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Impact of agricultural practices, elevated temperature and atmospheric carbon dioxide concentration on nitrogen and pH dynamics in soil and floodwater during the seasonal rice growth in Portugal

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ABSTRACT

Data on the movements of available N and non-exchangeable NH_4^+ in the soil are of crucial importance in designing an efficient plant N nutrition management scheme in paddy rice fields. To investigate the processes affecting the dynamics of N and pH under Mediterranean conditions, rice (*Oryza sativa* L. cv. Ariete) was cultivated in 2011 and 2012 in Salvaterra de Magos (central Portugal) under the following climate scenarios: (i) ambient temperature and ambient [CO_2] in the open-field, (ii) elevated temperature (+3 °C) and ambient [CO_2] in open-top chambers, and (iii) elevated temperature (+3 °C) and elevated [CO_2] (+175 μmol mol^{-1}) in open-top chambers. Plants were grown under an intermittent flooding regime. Soil and water samples were taken at eight different stages of plant growth, including before and after N basal and topdressing. Our study indicated that the processes underlying N changes in response to the timing of N fertilization were different depending on the N form. After basal dressing under aerobic conditions, both available and non-exchangeable NH_4^+ contents were increased. Following the topdressing under flooded conditions, the available content of soil N increased, whereas the non-exchangeable NH_4^+ content decreased. A negative relationship was found between soil pH and NH_4^+ "fixation" when roots were active, and vice-versa. Elevated temperature alone or in combination with elevated [CO_2] had no effect on the total available N content in the soil and floodwater. Under elevated temperature, however, the non-exchangeable NH_4^+ content was significantly reduced (11%), with the same magnitude of change (10%) observed under co-elevation of temperature and [CO_2]. These results suggested that non-exchangeable NH_4^+ in paddy fields might be insensitive to [CO_2] elevation under Mediterranean conditions, while reductions observed under co-elevation of [CO_2] and temperature might be associated with temperature alone. This information could be used to alter rice management practices and to adjust N application under climate change.

1. Introduction

Rice is ranked first among the widely consumed staple foods in the world. In Europe, Portugal is the first rice consumer (14 kg per capita per year) and the fourth producer (6 t ha^{-1} in 28,000 ha), contributing to the 5.3% of the total European production (Figueiredo et al., 2013a,b, 2014). Unlike other major crops, rice can be grown in different soils, including soils submerged by water and unflooded aerobic soils. In Portugal, rice cultivation is mostly located in the central and southern region (Mondego, Tagus and Sado Valleys) as monoculture, under continuous or intermittent

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flooding regimes (Figueiredo et al., 2013b). The height of floodwater varies considerably during the season depending on plant size, climatic conditions, soil type and agronomic practices. Rice growth is significantly improved when both ammonium (NH_4^+) and nitrate (NO_3^-) are provided simultaneously (Scherer and Zhang, 2002; Lu et al., 2010; Figueiredo et al., 2013b; Zhang et al., 2013). However, under flooded conditions the NH_4^+ is the preferred nitrogen (N) form for an efficient absorption by the plant. The dynamics of N and carbon (C) in the submerged rice field is different from that under aerobic conditions because submerged soils are maintained at lower redox potential (Eh), due to anaerobiosis. Flooding enhances ammonification by facultative anaerobic microorganisms, releasing ammonia (NH_3) which is usually retained in water or soil in the form of NH_4^+. This cation is then adsorbed in clay minerals of soil or "fixed" (non-exchangeable NH_4^+) in the silica sheets of clays, especially the 2:1 expansive minerals (e.g., illite, vermiculite, smectite) (Carranca, 1996). In general, the NH_4^+ "fixation" is stimulated by flooding because soil organic C enhances the decline in Eh which induces a reduction of octahedral iron (Fe) in the 2:1 clay minerals (Schneiders and Scherer, 1998; Scherer and Zhang, 1999; Buresh et al., 2008; Liu et al., 2008). However, some investigators have made the proposal that the retention of NH_4^+ is less in flooded than unflooded soils (De Datta, 1981). The "newly fixed" NH_4^+ is then protected in the soil from N losses via. nitrification, denitrification and volatilization processes which may occur during the drying and rewetting of paddy rice fields (Buresh et al., 2008; Liu et al., 2008), like the Portuguese condition with the intermittent water regime. In aerobic soils, the rate of "fixation" has been estimated and was found to be fast, with a proportion of "fixed" NH_4^+–N: total soil N $\geq$ 11% (Carranca, 1996; Qiu et al., 2011).

When the clay interlayers expand and/or when the NH_4^+ in the soil solution falls below a certain level, the non-exchangeable NH_4^+ can be diffused into the soil solution and again becomes available to plants and soil microorganisms. Studies on the availability of non-exchangeable NH_4^+ for crops have come to contradictory conclusions. According to De Datta (1981), "defixation" may occur more rapidly in submerged soils than in aerobic soils. A low availability of the non-exchangeable N fraction was reported by Said (1973) in several aerobic soils, whereas Schneiders and Scherer (1998) reported a complete availability in paddy soils.

The "fixation" and subsequent release of "recently fixed" NH_4^+ from N fertilizers is of crucial importance for plant N uptake. The two processes have been reported to differ with soil texture, clay minerals composition, soil pH, temperature, fertilization practices, and cropping system (Carranca, 1996; Lu et al., 2010; Nawaz et al., 2012; Figueiredo et al., 2013b). The rice plant rhizosphere can have completely different physico-chemical conditions, including soil pH, Eh and temperature, as compared to submerged soils without rice plant roots; this can affect the mechanism of "fixation"/diffusion of NH_4^+ when roots are active (Nawaz et al., 2012). The incorporation of crop residues into soil may result in more reducing conditions, either in the presence or absence of plant roots (Nawaz et al., 2012), enhancing the "fixation" of the cation.

Although the soils used by Portuguese rice farmers have been submitted to typical agricultural management practices in the last fourteen years (Pereira et al., 2013; Goufo et al., 2014a), no information is available about the availability of N in paddy fields and the mechanisms of "fixation" and release of NH_4^+ in these soils.

Besides fertilization practices and cropping systems, human activities such as deforestation and burning of fossil fuels may also indirectly influence the movement of N in rice fields, through their impact on the global climate. Since the mid-1800s, these human activities have contributed to an increase in atmospheric carbon dioxide concentration [CO_2] from 280 μmol mol^{-1} to a present-day concentration of 400 μmol mol^{-1} (http://co2now.org/, accessed 01.04.14); it is expected that this value could increase to ca. 550 μmol mol^{-1} by the middle of the century (IPCC, 2007). A predicted consequence of this rise in [CO_2] is warmer temperatures at the earth's surface. Depending on the types of global circulation model used for estimation, the global mean surface air temperature is anticipated to rise by about 1.1–2.9 °C (low scenario) and 2.4–6.4 °C (high scenario) (IPCC, 2007).

Elevated [CO_2] improves the productivity of C3 plants, including rice (Ainsworth, 2008; Madan et al., 2012; Figueiredo et al., 2013a, 2014; Pereira et al., 2013). Increase in plant growth leads to increased N uptake by plants, thereby promoting a large reduction in available NH_4^+. Moreover, when growth is enhanced, root exudates rich in soluble C and rhizodeposition in soil are increased, leading to changed Eh and disturbed microbial activities (Carranca, 1996). These processes could eventually trigger the release of non-exchangeable NH_4^+ into the submerged field, but as to our knowledge no data were found.

As for the temperature effect on non-exchangeable NH_4^+ dynamics, literature data are contradictory with increases, decreases or no effect. In the study by Juang (1990), no influence of temperature on non-exchangeable NH_4^+ in aerobic clay soils was observed when temperatures of 25 °C, 40 °C and 70 °C were compared; at 110 °C, however, the non-exchangeable cation in the clay fraction was significantly increased by 13% and 99%, respectively in a Latosol and in a recent sandstone-shale alluvial soil. This indicated that at very high temperatures (>100 °C), water molecules may be removed from the interlayers of the clay minerals, thus allowing more NH_4^+ to be "fixed". By contrast, Jai et al. (2000) showed that the "fixation" rate of fertilizer-NH_4^+ was 18–23% at normal temperature (25 °C) in the aerobic condition and increased by 38–45% at low temperatures (−5 °C–0 °C). Taken together, it seems unlikely that a narrow change in temperature (1.1–6.4 °C) anticipated by the middle of the current century could affect NH_4^+ "fixation" in rice soils.

However, forecasted climate trends are not related to increase the temperature alone, but also to increase atmospheric [CO_2] as well. Whilst the effects of temperature in aerobic soil processes have been examined, few studies have focused on the effects of elevated [CO_2], let alone or in combination with elevated temperatures, and in particular under the anaerobic condition.

In this study, we made use of open-fields and open-top chambers to investigate the effects of agricultural practices (e.g., N fertilization, flooding regime, cropping system) and climate change (simultaneous elevation of temperature and [CO_2]) on the dynamics of N and pH throughout the growth season in the flooded rice field. Our main objective was to examine if these treatments could affect soil and floodwater chemical characteristics (NH_4^+, $NO_3^-$and pH), with a particular emphasis on the mechanism of "fixation"/diffusion of soil NH_4^+. In a Portuguese clay soil cultivated with rice (*Oryza sativa* L. cv. Ariete) in 2011 and 2012, under the intermittent flooding regime and conventional agronomic practices, the dynamics of available N, non-exchangeable NH_4^+ and pH should be evaluated in the soil and floodwater, under (i) the ambient temperature and ambient [CO_2] in open-field, and under (ii) the elevated temperature (+3 °C) and ambient [CO_2]- and (iii) elevated temperature (+3 °C) and elevated [CO_2] (+175 μmol mol^{-1} air) in controlled open-top chambers (OTCs) placed in the field.

2. Materials and methods

2.1. Site description and layout of the field experiment

A rice field experiment was conducted over two consecutive seasons (2011 and 2012) at the experimental farm of COTArroz, an agri-food company with headquarters in Salvaterra de Magos