reliable physiological indicator. According to Hall and Cox (1995), a C:N ratio of approximately 9 was associated with optimal health in *Hydrodictyon spp.* In contrast, a ratio of approximately 24 was indicative of algal senescence, characterized by a yellowish coloration, uniform net size, absence of daughter nets, and therefore lack of reproductive activity. Overall, *Hydrodictyon spp.* was considered healthy when the C:N ratio remained below 18. In this study, C:N ratios ranged from 17.1 (organic), 18.49 (mineral) to 21.58 (unfertilized), implying that algae in unfertilized conditions were less healthy despite higher biomass. In the unfertilized treatments, nitrogen input was minimal – originating solely from the soil – while carbon input remained relatively consistent across all treatments. This imbalance resulted in an elevated C:N ratio compared to the fertilized treatments.

4.3.2 Influence of algae on rice growth

The greenhouse experiment provided a controlled environment to assess the interaction between algae and rice under varying fertilization regimes.

Water parameters

Algal presence significantly affected several water parameters, particularly pH and conductivity. In unfertilized treatments, algae elevated pH values. This is likely due to the reduced carbonic acid in the water due to photosynthetic CO_2 uptake by algae, which then increased alkalinity (Roger 1996). Conductivity decreased in algae-inoculated treatments, indicating nutrient uptake by algae, especially ammonium (Roger 1996).

Additionally, algal presence in unfertilized treatments correlated with slightly elevated water temperatures. Although not in rice paddies, snow green algae in Antarctica were shown to significantly reduce the albedo by absorbing solar energy and therefore increase the local snow melt (Gray et al. 2020). Furthermore, dense mats of blue-green-algae led to an increase in water temperature in Dutch freshwater lakes also due to reduced reflectivity and higher absorbance of sunlight (Kahru et al. 1993). These findings suggest that green algae in this experiment acted as a temperature enhancer.

Overall, algae had a greater influence on water parameters in unfertilized treatments, suggesting that fertilizer application may buffer or mask the algal effects. This was possibly due to the inhibiting effects of high N application on algae, attributing to the higher algal biomass in unfertilized systems, which may amplify such interactions.

Nutrient availability

Although ammonium (NH_4^+-N) concentrations only showed statistically significant differences with algae presence in the organic treatment, visible trends emerged for all treatments. Early in the experiment, NH_4^+-N levels were lower in algae-inoculated fertilized treatments, likely due to combined uptake by both algae and rice. Over time, NH_4^+-N persisted slightly longer in the presence of algae, suggesting a delayed release of nitrogen, possibly from algal decay.

Algae also significantly affected nitrate (NO_3^--N) concentrations, with eductions in all fertilizer regimes. This was most pronounced in the minerally fertilized treatment. This effect is likely due to rapid ammonium-to-nitrate conversion (nitrification) followed by uptake by algae, particularly in mineral systems where NH_4^+ is more readily available (Panda et al. 2019). In organic systems, microbial mineralization must precede nitrification, delaying NO_3^- -N availability (Keeney & Sahrawat 1986).

Orthophosphate levels remained undetectable across all treatments, for reasons that could not be clarified. Given the presence of phosphorus in organic fertilizer, this finding was unexpected and warrants further investigation into detection sensitivity or sampling methodology. Other rice paddies fertilized with organic fertilizer face severe water pollution with phosphorus runoff (Xu & Su 2020).

Ammonia volatilization

An aspect of this study was the conversion of Total Ammonia Nitrogen (TAN) into NH_4^+ and NH_3, using pH and temperature-based partitioning proposed by Purwono et al. (2017). Algal presence increased pH – especially in unfertilized treatments – shifting the TAN equilibrium toward gaseous ammonia (NH_3), which is subject to volatilization.

This is supported by the higher NH_3 concentrations observed in algae-inoculated treatments, particularly in unfertilized conditions, where levels reached 0.29 mg NH_3-N L^{-1}, compared to near-zero in algae-free systems. This ratio declined toward the end of the experiment, likely due to NH_3 loss and a drop in pH.

These findings highlight that algae can indirectly promote nitrogen loss via ammonia volatilization, especially under alkaline, warm conditions (Sand-Jensen et al. 2018). Since rice cannot assimilate NH_3, such volatilization not only represents nutrient loss but also lowers nitrogen uptake efficiency. Moreover, the rise in water pH may affect soil pH over time. If soil pH exceeds 7.5, this can negatively impact grain yield and biomass (Huang et al. 2017), suggesting that algae might contribute to long-term soil alkalization.

Rice biomass

Rice biomass results showed clear treatment-dependent patterns. In unfertilized treatments, algae presence led to significantly higher rice biomass, suggesting nutrient provisioning or indirect stimulation. In contrast, algae had no significant effect on rice biomass in fertilized regimes. This suggests that algae did not impair plant growth, even in competitive nutrient environments. As rice plants were harvested before reaching full maturity, reliable conclusions regarding grain mass and total aboveground biomass cannot be drawn.

Nitrogen and carbon content in rice shoots

Despite similar biomass levels, algae influenced nitrogen content in rice shoots. Across all fertilization regimes, algae presence reduced shoot nitrogen concentrations, indicating competition for nitrogen. This was particularly evident in mineral treatments. This suggests that rice could not fully utilize nitrogen released by decaying algae. This can further be seen in the nitrogen content in these rice plants which was lower in the presence of algae, instead of expectedly higher.

Interestingly, in unfertilized treatments, nitrogen content in rice tissue increased in the presence of algae, though this effect was not statistically significant. It's possible that field-derived algae were nutrient-enriched, or that algal decay contributed to bioavailable nitrogen. However, the uncertainty surrounding initial algal nutrient content complicates this interpretation.

But nonetheless, nitrogen content can influence the grain quality of the rice plant (Leesawatwong et al. 2005, Zhou et al. 2018, Shrestha et al. 2022). Although grain nitrogen content was not measured separately, previous studies have shown that shoot nitrogen content is a reliable proxy (Mondal et al. 2023). Therefore, the observed trends may suggest that algae negatively affect rice grain quality in mineral systems but could improve it in nutrient-poor systems.

Algae presence also affected carbon dynamics. In organic systems, carbon content in rice shoots decreased with algae, also seen in the slight decrease in rice biomass. In contrast, in unfertilized and minerally fertilized systems, carbon content increased, which reflects either enhanced photosynthetic activity (Liu et al. 2021) or an adaptation to low nitrogen availability (Li et al. 2018). Rice plants in treatments with lower nitrogen availability (with algae and/or unfertilized) may have reallocated resources to synthesize carbon-rich compounds like starch in stems, which require less nitrogen compared to protein-rich leaf tissues (Li et al. 2018). Furthermore, in nitrogen-low environments, rice plants tend to decrease their photosynthetic activity, due to nitrogen deficiencies leading to smaller leaf areas and chlorophyll concentrations (Hou et al. 2020).

These findings imply that algae influence both nitrogen and carbon metabolism in rice, potentially altering energy allocation, growth strategy, and grain quality in a treatment-dependent manner.

Effect of algae on Nitrogen Uptake Efficiency (NUpE) and Nitrogen Use Efficiency (NUE)

Nitrogen Uptake Efficiency (NUpE), which reflects how effectively plants absorb available nitrogen provided by fertilization, was higher in mineral fertilizer treatments than in organic treatments without algae. Algal presence reduced NUpE in both fertilizer regimes. This supports the hypothesis that algae compete with rice for available nitrogen, particularly in minerally fertilized systems.

These results also reinforce that algae-derived nitrogen from decay was not efficiently absorbed by rice, at least under mineral fertilizer regimes. It is likely that a portion of the nitrogen pool was lost via volatilization, rather than taken up by plants.

Nitrogen Use Efficiency (NUE), on the other hand, increased in the presence of algae, especially in minerally fertilized systems. This indicates that although less nitrogen was taken up, it was used more efficiently, meaning the plant still produced the same amount of biomass. This suggests a compensatory physiological response by the rice plants to nutrient stress, as documented by Li et al. (2018). Organic and unfertilized treatments showed smaller shifts in NUE, pointing to a more complex, treatment-dependent interaction between algae and plant nitrogen dynamics.

The absolute NUpE values reported in this study are not directly comparable to those from other studies, as they represent estimations based solely on shoot nitrogen content; nitrogen stored in the roots was not measured but is required for a complete calculation. As a result, the reported NUpE values likely underestimate the true uptake efficiency, particularly in treatments where root biomass may have been substantial. Therefore, the focus should be placed on relative differences between treatments rather than absolute values.

Chapter 5

Conclusion

This study investigated the role of macroscopic green algae in Swiss rice paddies by addressing three main research questions:

1. *What type of macroscopic green algae are common in Swiss rice paddies?*
2. *How does the amount and type (mineral vs. organic) of fertilizer influence macroscopic green algae growth?*
3. *How do macroscopic green algae influence rice in terms of rice biomass, rice quality and nutrient availability?*

The dominant macroscopic green algae observed were *Chara spp.* and *Hydrodictyon spp.*, with occasional occurrences of *Zygnema spp.* and *Spirogyra spp.*, aligning with ecological expectations for temperate freshwater systems. While water parameters remained relatively consistent among sites, paddies with higher pH (approx. 9) and lower conductivity (approx. 120 μS cm^{-1}) – notably at Untersiggenthal and La Sauge – favored *Chara spp.* colonization. Algal presence was also modulated by field-specific variables such as age (algae were absent in newly established fields in Brugg) and shading from rice canopies or *Lemna sp.*, both of which limited algal visibility and biomass.

Most fields supporting algae received moderate nitrogen inputs (21 – 42 kg N ha^{-1}), primarily via mineral fertilizers, suggesting that such fertilization regimes may facilitate algal growth. However, the hypothesis (H2) that nutrient availability universally promotes algal growth, modulated by fertilizer type, was only partially supported.

In the fertilizer experiment at La Sauge, no significant differences in algal biomass were observed across fertilization treatments. This may be attributed to even fertilizer distribution and/or delayed sampling, which likely homogenized environmental conditions. Furthermore, the shading effect from mature rice plants during the sampling period may have suppressed algal photosynthesis, obscuring potential fertilizer-driven differences. Under these real-world conditions, neither fertilizer type nor amount appeared to significantly influence macroscopic algal development – at least within the temporal and methodological constraints of this study.

In contrast, in the greenhouse experiment fertilizer type significantly influenced both algal biomass and physiological health. Algae thrived under unfertilized and organically fertilized conditions but declined sharply with mineral fertilization. This decline may stem from excessive mineral nitrogen concentrations that either directly inhibit algal growth or indirectly suppress it through enhanced rice shading. Despite the higher algal biomass observed in unfertilized treatments, its high C:N ratio (approx. 21.5) indicated lower algal health. Organic fertilizers supported moderate algal biomass with lower C:N ratios, indicating better physiological condition and potentially more sustainable algal communities.

With respect to research question 3, the hypothesis (H3) that algae negatively impact rice growth through nutrient competition – particularly for ammonium – was partially supported. In fertilized systems, especially those receiving mineral nitrogen, algal presence reduced rice shoot nitrogen concentrations and contributed to nitrogen loss via ammonia volatilization. However, this competition did not significantly reduce rice biomass, likely due to compensatory mechanisms such as increased Nitrogen Use Efficiency (NUE). Importantly, rice plants were not able to effectively utilize nitrogen released from decaying algae, resulting in lower Nitrogen Uptake Efficiency (NUpE).

Conversely, in nutrient-poor (unfertilized) systems, algae appeared to have a facilitative effect: enhancing rice biomass and marginally increasing shoot nitrogen content, potentially via nutrient recycling or improved microhabitat conditions (e.g., increasing temperature).

Overall, the presence of macroscopic green algae influenced rice performance in a context-dependent manner – acting as nutrient competitors in highly fertilized regimes and as potential facilitators in unfertilized environments. Future studies should address algal influence on rice quality in moderately fertilized systems, reflecting prevalent fertilizer strategies of Swiss farmers. The presence of algae also altered the water chemistry and nitrogen cycling, with implications for both short-term crop performance and possibly long-term soil and water quality. These findings underscore the complex and nuanced roles that algae play in rice agroecosystems, depending on fertilizer regimes and field conditions.

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Appendix A

Figures

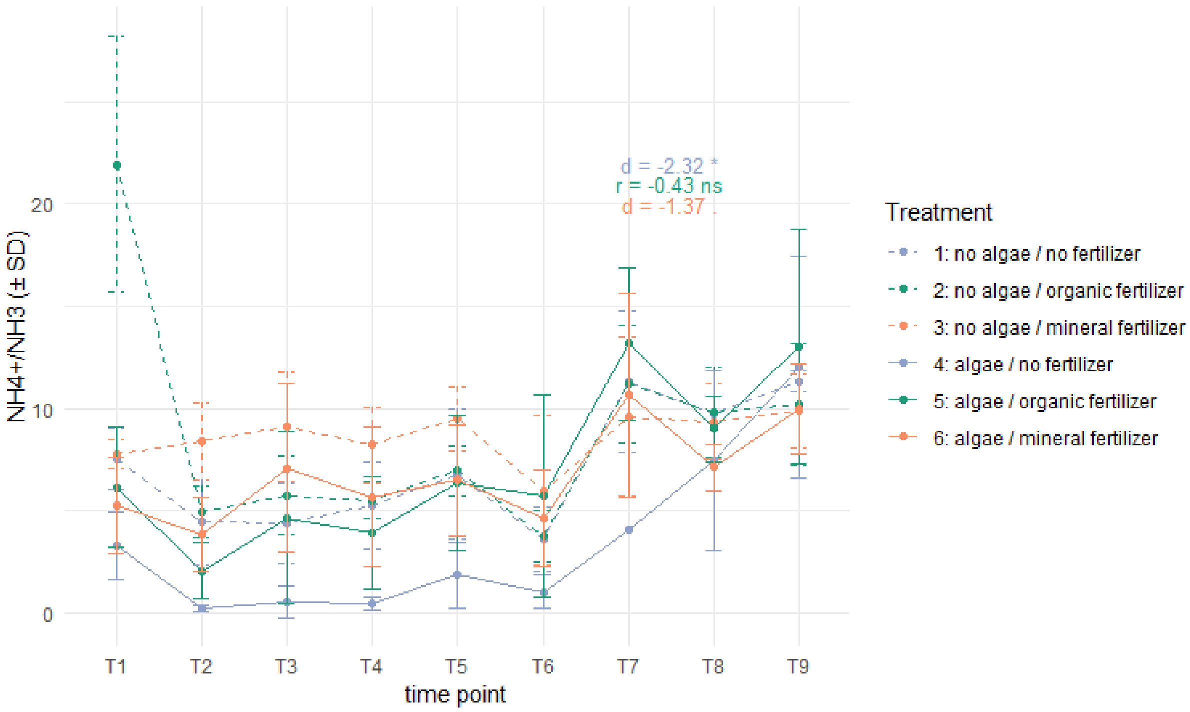

Figure A.1 Ammonium:ammonia (NH_4^+:NH_3) ratio over time by treatment in sub-project 3.

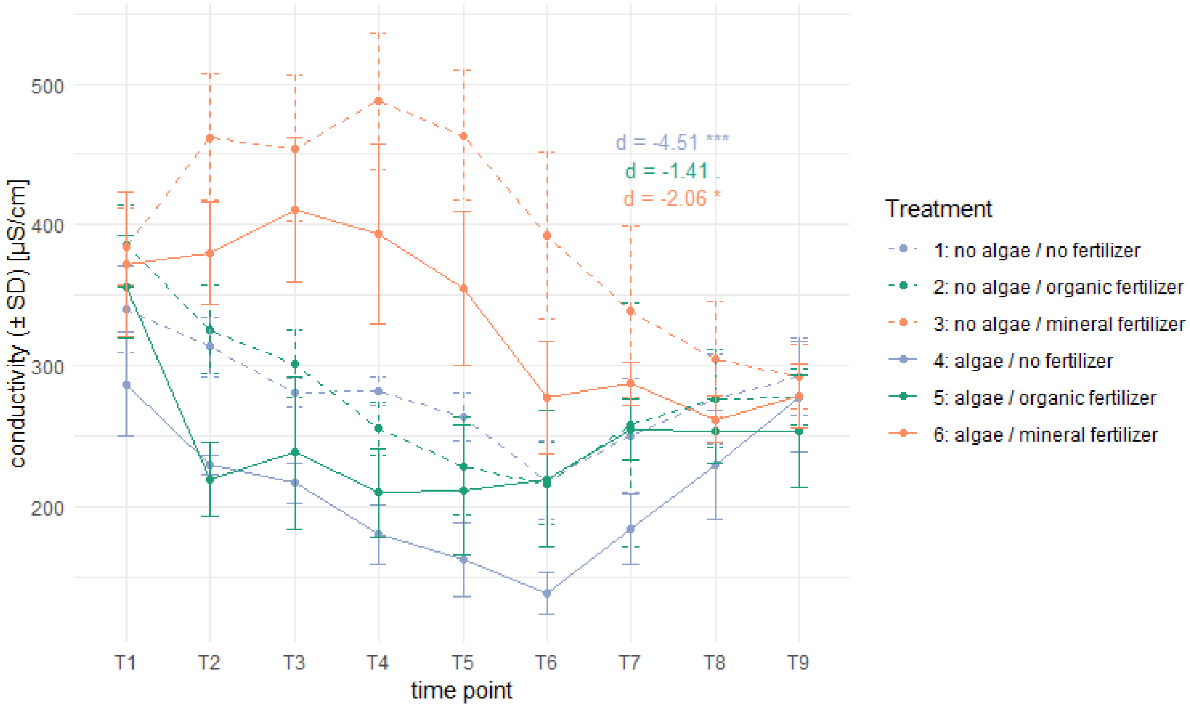

Figure A.2 Conductivity over time by treatment in sub-project 3.

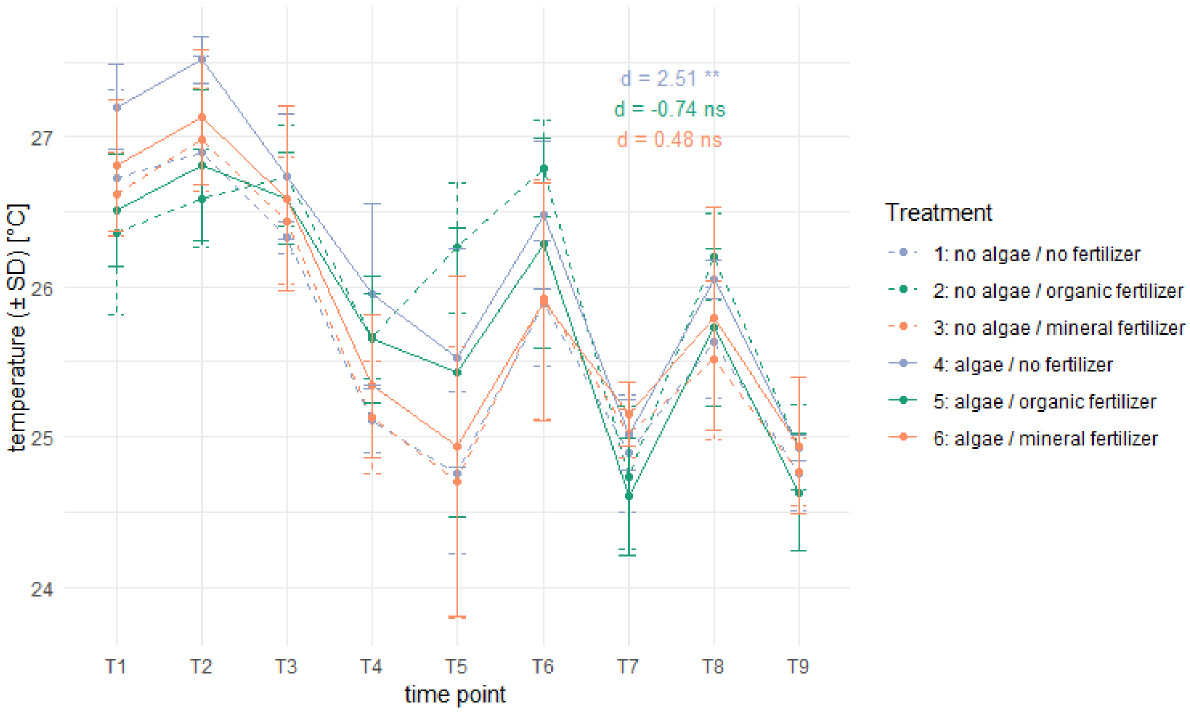

Figure A.3 Water temperature over time by treatment in sub-project 3.

Appendix B

Tables

Table B.1 Plant parameters (mean ± sd) of the investigated paddies in sub-project 1 per sampling date.

22./23.07.24						
	Brugg 1	Brugg 2	Mühlau	Stetten 1	Stetten 2	Unter-siggenthal
Algae cover [%]	0 ± 0 (n = 5)	0 ± 0 (n = 5)	41 ± 31.7 (n = 5)	58 ± 39.47 (n = 5)	0 ± 0 (n = 5)	85 ± 14.58 (n = 5)
Dry algal biomass [g]	0 ± 0 (n = 5)	0 ± 0 (n = 5)	0.68 ± 0.5 (n = 5)	0.36 ± 0.3 (n = 5)	0.54 ± 0.82 (n = 5)	1.28 ± 0.87 (n = 5)
Lemna cover [%]	0 ± 0 (n = 5)	0 ± 0 (n = 5)	0 ± 0 (n = 5)	11.6 ± 21.54 (n = 5)	91 ± 2.24 (n = 5)	11.2 ± 14.99 (n = 5)
Rice height [cm]	60 ± 2.83 (n = 5)	54.4 ± 3.36 (n = 5)	46.8 ± 4.6 (n = 5)	52 ± 10.17 (n = 5)	41.8 ± 3.27 (n = 5)	52.6 ± 4.34 (n = 5)
Wet algal biomass [g]	0 ± 0 (n = 5)	0 ± 0 (n = 5)	4.32 ± 3.3 (n = 5)	4 ± 2.94 (n = 5)	2.44 ± 2.92 (n = 5)	8.04 ± 2.7 (n = 5)
03./04.09.24						
	Brugg 1	Brugg 2	Mühlau	Stetten 1	Stetten 2	Unter siggenthal
Algae cover [%]	0 ± 0 (n = 5)	0 ± 0 (n = 5)	0 ± 0 (n = 5)	(n = 0)	0 ± 0 (n = 5)	(n = 0)
Dry algal biomass [g]	0 ± 0 (n = 5)	0 ± 0 (n = 5)	0 ± 0 (n = 5)	(n = 0)	0 ± 0 (n = 5)	(n = 0)
Lemna cover [%]	0.4 ± 0.55 (n = 5)	0 ± 0 (n = 5)	45 ± 33.54 (n = 5)	(n = 0)	98.2 ± 1.79 (n = 5)	(n = 0)
Rice height [cm]	75.6 ± 1.14 (n = 5)	71.4 ± 4.77 (n = 5)	64.8 ± 2.95 (n = 5)	(n = 0)	71.8 ± 4.09 (n = 5)	(n = 0)
Wet algal biomass [g]	0 ± 0 (n = 5)	0 ± 0 (n = 5)	0 ± 0 (n = 5)	(n = 0)	0 ± 0 (n = 5)	(n = 0)

Table B.2 Water parameters (mean ± sd) of the investigated paddies in sub-project 1 per sampling date.

22./23.07.24						
	Brugg 1	Brugg 2	Mühlau	Stetten 1	Stetten 2	Unter-siggenthal
Conductivity [µS/cm]	252.6 ± 9.79 (n = 5)	310.2 ± 12.6 (n = 5)	240.6 ± 22.43 (n = 5)	229.12 ± 51.08 (n = 5)	222.4 ± 44.75 (n = 5)	136.56 ± 38 (n = 5)
Nitrate-Nitrogen [mg/L]	0.03 (n = 1)	0 (n = 1)	0 (n = 1)	0 (n = 1)	0 (n = 1)	0.01 (n = 1)
Ortho-phosphate [mg/L]	0.04 (n = 1)	0.08 (n = 1)	0.11 (n = 1)	0.3 (n = 1)	1.7 (n = 1)	0.01 (n = 1)
Total Ammonia Nitrogen (TAN) [mg/L]	0.1 (n = 1)	0.04 (n = 1)	0.02 (n = 1)	0.13 (n = 1)	0.2 (n = 1)	0.04 (n = 1)
Water height [cm]	15.2 ± 0.45 (n = 5)	12.4 ± 0.55 (n = 5)	9.7 ± 1.79 (n = 5)	5.3 ± 2.11 (n = 5)	9.5 ± 0.71 (n = 5)	10.2 ± 2.95 (n = 5)
Water temperature [°C]	23.96 ± 0.38 (n = 5)	24.36 ± 0.5 (n = 5)	25.82 ± 0.22 (n = 5)	23.6 ± 0.46 (n = 5)	23.2 ± 0.21 (n = 5)	28.96 ± 1.11 (n = 5)
pH	7.53 ± 0.06 (n = 5)	7.59 ± 0.06 (n = 5)	7.53 ± 0.23 (n = 5)	8.47 ± 0.37 (n = 5)	7.39 ± 0.17 (n = 5)	8.98 ± 0.41 (n = 5)
03./04.09.24						
	Brugg 1	Brugg 2	Mühlau	Stetten 1	Stetten 2	Unter-siggenthal
Conductivity [µS/cm]	212.98 ± 16.61 (n = 5)	225.64 ± 9.46 (n = 5)	258.4 ± 23.59 (n = 5)	(n = 0)	260.6 ± 17.76 (n = 5)	(n = 0)
Nitrate-Nitrogen [mg/L]	0 (n = 1)	0 (n = 1)	0 (n = 1)	(n = 0)	0 (n = 1)	(n = 0)
Ortho-phosphate [mg/L]	0.2 (n = 1)	0.07 (n = 1)	0 (n = 1)	(n = 0)	2.86 (n = 1)	(n = 0)
Total Ammonia Nitrogen (TAN) [mg/L]	0 (n = 1)	0.01 (n = 1)	0.05 (n = 1)	(n = 0)	0.12 (n = 1)	(n = 0)
Water height [cm]	6.2 ± 0.45 (n = 5)	3.6 ± 0.55 (n = 5)	3.2 ± 2.05 (n = 5)	0 ± 0 (n = 5)	3 ± 1.87 (n = 5)	0 ± 0 (n = 5)
Water temperature [°C]	21.74 ± 0.09 (n = 5)	21.26 ± 0.23 (n = 5)	21.6 ± 0.27 (n = 5)	(n = 0)	24.21 ± 0.79 (n = 5)	(n = 0)
pH	7.81 ± 0.22 (n = 5)	8.2 ± 0.05 (n = 5)	7.46 ± 0.12 (n = 5)	(n = 0)	7.28 ± 0.25 (n = 5)	(n = 0)

Table B.3 Plant parameters (mean ± sd) per treatment and sampling date of sub-project 2.

01.07.2024				
	A (0_0)	B (0_2)	C (1_0)	D (1_2)
Algae cover [%]	90 ± 0 (n = 4)	90 ± 0 (n = 4)	90 ± 0 (n = 4)	90 ± 0 (n = 4)
Dry algal biomass [g]	1.29 ± 1.08 (n = 4)	1.25 ± 0.43 (n = 4)	2.3 ± 1.67 (n = 4)	2.91 ± 2.08 (n = 4)
Lemna cover [%]	0 ± 0 (n = 4)	0 ± 0 (n = 4)	0 ± 0 (n = 4)	0 ± 0 (n = 4)
Rice height [cm]	38.75 ± 3.2 (n = 4)	38.5 ± 1.29 (n = 4)	41.75 ± 2.99 (n = 4)	40 ± 0.82 (n = 4)
Wet algal biomass [g]	9.54 ± 6.63 (n = 4)	10.83 ± 1.53 (n = 4)	11.68 ± 2.6 (n = 4)	13.99 ± 6.29 (n = 4)
26.08.2024				
	A (0_0)	B (0_2)	C (1_0)	D (1_2)
Algae cover [%]	85 ± 12.91 (n = 4)	78.75 ± 13.15 (n = 4)	83.75 ± 11.09 (n = 4)	73.75 ± 11.09 (n = 4)
Dry algal biomass [g]	1.83 ± 1.09 (n = 4)	1.48 ± 0.61 (n = 4)	1.45 ± 0.85 (n = 4)	1.28 ± 0.17 (n = 4)
Lemna cover [%]	0 ± 0 (n = 4)	0.25 ± 0.5 (n = 4)	0.25 ± 0.5 (n = 4)	0.5 ± 0.58 (n = 4)
Rice height [cm]	64.75 ± 3.4 (n = 4)	70 ± 5.48 (n = 4)	67 ± 2.94 (n = 4)	70.25 ± 5.32 (n = 4)
Wet algal biomass [g]	9.76 ± 5.15 (n = 4)	8.89 ± 2.41 (n = 4)	6.97 ± 1.14 (n = 4)	7.24 ± 1.44 (n = 4)

Table B.4 Water parameters (mean ± sd) per treatment and sampling date of sub-project 2.

01.07.2024				
	A (0_0)	B (0_2)	C (1_0)	D (1_2)
Conductivity [μS/cm]	105.78 ± 2.67 (n = 4)	109.5 ± 4.93 (n = 4)	106.12 ± 2.93 (n = 4)	104.4 ± 4.1 (n = 4)
Water height [cm]	17 ± 1.41 (n = 4)	17 ± 1.41 (n = 4)	17 ± 0 (n = 4)	16.75 ± 1.26 (n = 4)
Water temperature [°C]	27.08 ± 2.59 (n = 4)	27.18 ± 2.78 (n = 4)	26.18 ± 2.07 (n = 4)	26.38 ± 2.19 (n = 4)
pH	10.02 ± 0.14 (n = 4)	10.1 ± 0.06 (n = 4)	9.86 ± 0.21 (n = 4)	9.64 ± 0.7 (n = 4)
26.08.2024				
	A (0_0)	B (0_2)	C (1_0)	D (1_2)
Conductivity [μS/cm]	255.5 ± 21.36 ((n = 4))	248.25 ± 6.24 (n = 4)	235.93 ± 21.58 (n = 4)	248.5 ± 18.86 (n = 4)
Water height [cm]	6.25 ± 2.63 (n = 4)	5 ± 0.82 (n = 4)	7 ± 3.16 ((n = 4))	7.25 ± 3.2 (n = 4)
Water temperature [°C]	18.98 ± 2.63 (n = 4)	19.48 ± 1.07 (n = 4)	20.38 ± 1.26 ((n = 4))	19.32 ± 0.87 (n = 4)
pH	8 ± 0.21 (n = 2)	7.98 ± 0.04 (n = 2)	7.88 ± 0.26 (n = 2)	8.06 (n = 1)

Table B.5 Significance testing of parameters between different treatments of sub-project 2.

			Test		**Effect size**	
Date	**Compared Treatments**	**Parameter**	type	p	type	value
01.07.2024	AB vs CD	dry algal biomass	Kruskal-Wallis	0.2076	ε^2	0.0392
28.08.2024	A vs B vs C vs D	dry algal biomass	ANOVA	0.778	η^2	0.0841
01.07.2024	AB vs CD	pH	Kruskal-Wallis	0.03058	ε^2	0.2451
28.08.2024	A vs B vs C vs D	pH	Kruskal-Wallis	0.4232	ε^2	-0.0310
01.07.2024	AB vs CD	conductivity	ANOVA	0.234	η^2	0.0995
28.08.2024	A vs B vs C vs D	conductivity	ANOVA	0.515	η^2	0.1675
01.07.2024	AB vs CD	temperature	Kruskal-Wallis	0.3865	ε^2	0.0072
28.08.2024	A vs B vs C vs D	temperature	ANOVA	0.659	η^2	0.1206

Table B.6 Nutrient concentrations [mg/L] (nitrate-nitrogen (NO3-N) and ammonium-nitrogen (NH4-N)) in plots varying in fertilizer application over time in sub-project 2.

Time after fertilization	Fertilization	NO3-N	NH4-N
0h (before fertilization)	without	< 0.06	< 0.07
0h (before fertilization)	with	< 0.06	< 0.07
6h	without	< 0.06	< 0.07
6h	with	< 0.06	0.393
1d	without	< 0.06	< 0.07
1d	with	< 0.06	2.82
3d	without	< 0.06	< 0.07
3d	with	< 0.06	0.213
4d	without	< 0.06	< 0.07
4d	with	< 0.06	< 0.07
5d	without	< 0.06	< 0.07
5d	with	< 0.06	< 0.07
7d	without	< 0.06	0.095
7d	with	< 0.06	< 0.07

Table B.7 Measured parameters (mean ± sd) per treatment of sub-project 3.

	without algae			with algae		
Fertilizer type	none	organic	mineral	none	organic	mineral
Treatment nr.	1	2	3	4	5	6
Nutrients						

TAN [mg/L]	0.04 ± 0.04 (n = 45)	0.81 ± 0.84 (n = 45)	0.68 ± 0.82 (n = 45)	0.09 ± 0.09 (n = 36)	0.66 ± 0.75 (n = 45)	0.67 ± 0.79 (n = 44)
NH_3 [mg/L]	0.01 ± 0.01 (n = 45)	0.12 ± 0.14 (n = 45)	0.08 ± 0.1 (n = 45)	0.06 ± 0.08 (n = 36)	0.18 ± 0.26 (n = 45)	0.13 ± 0.18 (n = 44)
NH_3-N [mg/L]	0.01 ± 0.01 (n = 45)	0.12 ± 0.14 (n = 45)	0.08 ± 0.1 (n = 45)	0.06 ± 0.08 (n = 36)	0.18 ± 0.26 (n = 45)	0.13 ± 0.18 (n = 45)
NH_4^+[mg/L]	0.04 ± 0.05 (n = 45)	0.89 ± 0.93 (n = 45)	0.77 ± 0.93 (n = 45)	0.04 ± 0.05 (n = 36)	0.61 ± 0.72 (n = 45)	0.7 ± 0.84 (n = 44)
NH_4^+-N [mg/L]	0.03 ± 0.04 (n = 45)	0.69 ± 0.72 (n = 45)	0.6 ± 0.72 (n = 45)	0.03 ± 0.04 (n = 36)	0.47 ± 0.56 (n = 45)	0.54 ± 0.65 (n = 44)
NH_4^+:NH_3	8.58 ± 4.21 (n = 42)	10.79 ± 7.18 (n = 44)	10.52 ± 3.01 (n = 45)	3.61 ± 5.09 (n = 31)	8 ± 5.7 (n = 40)	7.88 ± 4.17 (n = 40)
NO_2^--N [mg/L]	0.01 ± 0.02 (n = 28)	0.17 ± 0.27 (n = 27)	0.29 ± 0.32 (n = 27)	0.03 ± 0.05 (n = 22)	0.11 ± 0.25 (n = 27)	0.32 ± 0.34 (n = 28)
NO_3^--N [mg/L]	20.66 ± 1.68 (n = 5)	1.04 ± 0.48 (n = 5)	138.45 ± 9.96 (n = 5)	10.12 ± 4.48 (n = 4)	0.41 ± 0.12 (n = 5)	77.83 ± 19.07 (n = 5)
PO_4^{3+} [mg/L]	0.03 ± 0.04 (n = 26)	0.03 ± 0.03 (n = 25)	0.03 ± 0.03 (n = 26)	0.04 ± 0.04 (n = 21)	0.05 ± 0.12 (n = 26)	0.03 ± 0.03 (n = 25)
PO_4-P [mg/L]	0.01 ± 0.01 (n = 26)	0.01 ± 0.01 (n = 25)	0.01 ± 0.01 (n = 26)	0.01 ± 0.01 (n = 21)	0.01 ± 0.04 (n = 26)	0.01 ± 0.01 (n = 25)
Water parameters						
pH	8.46 ± 0.23 (n = 45)	8.37 ± 0.24 (n = 45)	8.34 ± 0.16 (n = 45)	9.09 ± 0.67 (n = 36)	8.56 ± 0.39 (n = 45)	8.5 ± 0.29 (n = 45)
Conductivity [μS/cm]	279.88 ± 40.89 (n = 45)	280.72 ± 60.7 (n = 45)	397.87 ± 81.48 (n = 45)	211.99 ± 53.55 (n = 36)	246.48 ± 54.92 (n = 45)	335.24 ± 67.5 (n = 45)
Temperature [°C]	25.66 ± 0.89 (n = 45)	26.03 ± 0.8 (n = 45)	25.68 ± 0.93 (n = 45)	26.15 ± 0.94 (n = 36)	25.8 ± 0.92 (n = 45)	25.84 ± 0.98 (n = 45)
Biomass rice						
Total dry rice biomass [g]	1.26 ± 0.23 (n = 5)	2.78 ± 0.72 (n = 5)	2.28 ± 0.89 (n = 5)	1.73 ± 0.35 (n = 4)	2.28 ± 0.46 (n = 5)	2.58 ± 0.85 (n = 5)
Rice leaves biomass [g]	1.08 ± 0.18 (n = 5)	2.26 ± 0.59 (n = 5)	1.98 ± 0.76 (n = 5)	1.32 ± 0.24 (n = 4)	1.9 ± 0.39 (n = 5)	2.26 ± 0.63 (n = 5)

Rice panicles biomass [g]	0.18 ± 0.08 (n = 5)	0.52 ± 0.19 (n = 5)	0.3 ± 0.19 (n = 5)	0.4 ± 0.14 (n = 4)	0.38 ± 0.08 (n = 5)	0.32 ± 0.26 (n = 5)
Ratio leaves:panicles	7.07 ± 3.34 (n = 5)	4.65 ± 1.59 (n = 5)	6.14 ± 2.43 (n = 4)	3.48 ± 0.77 (n = 4)	5.05 ± 0.78 (n = 5)	7.39 ± 2.98 (n = 4)
Biomass algae						
Dry algal biomass [g]	0.02 ± 0.04 (n = 5)	0.02 ± 0.04 (n = 5)	0 ± 0 (n = 5)	0.55 ± 0.34 (n = 4)	0.64 ± 0.18 (n = 5)	0.06 ± 0.13 (n = 5)
Wet algal biomass [g]	0.12 ± 0.27 (n = 5)	0.46 ± 1.03 (n = 5)	0 ± 0 (n = 5)	8.38 ± 1.69 (n = 4)	6.78 ± 2.59 (n = 5)	0.6 ± 1.34 (n = 5)
Algae growth [g] (wet algal biomass - wet inoculated algal biomass)	0.12 ± 0.27 (n = 5)	0.46 ± 1.03 (n = 5)	0 ± 0 (n = 5)	3.38 ± 1.69 (n = 4)	1.78 ± 2.59 (n = 5)	-4.4 ± 1.34 (n = 5)
CN rice						
C:N	26.5 ± 3.93 (n = 5)	31.6 ± 7.85 (n = 5)	21.21 ± 4.84 (n = 5)	34.33 ± 2.18 (n = 4)	31.81 ± 5.74 (n = 5)	32.12 ± 10.17 (n = 5)
C [%]	37.94 ± 0.94 (n = 5)	41.14 ± 0.38 (n = 5)	41.72 ± 1.02 (n = 5)	42.13 ± 0.65 (n = 4)	41.77 ± 1.47 (n = 5)	39.79 ± 0.82 (n = 5)
C [mg]	478.91 ± 94.36 (n = 5)	1144.98 ± 299.13 (n = 5)	957.58 ± 386.74 (n = 5)	727.65 ± 152.91 (n = 4)	951.02 ± 188.72 (n = 5)	1031.02 ± 347.83 (n = 5)
N [%]	1.45 ± 0.17 (n = 5)	1.36 ± 0.31 (n = 5)	2.06 ± 0.53 (n = 5)	1.23 ± 0.09 (n = 4)	1.35 ± 0.27 (n = 5)	1.39 ± 0.57 (n = 5)
N [mg]	18.12 ± 2.7 (n = 5)	36.44 ± 7.09 (n = 5)	43.64 ± 9.47 (n = 5)	21.34 ± 5.12 (n = 4)	30.41 ± 7.15 (n = 5)	32.76 ± 7.64 (n = 5)
CN algae						
C:N	16.73 (n = 1)	12.34 (n = 1)	(n = 0)	20.88 ± 1.3 (n = 4)	17.1 ± 2.1 (n = 5)	18.49 (n = 1)
C [%]	11.23 (n = 1)	34.93 (n = 1)	(n = 0)	28.93 ± 4.97 (n = 4)	25.63 ± 4.09 (n = 5)	28.78 (n = 1)
C [mg]	11.23 (n = 1)	34.93 (n = 1)	(n = 0)	147.52 ± 66.66 (n = 4)	161.18 ± 40.82 (n = 5)	86.35 (n = 1)
N [%]	0.67 (n = 1)	2.83 (n = 1)	(n = 0)	1.4 ± 0.29 (n = 4)	1.53 ± 0.43 (n = 5)	1.56 (n = 1)

N [mg]	0.67 (n = 1)	2.83 (n = 1)	(n = 0)	6.95 ± 2.88 (n = 4)	9.61 ± 3.04 (n = 5)	4.67 (n = 1)
Efficiency						
Nitrogen Use Efficiency (NUE)	69.71 ± 8.95 (n = 5)	76.68 ± 18.4 (n = 5)	50.64 ± 10.66 (n = 5)	81.52 ± 6.29 (n = 4)	76.55 ± 16.48 (n = 5)	79.59 ± 24.12 (n = 5)
Nitrogen Uptake Efficiency (NUpE) [%]	-	40.9 ± 7.95 (n = 5)	48.98 ± 10.62 (n = 5)	-	34.13 ± 8.02 (n = 5)	36.77 ± 8.58 (n = 5)

Table B.8 Significance testing of parameters between treatments with and without algae and their respective statistical test used of sub-project 3.

Parameter	Fertilizer	Mean of Treatment		Test	p	Effect size
		with algae	without algae			
Rice						
Total dry rice biomass [g]	none	1.725	1.26	t-test	0.0468	1.616
	organic	2.28	2.78	t-test	0.2253	-0.831
	mineral	2.58	2.28	t-test	0.5993	0.346
Panicles biomass [g]	none	0.4	0.18	t-test	0.0222	1.962
	organic	0.38	0.52	t-test	0.1739	-0.944
	mineral	0.32	0.3	t-test	0.8921	0.089
Leaves biomass [g]	none	1.325	1.08	t-test	0.1187	1.192
	organic	1.9	2.26	t-test	0.287	-0.721
	mineral	2.26	1.98	t-test	0.5437	0.401
Ratio leaves:panicles	none	3.479	7.067	t-test	0.0763	-1.394
	organic	5.047	4.647	t-test	0.6268	0.32
	mineral	7.387	6.142	t-test	0.541	NA
Nutrients						
NH_4^+-N [mg L^{-1}]	none	0.03	0.032	Wilcoxon	0.9048	-0.082
	organic	0.475	0.692	t-test	0.0129	-2.014
	mineral	0.543	0.598	Wilcoxon	1	-0.033
NH_3-N [mg L^{-1}]	none	0.058	0.006	t-test	0.0023	3.138
	organic	0.182	0.115	t-test	0.0813	1.261
	mineral	0.133	0.078	Wilcoxon	0.0159	-0.76
NH_4^+:NH_3	none	2.839	6.952	t-test	0.0105	-2.324
	organic	6.582	8.86	Wilcoxon	0.2222	-0.429
	mineral	6.364	8.649	t-test	0.063	-1.365
NO_2^--N [mg L^{-1}]	none	0.028	0.012	Wilcoxon	0.1905	-0.49
	organic	0.11	0.167	Wilcoxon	0.0278	-0.729
	mineral	0.312	0.285	t-test	0.3806	0.587
NO_3^--N [mg L^{-1}]	none	10.115	20.662	Wilcoxon	0.0159	-0.816
	organic	0.408	1.04	t-test	0.0213	-1.806
	mineral	77.826	138.452	t-test	2.00E-04	-3.984
Physiological water parameters						

pH	none	9.086	8.464	t-test	0.0021	3.175
	organic	8.555	8.367	t-test	0.111	1.133
	mineral	8.5	8.338	Wilcoxon	0.0952	-0.561
Conductivity [μscm^{-1}]	none	211.986	279.882	t-test	3.00E-04	-4.507
	organic	246.478	280.72	t-test	0.0561	-1.412
	mineral	335.244	397.867	t-test	0.0117	-2.056
Temperature [°C]	none	26.154	25.664	t-test	0.0073	2.505
	organic	25.804	26.03	t-test	0.275	-0.741
	mineral	25.843	25.677	t-test	0.4677	0.482
C/N analysis in rice						
N concentration [%]	none	1.232	1.452	t-test	0.0538	-1.553
	organic	1.352	1.362	t-test	0.9591	-0.034
	mineral	1.39	2.063	t-test	0.0884	-1.227
C concentration [%]	none	42.134	37.945	t-test	1.00E-04	5.036
	organic	41.775	41.137	t-test	0.375	0.594
	mineral	39.794	41.721	t-test	0.011	-2.081
C:N ratio	none	34.333	26.503	t-test	0.0095	2.373
	organic	31.811	31.598	t-test	0.9621	0.031
	mineral	32.119	21.211	t-test	0.0623	1.369
N content [mg]	none	21.338	18.116	Wilcoxon	0.4127	-0.327
	organic	30.412	36.442	t-test	0.2171	-0.847
	mineral	32.76	43.644	Wilcoxon	0.0556	-0.628
C content [mg]	none	727.651	478.913	t-test	0.0195	2.024
	organic	951.015	1144.982	t-test	0.255	-0.776
	mineral	1031.016	957.578	t-test	0.7603	0.2
NUE	none	81.519	69.708	t-test	0.0615	1.492
	organic	76.554	76.684	t-test	0.9909	-0.007
	mineral	79.593	50.638	t-test	0.0396	1.553
NUpE [%]	organic	34.132	40.901	t-test	-6.769	-0.847
	mineral	36.768	48.983	Wilcoxon	-12.215	-0.628

Declaration of Authorship

Personal declaration: I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Svenja Poik: 

Place, date: *Richterswil, 24.4.2025*