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P for two – intercropping as a means to better exploit soil P resources under low input conditions

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Abstract

We need to aim for ecological intensification of agroecosystems, in order to cover an increasing global food demand while decreasing agricultural inputs such as fertilisers is required to maintain ecosystem services. Increasing the efficiency of nutrients to plants while decreasing nutrient inputs means that better exploration and exploitation of soil resources must be achieved in agroecosystems. This paper focusses on intercropping, which proved efficient to increase agroecosystem productivity, via better exploitation of soil resources. We studied the underlying processes of acquisition of soil phosphorus (P) by plants in cereal/legume agroecosystems, with a particular focus on rhizosphere processes. The working hypothesis is that the two intercropped species may access different P pools, the legume being responsible for greater changes in P availability in the rhizosphere, as a consequence of root-induced acidification resulting from nitrogen fixation. We sampled the rhizosphere of field-grown plants at two stages of growth of durum wheat and pea/faba bean along a gradient of soil P availability. Available P increased in the rhizosphere, especially for the legumes, and more so when intercropped. This was possibly due to the increased proportion of nitrogen fixation in the intercropped legumes, thereby resulting in inter-species facilitation for P acquisition.

Key Words

Phosphorus, rhizosphere, intercropping, availability, legume, cereal.

Introduction

A major challenge for agroecosystem management in the coming decades is to succeed their necessary ecological intensification, in order to cover global food demand while decreasing agricultural inputs such as fertilisers (Cassman 1999). As pointed out by Vance *et al.* (2003), by 2030, world population shall increase by about +33 to +67%, while in the mean time, the potential increase in surface area of arable land will reach at most +20%, and that of irrigated land less than +10%. Given the climate changes which operate and the increasing use of arable land for other uses than food production, the challenge in front of us is even bigger (Tilman *et al.* 2002) : the level in agriculture productivity needs to be maintained, but this has to be achieved in a sustainable manner, both environmentally and economically, in order to preserve ecosystem services. The Millennium Ecosystem Assessment underlined that the cycles of nutrients, especially nitrogen (N) and phosphorus (P) were among the most affected ecosystem services, leading to a massive and fast-increasing eutrophication of aquatic ecosystems (Mackenzie *et al.* 2002) and contamination of groundwaters by nitrate. These phenomena are the direct consequence of the considerable increase in agricultural inputs and the steady decrease of their efficiency (Tilman *et al.* 2002) : from 1965 to 2000, the doubling of the production of world agriculture corresponded with a 3.5- and 6.9-fold increase in the amounts of P and N fertilisers applied, respectively (Tilman 1999). Besides the effects of eutrophication and of nitrate in drinking water, the high and fast-increasing cost of energy and thus that of manufactured N fertilisers, as well as the negative impacts of greenhouse gas emissions invalidate the perspective of pursuing the steady increase in N fertiliser application. For P, the fast exhaustion of high grade phosphate ores worldwide in the coming decades at the current rate of consumption of P fertilisers (Cordell *et al.* 2009) clearly challenges the sustainability of current P fertiliser use in developed countries. This rather short deadline which may be further extended by using lower quality resources and paying a greater cost clearly challenges the sustainability of current practices (Cordell *et al.* 2009).

While most natural ecosystems are made of complex assemblages of plant species, agrosystems are characterised by extremely simple plant communities (most often a single species and a single variety in a field). A better nutrient use efficiency shall be expected from more diverse systems, either pluri-specific such as intercropping or agroforestry (Tilman *et al.* 2002 ; Li *et al.* 2007). Intercropping is defined as the growing of two or more species simultaneously on the same area of land. Plant species grown in intercropping systems are rather diverse, and most often combine a cereal and a legume. Intercropping are millenary-old

practices in Chinese agriculture (Zhang *et al.* 2003). Its success (>28 10⁶ ha in China according to Li *et al.* 2007) is due to the overyielding phenomenon which is frequently observed when two species are intercropped, relative to corresponding monocropping : over a 4-yr field trial in China, Li *et al.* (2007) reported that intercropped plants could yield up to 20-50% more than when grown separately. Intercropping is not very widespread in temperate agroecosystems but cereal legume intercrops are gaining increasing interest in low input farming systems especially in organic farming in Europe. Indeed this practice is known to increase yields, stability, decrease weed pressure, diseases, N leaching and increase grain N concentration of cereal and therefore can contribute to develop agrosystems wich combine high productivity and ecological services (Jensen *et al.* 2006). In addition, the implication of P nutrition in facilitation among intercropped cereal-legume species is quite documented, although the underlying rhizosphere processes have not been fully elucidated. Several works have suggested that the legume could facilitate the acquisition of P by the intercropped cereal via (i) exudation of organic acids (e.g. Li *et al.* 2007) or phosphatase enzymes (e.g. Gunes *et al.* 2007). Li *et al.* (2008) advocated for the potential implication of protons released in the legume rhizosphere as a consequence of N₂ fixation. A large proportion of former works has been conducted in pot experiments. The aim of this work was to evaluate in field-grown plants whether the two intercropped species accessed different P pools, and to check whether the legume was responsible for greater changes in P availability in the rhizosphere, as a consequence of root-induced acidification resulting from nitrogen fixation. We evaluated this in intercropped versus monocropped systems at 3 levels of soil P availability.

Methods

Field experiment

The experiment was conducted in 2009 at Auzeville experimental station near Toulouse, South-Western France, in a long term fertiliser experiment (Colomb *et al.* 2007). The soil is neutral to slightly alkaline. Three levels of P application were compared : no application for 40 years (P0) and levels either balancing crop offtake (P1) or four-fold larger than crop offtake (P4). There was a considerable discrepancy in P availability between the 3 levels, from 4 to 60 mg kg⁻¹. Four replicates of each P treatment were compared. There were 6 crop treatments for each of the P level : durum wheat was cropped on its own (monocropping) or intercropped with either faba bean or pea. These two legumes were also grown on their own. A different durum wheat genotype was used for each legume species.

Measurements

The roots and surrounding soil of several plants were sampled from the topsoil (0-20 cm) at two stages of growth (when the wheat ear was at 1 cm, by end of April 2009 and when the legumes were flowering by end of May 2009). The roots and adhering soil were separated from the bulk of the soil. The rhizosphere (strongly adhering soil) was collected by shaking the roots in deionised water. The same procedure was applied to bulk soil samples. Then, the soil suspensions were air-dried at 40°C in an oven. Soil pH and P concentration were measured in a water extract, while P availability was measured on a separate sample with the Olsen method.

Results

At the first stage of sampling, Olsen P showed no significant change in the rhizosphere of monocropped durum wheat compared with bulk soil, whatever the level of P application. In contrast, Olsen P systematically increased in the rhizosphere of the two legume species, either monocropped or intercropped, except for faba bean in the P0 treatment. This effect was more important for pea in the P0 treatment and for faba bean in the P1 treatment. Interestingly, there was a significant increase in Olsen P in the rhizosphere of durum wheat when intercropped with the legumes (pea only in the P0 treatment, and faba bean only in the P4 treatment).

At the second stage of sampling which coincided with legume flowering, i.e. a stage at which N₂ fixation is supposedly effective, Olsen P was found to systematically increase in the rhizosphere of all plant species and genotypes. At P0 and P1, this increase in P availability was significant only for the two legume species, either monocropped or intercropped. At P4, this was hardly significant at all. No significant pH change was measured in the rhizosphere, whatever the P and crop treatment.

The absence of any significant decrease in Olsen P in the rhizosphere was surprising as most models of P nutrition assume that depletion of available P is the driving force of P acquisition in crops (e.g. Mollier *et al.* 2008). The observed increase in available P, which tended to occur especially for the monocropped legumes

or for the intercropped plants (either the cereal or the legumes) suggest that another process occurred concurrently to P uptake in the rhizosphere, thereby leading to an increase in Olsen P. Although, no significant pH change was measured as a consequence of the large proton buffering capacity of the studied soil, it is assumed that proton efflux from roots of legumes was responsible for this, as N₂-fixation is known to be responsible for such process. Quantitative assessment of N₂-fixation by the natural ¹⁵N technique (ongoing measurements) shall enable to further address this hypothesis.

Conclusion

Intercropping cereals with grain legumes is an efficient management practice for increasing the acquisition of soil resources such as N and P. There is however a need for better understanding the underlying facilitation processes, especially in the case of P under field conditions. This shall enable to select the best intercropping options (combination of species, spatial arrangements). In this work, we showed the evidence of an increase in P availability, which occurred especially in the rhizosphere of the legumes. Interestingly, it also occurred, although not systematically, in the rhizosphere of durum wheat when intercropped with the legumes, suggesting that the legume may have facilitated P acquisition of the intercropped cereal. We hypothesised that this was related to proton efflux from the roots of legumes as a consequence of N₂ fixation, although no significant rhizosphere acidification was measured. Worth to be noted, we showed that such processes were not so clear under low input conditions, at the lowest level of P application, possibly because the poor availability of P after 40 years without P application was limiting N₂ fixation by the legumes.

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