Phytopathologia Mediterranea
The international journal of the
Mediterranean Phytopathological Union

Firenze University Press
www.fupress.com/pm

EUPHRESCO III-Special Issue on Plant Health Priorities
RESEARCH PAPERS

Soil moisture and soil type affect Rhizoctonia root rot and yield components of soybean plants

Maicon BALBINOTTI[1,2,3*], Jaqueline HUZAR-NOVAKOWISKI[1,4], Júlia DOS SANTOS DE BRITTO[1,5], Milena BALBINOTTI FERREIRA[2], Pedro Alexandre VARELLA ESCOSTEGUY[6], José Luís TREVIZAN CHIOMENTO[1,6], Mateus POSSEBON BORTOLUZZI[6], Luciane Maria COLLA[6], Laura MUGNAI[3], Nadia CANALI LÂNGARO[6]

[1] *Agricultural Microbiology Laboratory, Graduate Program in Agronomy, University of Passo Fundo, Passo Fundo, Rio Grande do Sul, Brazil*
[2] *MB Consultoria Agrícola, Soledade, Rio Grande do Sul, Brazil*
[3] *Department of Agriculture, Food, Environment and Forest Science and Technology, Plant Pathology and Entomology Section, University of Firenze, Firenze, Italy*
[4] *Volvere Biotech, Guarapuava, Paraná, Brazil*
[5] *GDM Genética do Brasil, Passo Fundo Rio Grande do Sul, Brazil*
[6] *Graduate Program in Agronomy, School of Agricultural Sciences, Innovation and Business, University of Passo Fundo, Passo Fundo, Rio Grande do Sul, Brazil*
*Corresponding author E-mail: balbinottimaicon@gmail.com

Summary. Rhizoctonia root rot (RRR) reduces soybean yields, and is influenced by soil conditions, but there is a lack of knowledge on effects of soil moisture and soil type on disease severity, in subtropical environments. Increased RRR during periods of water deficit in southern Brazil reinforces requirement to understand interactions between soils and moisture affect severity of the disease and crop yields. Two greenhouse experiments were conducted to evaluate combined effects of soil moisture (50, 65, 80, or 95% water holding capacity; WHC) and soil type (Acrisol, Cambisols, Leptosol, or Nitisol) on soybean RRR severity and yield components. Increasing soil moisture from 50 to 95% WHC linearly reduced RRR severity and linearly increased numbers of soybean pods, grains, and grain weights, inside and outside RRR patches. In Experiment 1, at 65% WHC, RRR severity was less in Leptosol than on Acrisol, but there were no differences between these two soils and the other soil types. In Experiment 2, soil type did not affect RRR severity evaluated at all the tested soil moistures. High soil moisture (≥ 80% WHC) mitigated RRR, and extended the soybean growth cycle. Low soil moisture (50–65% WHC) intensified RRR severity, increased plant death, and reduced soybean grain yields.

Keywords. Glycine max, edaphic factors, disease management, water deficit, soilborne pathogen.

OPEN ACCESS

Citation: Balbinotti, M., Huzar-Novakowiski, J., Dos Santos De Britto, J., Balbinotti Ferreira, M., Varella Escosteguy, P. A., Trevizan Chiomento, J. L., Possebon Bortoluzzi, M., Colla, L. M., Mugnai, L., & Canali Lângaro, N. (2026). Soil moisture and soil type affect Rhizoctonia root rot and yield components of soybean plants. *Phytopathologia Mediterranea* 65 (EUPHRESCO III - Special Issue): 49-78. doi: 10.36253/phyto-17030

Accepted: May 7, 2026

Published: June 12, 2026

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

Editor: Thomas A. Evans, University of Delaware, Newark, DE, United States.

ORCID:
MB: 0000-0002-7296-2976
JHN: 0000-0003-1037-2396
JSB: 0009-0005-7083-3205
MBF: 0009-0004-3156-325X
PAVE: 0000-0001-8212-387X
JLTC: 0000-0003-4819-2761
MPB: 0000-0002-7257-5802
LMC: 0000-0001-9745-4452
LM: 0000-0002-2508-9764
NCL: 0000-0002-2031-5152

INTRODUCTION

Among the soilborne diseases of soybean, Rhizoctonia root rot (RRR) caused by the fungus *Rhizoctonia solani* J. G. Kühn, is important (Balbinotti *et al*., 2022). This disease can cause up to 50% yield losses in soybean (Balbinotti *et al*., 2025). *Rhizoctonia solani* is a natural soil inhabitant that can survive as microsclerotia or mycelium, and is commonly present in crop residues (Spurlock *et al*., 2016; Nasimi *et al*., 2024). Since microsclerotia are capable of surviving under adverse conditions (Abbas *et al*., 2019; Abbas *et al*., 2022), they can remain viable in soil for several years (Akber *et al*., 2023), which makes RRR a difficult disease to control (Balbinotti *et al*., 2025).

Management of soybean involves the use of chemical seed treatments (Ajayi-Oyetunde and Bradley, 2018; Navi *et al*., 2019) or biological fungicides (Mello *et al*., 2020; Sallam *et al*., 2021), which protect seeds and seedlings at the beginning of crop cycles (Rahman *et al*., 2020). However, in later stages of soybean development, there are no efficient chemical control methods for managing RRR (Dorrance *et al*., 2003). On the other hand, improving soil chemical (Balbinotti *et al*., 2022) and physical conditions (Stamford *et al*., 2005) can minimize RRR-induced soybean yield losses. Management of soil pH, nutrient availability (K, Cu), and soil acidity (exchangeable Al, Ca, Mg) can influence soybean susceptibility to *R. solani* (Balbinotti *et al*., 2023). Combination of liming with nutrient management, particularly maintaining pH in the range 6.6 to 7.0, and increased calcium availability, have been shown to suppress *R. solani* and improve plant health. Despite its strategic potential, several challenges hinder large-scale adoption of soil nutrient management, particularly the high costs of soil amendments (Balbinotti *et al*., 2025).

Severity of RRR can be considered at two complementary levels: (1) success of *R. solani* penetration of host root and crown tissues; and (2) ability of the fungus to grow and spread in soil, favoured by moisture and soil characteristics (Naqvi *et al*., 2024). Soil types play key roles in soil moisture and nutrient availability, and in the dynamics of soilborne phytopathogens (Coque *et al*., 2020; Jayaraman *et al*., 2021). Among edaphic factors, moisture influences the soil microbiota (Gill, 2001a; 2001b; Stamford *et al*., 2005), including survival of *R. solani* microsclerotia and infection capacity of the fungus (Ghorbani *et al*., 2008; Homet *et al*., 2019). However, information on the influence of soil moisture on RRR has been inconsistent and inconclusive.

High soil moisture levels favour growth of fungal mycelium and increase contacts of fungi with host plants, while low moisture, although limiting fungal activity, can enhance stress environments for plants, increasing their susceptibility to pathogens (Datta *et al*., 2022; Nasimi *et al*., 2024). Many soil fungi (e.g., *Phytophthora*, *Rhizoctonia*, *Sclerotinia*) usually cause severe symptoms on plants when soil moisture levels are high. Increased moisture probably affects pathogens, which multiply in wet soils. High moisture levels may also decrease host defence, through reduced temperatures and oxygen availability in waterlogged soils (Ghorbani *et al*., 2008). Compacted and poorly drained soils also provide conditions that favour proliferation of *R. solani* (Höper and Alabouvette, 1996; Dixon and Tilston, 2010). These physical conditions decrease host defense by reducing oxygen availability (Stamford *et al*., 2005; Ghorbani *et al*., 2008). In addition, low soil moisture can also inhibit the processes of germination, growth, and development of phytopathogens (Ajayi-Oyetunde and Bradley, 2018), including *Fusarium solani*, and *F. tricinctum* (Yan and Nelson, 2022), *Phytophthora sojae* (Clevinger *et al*., 2025), and the *Globisporangium/Pythium* complex (Molin *et al*., 2022).

Saturated or waterlogged soils favour fungal diseases of young host plant tissues (Agrios, 1997). However, Cruz *et al*. (2020) showed that in sandy loam and loam soils, high soil moisture levels (pot saturation) gave lowest levels of *Fusarium graminearum* root rot of soybean. Gill *et al*. (2000) showed that soil moisture above 20% WHC did not affect spread of *R. solani* in soil, and that colonization of wheat roots by young unpigmented hyphae diminished with increasing soil moisture, from 80% of root length colonized at 15% WHC to 20 to 25% at 75% WHC. Similarly, in soils with moisture below 60%, propagule survival was favoured for the phytopathogen *Macrophomina phaseolina* (Marquez *et al*., 2021). These effects are probably related to pathogen ability to propagate and grow within soil pore spaces (Otten *et al*., 1999; Otten and Gilligan, 2006).

Conversely, increased soil moisture can affect fungus growth, possibly because of reduced air-filled pore space, or competition from soil microorganisms that suppresses pathogen activity through competition (Gill *et al*., 2001b). In this way, increases of RRR patches in soybean crops during periods of water deficit have been observed in soybean crops in southern Brazil (Balbinotti *et al*., 2022).

Although disease severity from root pathogens is influenced by soil physiochemical conditions and biodiversity of soil microbial populations (Ghorbani *et al*., 2008), there are inconsistent results on influence of soil moisture on incidence and severity of root rot of soybean caused by *R. solani*. Detailed information is also

lacking on effects of combinations of soil moisture levels and soil types on the disease and grain yield of soybean. Understanding effects of soil moisture on the dynamics of RRR, and how these vary among different soil types, is important for formulating efficient disease management strategies. These could guide farmers who report damage and yield losses in their soybean fields.

The hypothesis examined in the present study was that low soil moisture intensifies severity of RRR, and that this effect is modulated by soil type. The research objective was to evaluate the influence of soil moisture in different soils on occurrence of this disease, and on soybean yield components.

MATERIALS AND METHODS

Plant material and experiment site

The soybean cultivar 'BMX Lança IPRO' was used in this study. This cultivar is adapted to southern Brazil, and is susceptible to RRR. The experiments described below were carried out at the Research Greenhouse (90 m^2) of the School of Agricultural Sciences, Innovation and Business, University of Passo Fundo (28°13′47.91″S; 52°23′1.58″W), Rio Grande do Sul, Brazil, from January (summer) 2021 to May (autumn) 2022. The greenhouse has a semicircular roof, oriented northwest-southeast, and is made of galvanized steel and covered with a low-density polyethylene film (150 μm thick) with an anti-ultraviolet additive. Inside, a 60% thermo reflective screen was installed, and greenhouse sides were covered with aphid-proof mesh.

Evaluated factors

Effects of the following factors and their interactions were evaluated: two experiments × four soil moisture levels × five soil types × two locations of RRR occurrence (inside or outside the disease patch). For each experiment, a randomized complete block design was used, with four replications.

Experiment

The experiment was carried out twice (Experiment 1 and Experiment 2), with a 15-day interval between establishment dates. The greenhouse used had internal divisions separating environments, and each experiment was set up in a different compartment and positioned in a distinct area within the greenhouse. This separation aimed to ensure independence of the experiments and minimize possible environmental interference.

Soil

Soils were collected from five cultivated soybean fields that were under a no-tillage system, had histories of RRR, in the Soledade municipality (28°49′51.1″S, 52°30′39.1″W), Rio Grande do Sul, Brazil (Balbinotti *et al*., 2023). Each experimental unit consisted of two soybean plants cultivated in one pot, which contained one of the following soil types: Rhodic Acrisol (Ac), Dystric-Haplic Cambisol (CaTa), Eutric-Haplic Cambisol (CaTb), Dystric-Lithic Leptosol (Lep), or Dystrophic Red Nitisol (Nit) (Figure 1; Supplementary Tables S1 and S2).

In the Acrisol and the two Cambisols, RRR had been recorded since the 2009–2010 growing season, and in the Leptosol and Nitisol this disease had been recorded since the 2013–2014 growing season. After the first identifications, incidence of RRR was observed in all subsequent growing seasons, with greater apparent severities in years of low rainfall. Initial symptoms of RRR in soybean crops appeared each growing season at the beginning of crop reproductive periods.

Field patches of Rhizoctonia root rot

In each soil type, soil samples were collected from patches of RRR occurrence (Figure 1F). Samples from inside the patches were separated from those collected from outside the patches. The patches were identified and marked in March (autumn) 2020, based on observations of soybean plants showing symptoms of RRR. The affected plants had brownish-purple discolourations at the stem bases, were wilted or dead.

Fragments of tissue from the collar regions of the diseased soybean plants were sampled at the transitions between healthy and diseased areas, o confirm if the disease was caused by *R. solani*. These fragments were surface-sterilized and then plated onto potato sucrose agar supplemented with streptomycin. After incubation, resulting fungi were initially identified based on morphology of growing mycelium. To confirm the anastomosis groups, the method of Carling (1996) was used. The *R. solani* anastomosis group AG-4 was identified for the *R. solani* isolates obtained (Balbinotti *et al*., 2022).

Soil samples were collected in June (winter) 2020 from the 0–20 cm surface-layers, and immediately transferred to pots (each of 30 cm diam., 25 cm depth, 12,000 cm^3 volume), maintaining soil field structures (Figure 2). The pots were then stored in a covered

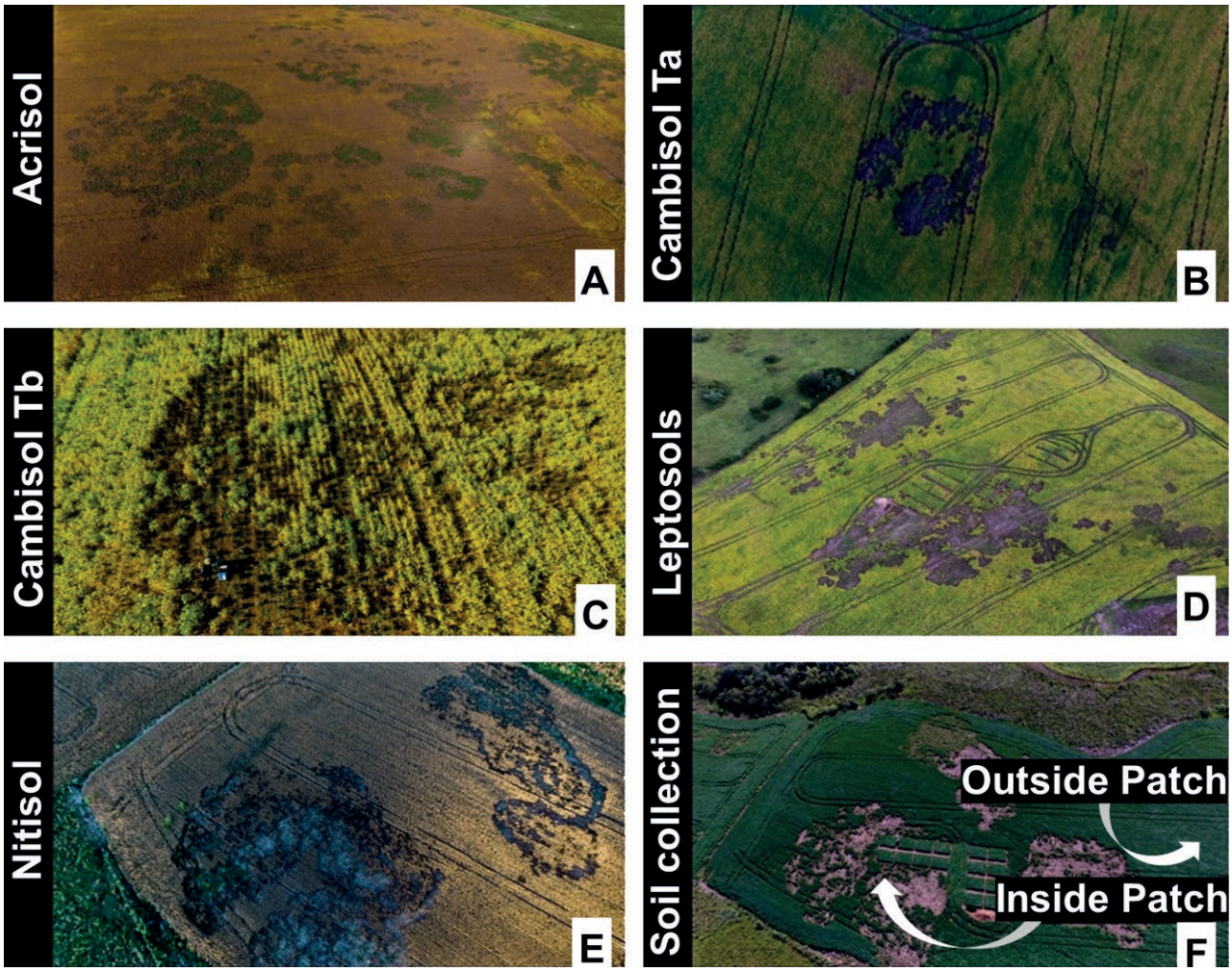


Figure 1. General views of fields where soils were collected for the experiment carried out in the present study: (A) Acrisol; (B) Dystric-Haplic Cambisol; (C) Eutric-Haplic Cambisol;(D) Leptosol; and (E) Nitisol. (F) indicates Locations of soil sampling inside or outside a soybean field disease patch affected by Rhizoctonia root rot.

environment for 180 d (Figure 2E), and were irrigated every 10 d to maintain soil moisture until the start of the experiment.

Soil moisture

In January 2021, the pots were transferred to a greenhouse, and were irrigated by micro-sprinkling. This produced a light mist over the pots, preventing abrupt drying and aimed to avoid scalding and the losses of microsclerotium viability. After 60 d of micro-sprinkling irrigation, this was stopped and drying occurred for 120 d. Thus, the total time until the soil in the pots was completely dry was 180 d. The pots were weighed each week during the last 30 d of drying until the weights became constant. This soil drying protocol at room temperature to maintain viability of resident *R. solani* inoculum.

The air-dried soils varied in moisture contents from 2 to 6%, depending on the soil type. As the experiment comprised five soil types, a residual moisture content of 3% was assumed for all the experimental units. The soil mass in each pot was standardized to 8 kg of air-dried soil (Figure 3B), and this mass was considered to be equivalent to 0% of each soil's maximum water holding capacity (WHC).

A tank was built (length 13 m, width 1.3 m, depth 0.4 m) using bricks and wooden boards. The tank interior was lined with plastic sheeting and filled with water (Figure 3). The pots were then placed inside the tank for soil saturation (Figure 4).

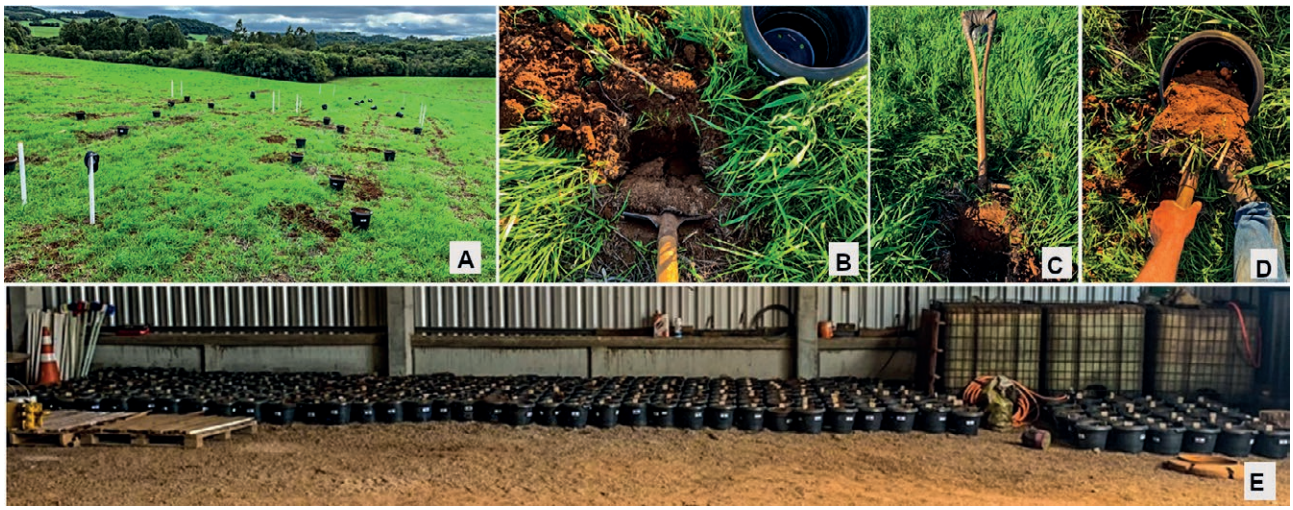


Figure 2. Field soil sampling and storage. (A) soil sample distribution in a field indicated by pots to which the sample were added. (B) trench opening, and (C) use of a cutting spade. (D) soil transfer to a pot. (E) Storage of the field soil samples in a covered and sheltered environment.

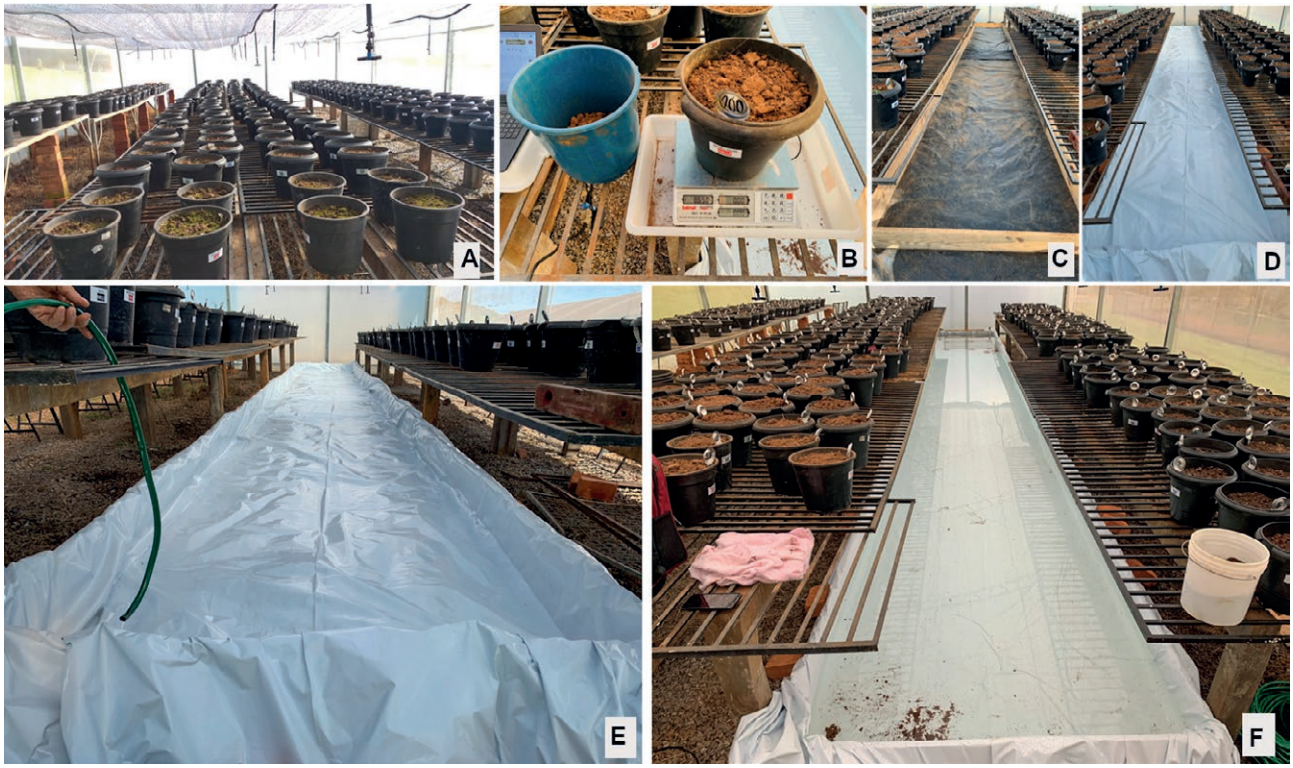


Figure 3. (A) Drying of field soil samples in pots. (B) Pot and soil weighing. (C) Construction of pot holding tank. (D) Placement of sheet plastic tank liner, (E) Filling tank with water. (F) Completed tank.

Soil saturation was carried out by capillarity over 7 d (Figure 4, A, B, C, D and E), with water entering each pot through the base holes. The water level in the tank was raised until the water front in each pot reached the soil surface, which occurred after 7 d (Figure 4E). After this saturation period, the pots were removed from the

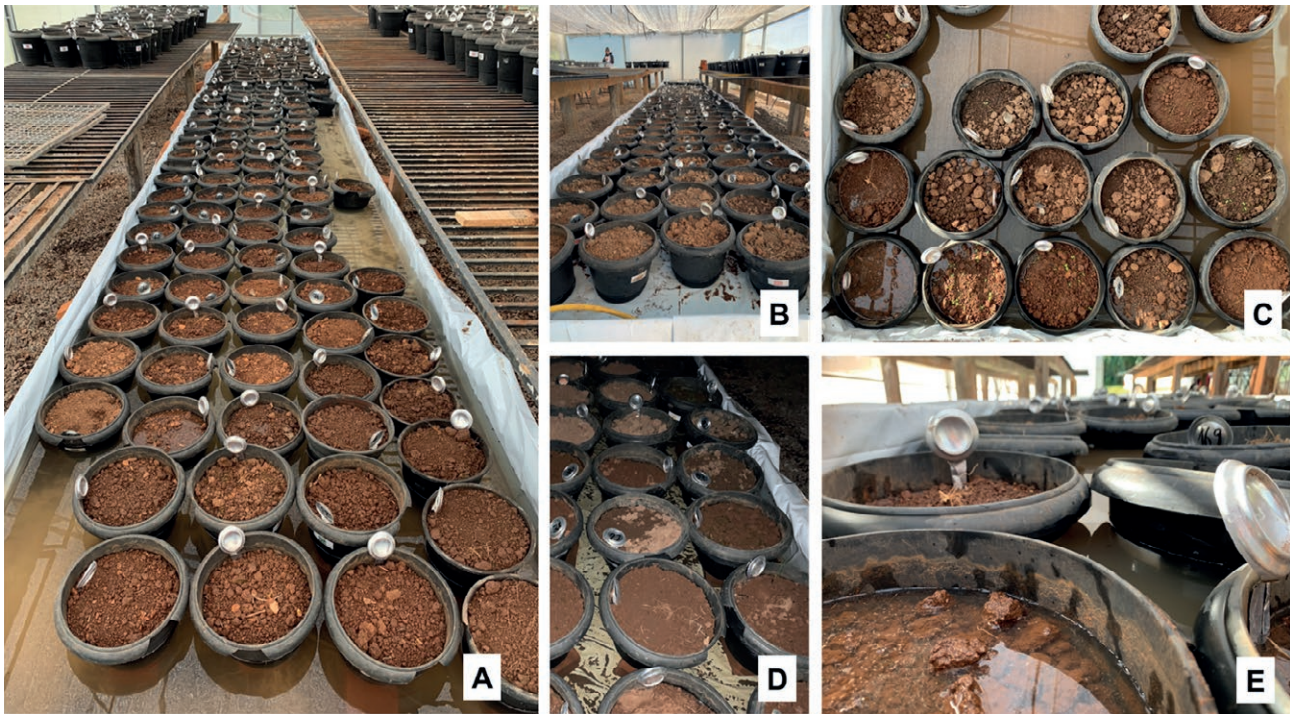


Figure 4. (A) Pots containing field soils in the tank for saturation by capillarity. (B) 25% water in the tank on the first day of soil saturation. (C) 50% water in the tank on the third day of saturation. (D) 75% water in the tank on the fifth day of saturation. (E) 100% water in the tank on the seventh day of soil saturation.

tank, and excess water was drained until gravitational flow ceased or became negligible. This condition soil moisture at this stage was assumed as maximum (100% soil WHC), equivalent to the soil moisture content at field capacity (pot capacity in the experimental context). This was confirmed by previously measuring the gravimetric water content of each field soil, and for both experiments, using porous plate funnels at -10 kPa tension. The results obtained with this approach were similar to the values of the gravimetric water obtained after the soil saturation period by capillarity, and subsequent drainage of the excess water (Supplementary Table S3). Soil saturation by capillarity was considered an effective approach to prepare sufficient pot capacity homogeneous wetting of the soils.

The pots containing the drained soil were then weighed, to determine the amount of water that correspond to 100% of soil WHC (Equation 1):

$$WHC = (PM_{pc} - PM_{ds}) \quad (1)$$

where *WHC* is the amount of water at 100% holding capacity, PM_{pc} is the mass of the pot plus the mass of soil at pot capacity, and PM_{ds} is the mass of the pot plus the dry soil mass.

After 10 d, the pots were again submerged in the water tank, where they remained for further 7 d before being weighed again to confirm their maximum (100%) WHC values. Care was taken not to mix the pots containing soil collected from within or outside the RRR field patches, so that cross-contamination was avoided between the two soil sample types. This determined WHC values for pots of soils from outside the RRR patches, and separately for pots of soil from inside the patches. Each soil type was saturated separately, followed by drainage and cleaning of the saturation tank, water replacement, and subsequent soil saturation (Figure 4).

Greenhouse cultivation of soybean

Soybean cultivation was carried out in a greenhouse (390 m^2) with controlled temperature (22 to 28°C daytime, 18 to 21°C at night). Soybean seeds were treated with the Apron RFC fungicide (fludioxonil 25 g L^{-1} + metalaxyl-M, 37.5 g L^{-1}) at 200 mL 10 kg^{-1}. Seeds were inoculated with *Bradyrhizobium elkanii* (strain SEMIA 5019) and *Bradyrhizobium japonicum* (strain SEMIA 5079) using the inoculant Masterfix® (5×10^9 cfu mL^{-1}).

Ten seeds were sown per pot at 5 cm depth. Fifteen days after emergence, resulting seedlings were thinned to two plants per pot. YaraTera™ Kristalon fertilizer (6% N, 12% P, 36% K, 1.8% Mg, 8% S) was applied weekly to the pots, commencing when seedling unifoliate leaves were fully developed, and continuing until the beginning of plant physiological maturity, when each plant had at least one mature pod (growth stage R7) (Fehr and Caviness, 1977; Ritchie *et al*., 1977). Fertilization was applied through fertigation (4 g L^{-1}), at 150 mL pot^{-1} $week^{-1}$. Applications of fungicides, insecticides and acaricides (Supplementary Table S4) were carried out as required to control foliar diseases and insect pests.

Maintenance of soil moisture

Throughout the soybean growth cycle, the pots were weighed and the lost water was replenished to maintain soil moisture level treatments at 50%, 65%, 80%, or 95% of the WHC. During vegetative plant growth, the pots were weighed, then watered, three times per week, and during the reproductive stage they were weighed, then watered every 2 d. The soil moisture level treatments required different amounts of water to be applied throughout the crop cycle (Supplementary Figure S1).

Disease assessments

A preliminary experiment was conducted prior to the main experiment to confirm inoculum viability following the 120 d soil drying period. Pots with soil were rehydrated and soybean plants were grown for approx. 25 d after emergence under conditions similar to those of the main experiment, to allow symptom expression. This preliminary assessment was used to verify presence and viability of *R. solani* in the soil, based on the observation of typical damping-off and root rot symptoms. Symptomatic plants were sampled at the collar region, and subsequent isolations and plating confirmed presence of viable *R. solani*.

At weekly intervals, soybean plants were assessed for RRR incidence by visual analysis of the symptoms on the two soybean plants per pot. The assessments were for visual disease symptoms of brownish-purple discolourations at stem bases, wilting, or plant death (Figure 5). In addition, the period (days) until plant death was recorded. Data obtained from the two plants in each pot were averaged for statistical analyses.

At 90 d after soybean plant emergence, severity of RRR was evaluated based on a five point scale (Figure 6), where: 0 = no symptoms; 1 = slight symptoms at the stem base up to 1 cm; 2 = mild symptoms at the collar region; 3 =well-developed symptoms at the collar; or 4 = well-developed symptoms extending beyond the first node on the plant stem. This severity scale was adapted from Goulart (2018). Data from the two plants in each pot were averaged for statistical analyses, as described above for the disease incidence assessments.

After assessments of yield components at the end of the experiment, both soybean plants from each pot were collected and carefully washed under running water to remove soil particles from the roots and collar regions. The plants were then air-dried on a laboratory bench at room temperature. From the full experimental design (five soil types × four moisture levels × two sampling locations relative to field Rhizoctonia root rot patches [inside or outside] × four replicates × two experiments), a total of 640 plants were sampled for pathogen isolations. The plants were each washed with neutral detergent and tap water, and a stem fragment (approx. 1 cm) excised from the collar region of each plant (where Rhizoctonia root rot symptoms are expressed), at the interface

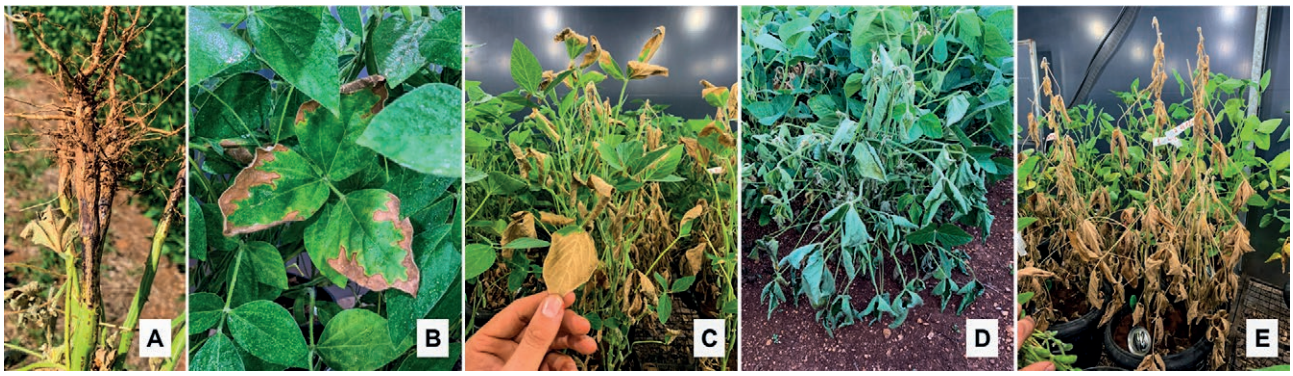


Figure 5. Symptoms of Rhizoctonia root rot in soybean. (A) Brownish-purple discolouration at a stem base. (B) Leaf edge scorch. (C) Leaf necrosis. (D) Wilting plant with leaf blade collapse. (E) Plant death with leaves remaining attached to petioles.

Figure 6. Disease severity scale (see text) used for assessing severity of Rhizoctonia root rot in soybean plants.

between symptomatic and apparently healthy tissues. The stem fragments were surface-disinfested in a 1% sodium hypochlorite solution for 1 min, followed by two rinses in sterile distilled water, and after drying for 30 min on sterile paper towels, they were placed into Petri plates containing potato sucrose agar (200 g L^{-1} potato; 20 g L^{-1} sucrose; 0.2 g L^{-1} streptomycin sulfate; 12 g L^{-1} agar). The plates were then incubated in a growth chamber at 25°C and with a 12 h light, 12 h dark for 5 d, and fungal identifications were carried out based on the morphological characteristics of mycelium growth originating from each stem fragment. Results were expressed as percentage of isolations. The anastomosis group of one *R. solani* isolate per field was determined according to Carling (1996).

Evaluations of plant growth and grain yield components

After physiological maturity, the soybean plants were removed from the pots and plant growth and grain yield components were measured. These included shoot height and first fertile node height (both measured from the plant collar), total number of nodes, number of fertile nodes, number of pods, number of grains per pod, and grain dry weight, evaluated after drying at 65°C (Balbinotti *et al*., 2022). Plants that died prematurely due to RRR were harvested 10 d after senescence for assessment of these yield components.

Statistical analyses

Normal distributions of data residuals were assessed using the Shapiro-Wilk test at $P \leq 0.05$, and outliers were checked using box-plots and histogram. Data were then analyzed using generalized linear mixed models (GLMM), in which the following fixed factors were tested: Experiment (1 or 2), soil type, RRR occurrence inside or outside the field patch, moisture, interactions between these factors, and block nested within experiment (as a random effect). Due to absence of RRR in pots containing soil from outside the field disease patches, only data from pots of inside patch soils were considered for disease severity analyses. Data of number of days until death of soybean plants, and soybean yield components were analyzed using GLMM, assuming Poisson distributions. Disease severity data were analyzed using cumulative link mixed models (CLMM). Mean separation analyses of qualitative factors (experiment, soil type, patch or non-patch soil, and their interactions) were carried out using Tukey's test at $P \leq 0.05$. Regression analyses were carried out to compare RRR severity and soil moisture, in which the choice of the mathematical model (first- or second-degree polynomial) was based on model significance ($P \leq 0.10$) and the greatest coefficient of determination (R^2).

All statistical analyses were carried out using RStudio software version 2022.07.0 (R Core Team., 2022). For linear mixed model analysis, the package '*lme4*' (Bates *et al*.,

2024) was used; for GLMM analysis, the packages *'lme4'* and *'glmmTMB'* (Brooks *et al*., 2024) were employed; for CLMM analysis, the package *'clmm'* (Christensen, 2024) was used. Adjusted means were obtained using the *'lsmeans'* package (Lenth, 2018), while Tukey's test was applied with the aid of the *'multcomp'* package (Hothorn *et al*., 2024). Regression and box-plot graphs were created using the *'ggplot2'* package (Wickham *et al*., 2024).

An unprecedented method was developed to evaluate, under controlled conditions, interactions effects between soil types and moisture levels on the severity of RRR in the soybean plants. This approach allowed integration of edaphic and water factors within the same design, accurately simulating the conditions that favour disease establishment in the field.

RESULTS

Disease severity

Analysis of variance indicated significant effects ($P \leq 0.005$) of soil moisture and soil types, as well as for the interaction between these two factors and the experiments (E × S × M), for RRR severity (Supplementary Table S5). This interaction indicated that the level of disease varied across the experiments, the soil types, and soil moisture. As illustrated on Figures 7, 8, and 9, RRR severity was strongly affected by soil moisture, and decreased linearly as soil moisture increased in both experiments and for all the field soils.

When comparing Experiment 1 and Experiment 2, at each tested soil moisture level, only two statistically significant differences for severity were observed (Figure 7). In the Cambisol Tb, at the greatest soil moisture (95% of WHC), RRR was less in Experiment 2 than in Experiment 1. The other difference between the experiments was observed in Cambisol Ta at the 65% of WHC, where severity was greater in Experiment 1 than in Experiment 2.

The relationship between RRR severity and soil moisture was negative and linearly correlated with high coefficients of determination ($R^2 > 0.70$) across soils and experiments, except for plants growing in Leptosol in Experiment 2. For these, the correlation coefficient was moderate ($R^2 = 0.62$; Figure 7). In this soil and experiment, the estimated effect of soil moisture on disease severity was less than in the Cambisols and in Acrisol, as indicated by the low slope coefficient (-0.03) for the linear equation, which was half that for the Cambisols and Acrisol (-0.06) (Figure 7).

In both experiments, at ≥ 80% of WHC, lesser (Severity ≤ 1) or mild RRR symptoms (Severity ≤ 2) were observed for all the soil types, except in the Cambisol Tb. In this soil, however, the symptoms were closer to those considered for mild severity. Furthermore, in Experiment 2, The mean RRR severity score in Cambisol Tb, at 95% WHC, was approx. 1 (Figure 8). Then, at ≥ 80% WHC, the soil moisture effect was a more dominant factor than soil type. This also occurred at 50% WHC, in both experiments, where RRR symptoms were well-developed (mean severity scores ≥ 3), and no statistically significant differences among soil types were observed (Figure 8). The results showed that increasing soil moisture from 50% to 95% of WHC reduced mean disease severity score from 3.3 to 1.3, representing an approx. 60% reduction in RRR severity (Supplementary Table S6).

In Experiment 1, at 65% WHC, the Tukey's test indicated that mean severity was less in Leptosol than in Acrisol, and did not vary among these two soils, nor in the other three soil types (Figure 8). These results from Experiment 1 were similar to the mean severity scores, which were based on a scale of symptoms used to assess soybean stem lesions. In Experiment 2, the soil types had no effect on disease severity evaluated at all four soil moistures. This was similar in Experiment 1 for the 50 and 95% WHC treatments. Also in Experiment 1, at 80% WHC, mean severity was less in Nitisol than in the Cambisol Tb, and did not vary ($P > 0.05$) among these soils, nor between the other three soil types.

Plant growth and grain yield components

Beside the three-way soil moisture × soil types × experiment interaction effect on RRR severity, soil moisture alone affected most of the soybean plant growth parameters and all assessed yield components (Supplementary Table S5). In addition, the soil moisture × field patch type interaction also influenced ($P \leq 0.05$) numbers of days until plant death, and grain weight (Supplementary Table S5).

There was a linear increase in the yield components as soil moisture increased. Mean number of fertile nodes increased from 11, at 50% WHC, to 13, at 95% WHC (Figure 10 A), and mean number of pods was 28.4 at 50% WHC and 35.2 at 95% WHC (Figure 10 B). Both of these variables reflected the increased number of plant nodes observed for pots containing field soil from both inside and outside the field disease patches as a function of greater soil water content (Figure 11 A).

Means of numbers of grains (Figure 10 C) and grain weights (Figure 11 B) also increased as the soil moisture increased, reinforcing the importance of water availability during grain development. Mean numbers of grains varied were 54.7, at 50% WHC, and 79.2, at 95% WHC (Figure 10 C). Increased soil moisture also increased

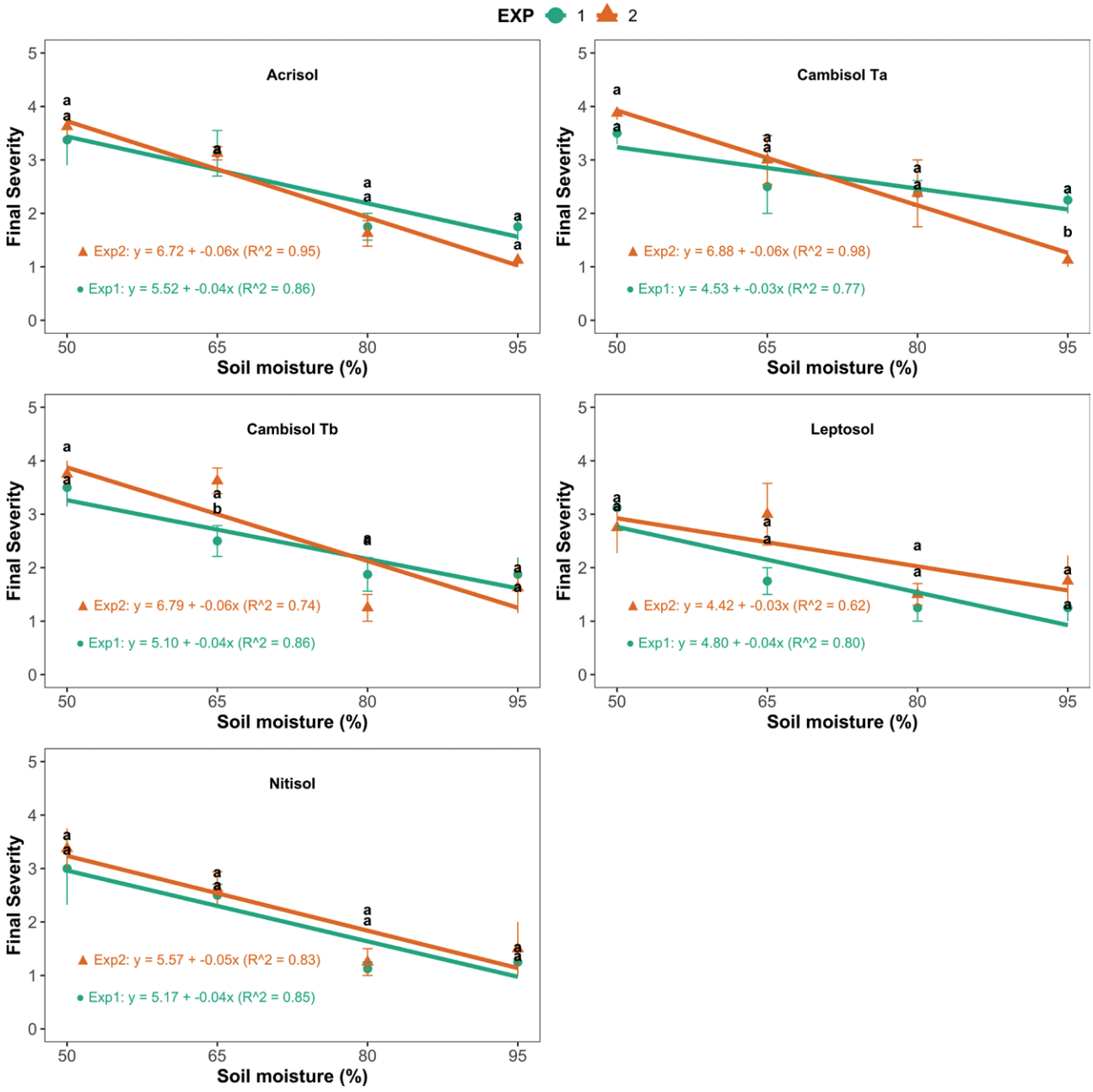


Figure 7. Mean final Rhizoctonia root rot severity scores for soybean plants grown in pots containing five different field soils, as affected by different soil moisture regimes (% of water holding capacity) and in two Experiments (Experiments 1 and 2). Means accompanied by the same letters are not different (Tukey's HSD test; $P \leq 0.05$). Comparisons were made separately by soil moisture content for Experiment 1 against Experiment 2. Error bars indicate standard errors of the means. $R^{\wedge 2}$ values are coefficients of determination for the regression equations.

mean grain weights from plants in field soil collected inside RRR patches (3.2 to 8.6 g plant^{-1}) to from 7.8 to 10.6 g plant^{-1} for outside patch soil (Figure 11 B; Supplementary Table S6). The greatest mean numbers of fertile plant nodes (14.8), pods (36.8), and grains (81.0) were measured at 80% WHC (Figure 10).

Soybean plants grown in pots containing soils collected from inside field RRR patches and maintained at the lowest soil moisture content had greater RRR incidence and earlier dates of death than plants grown at greater soil moisture levels (Figures 12 and 13). This effect was not detected, however, for plants grown in soil

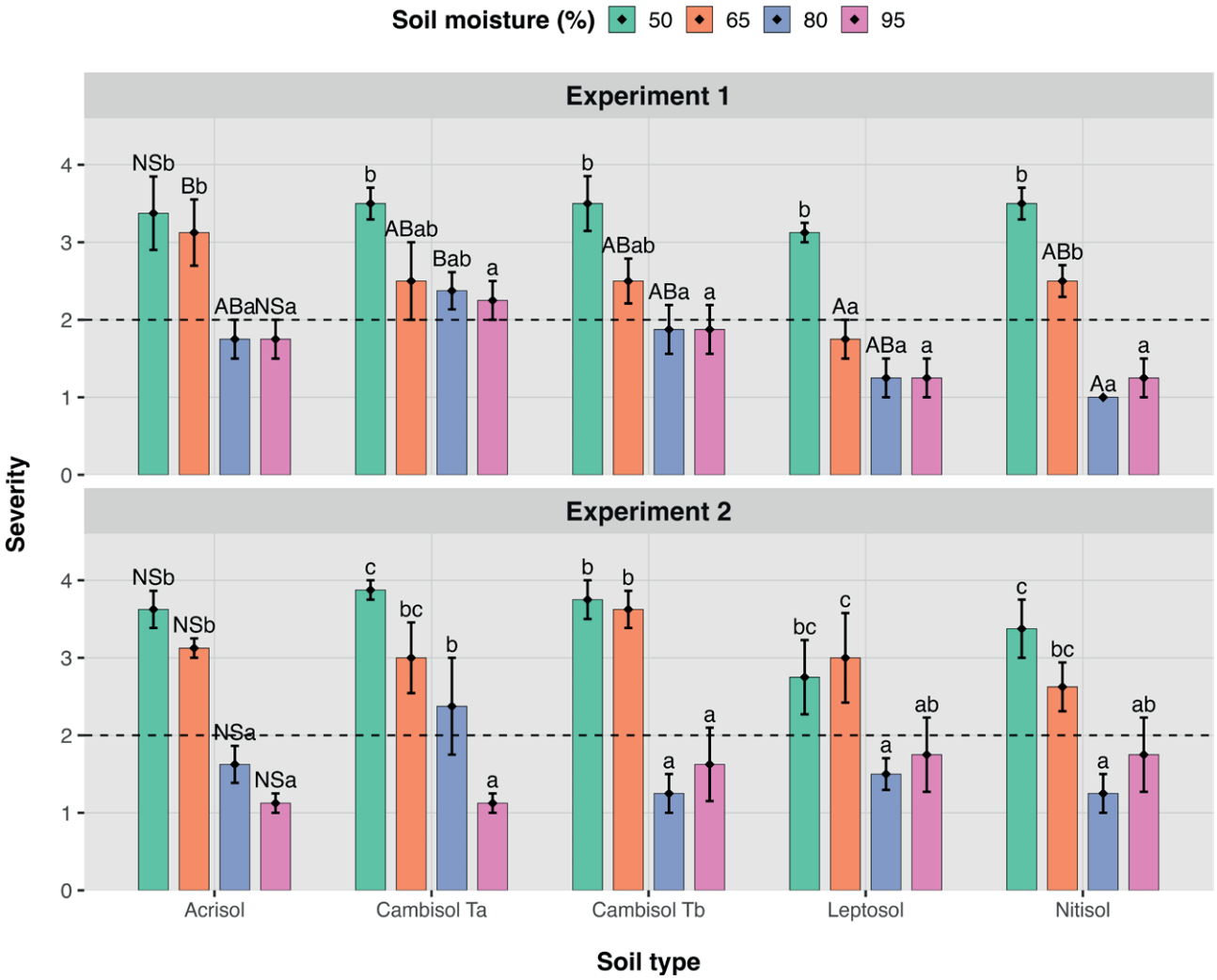


Figure 8. Mean Rhizoctonia root rot severity scores (in two Experiments, 1 and 2) for soybean plants grown in pots containing five different field soils, which were maintained at four different soil moisture proportions (50, 65, 80 or 95% water holding capacity). Different capital letters accompanying means indicate statistical significance for mean differences between the five soil types within each soil moisture, and lower case letters indicate differences for soil moistures within each soil type. Different letters indicate significant differences, and NS indicates no significant differences (Tukey's HSD tests, P ≤ 0.05). Bars accompanying each mean are their standard errors.

collected from outside the field RRR patches. For example, plants cultivated in soil from inside RRR patches and treated at 50% WHC, died after a mean period of 81 d, while plants in outside patch soil at 50% WHC reached physiological maturity at a mean of 133 d (Figures 12 and 13). Furthermore, at all four moisture levels, the mean period to plant death was greatest outside patch soil than inside patch soil (Figure 13).

The field patch and soil moisture factors both affected mean numbers of fertile nodes (FN), mean numbers of pods (NP), and mean numbers of grains (NG) on the soybean plants (Supplementary Table S5). The combined effects of patch and soil moisture also affected the means of period (number of days until plant death; PPD), total number of plant nodes, and grain weights (Supplementary Table S5). The interactions for experiment × soil type × moisture also affected mean RRR severities (SEV). No differences ($P > 0.05$) were detected for variables across the other assessed combined treatment effects (Supplementary Table S5).

Results from samples taken from inside or outside field RRR patches when analyzed as a one-way factor, showed that the soybean plant yield components were greater in plants in soils taken from outside the disease patches than inside the patches. Outside patch soil gave plants with greater numbers fertile nodes (Figure 14 A),

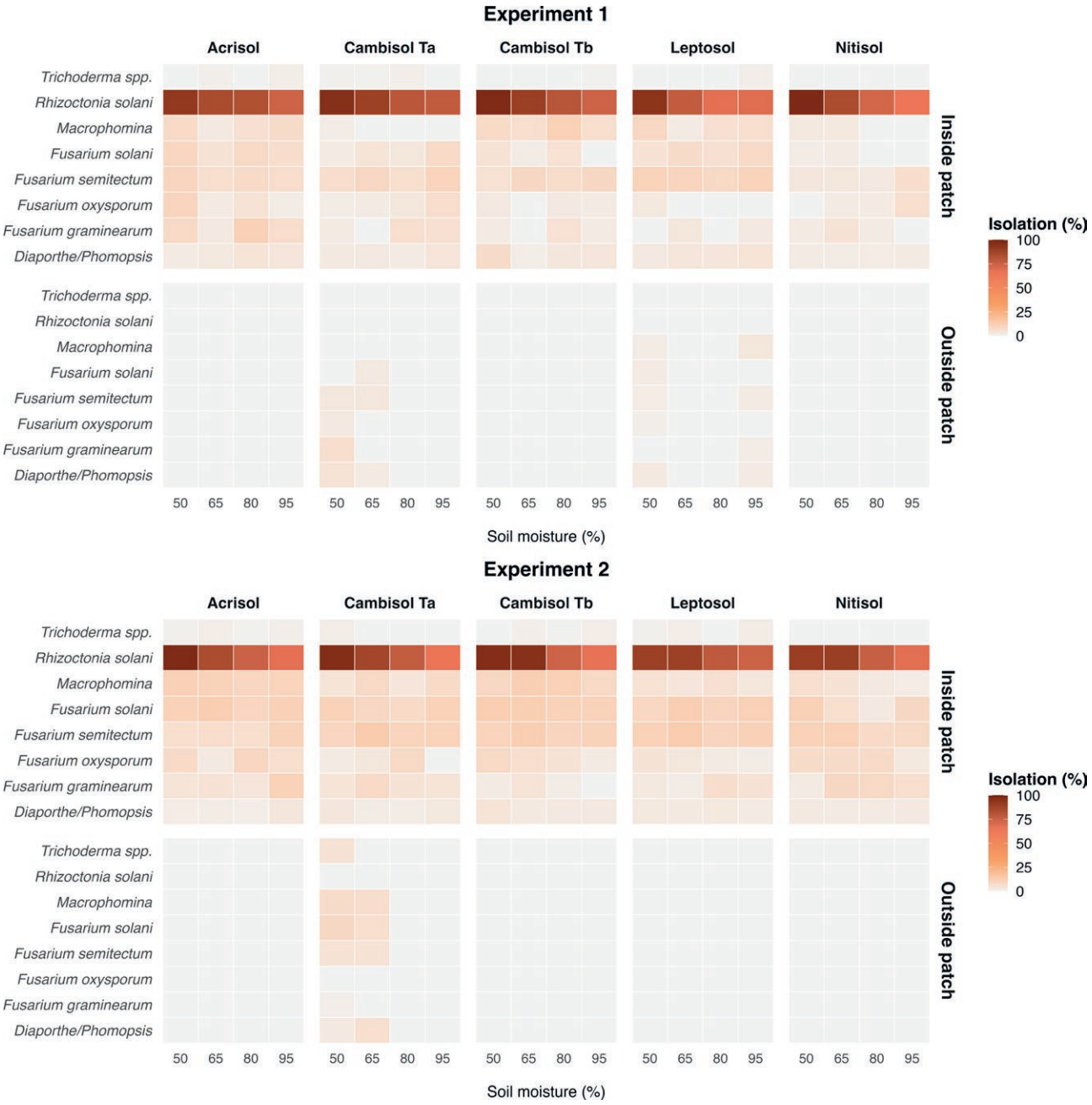


Figure 9. Heatmaps illustrating variations in Rhizoctonia solani and other species of pathogenic fungi isolated from stem collar fragments collected from soybean plants grown in pots containing five different field soils that were maintained at 50, 65, 80 or 95% water holding capacity. Results for field soils collected from either inside or outside Rhizoctonia patches, and results from two greenhouse experiments (Experiments 1 and 2) are illustrated separately.

greater numbers of pods (Figure 14 B), and greater numbers of grains (Figure 14 C), than plants in inside patch soils. Plants in outside patch soil had approx. 14 fertile nodes compared to 11 in inside patch soil (Figure 14 A). Numbers of pods were greater for plants in outside patch soil (mean = 38 pods), compared to plants in within path soil (mean = 27) (Figure 14B). numbers of grains for plants in outside patch soil were greater (mean = 81) than for plant in soil from inside patches (mean = 58; Figure 14C).

In contrast to grain yield components, no statistically significant effects ($P > 0.05$) of the soil moisture

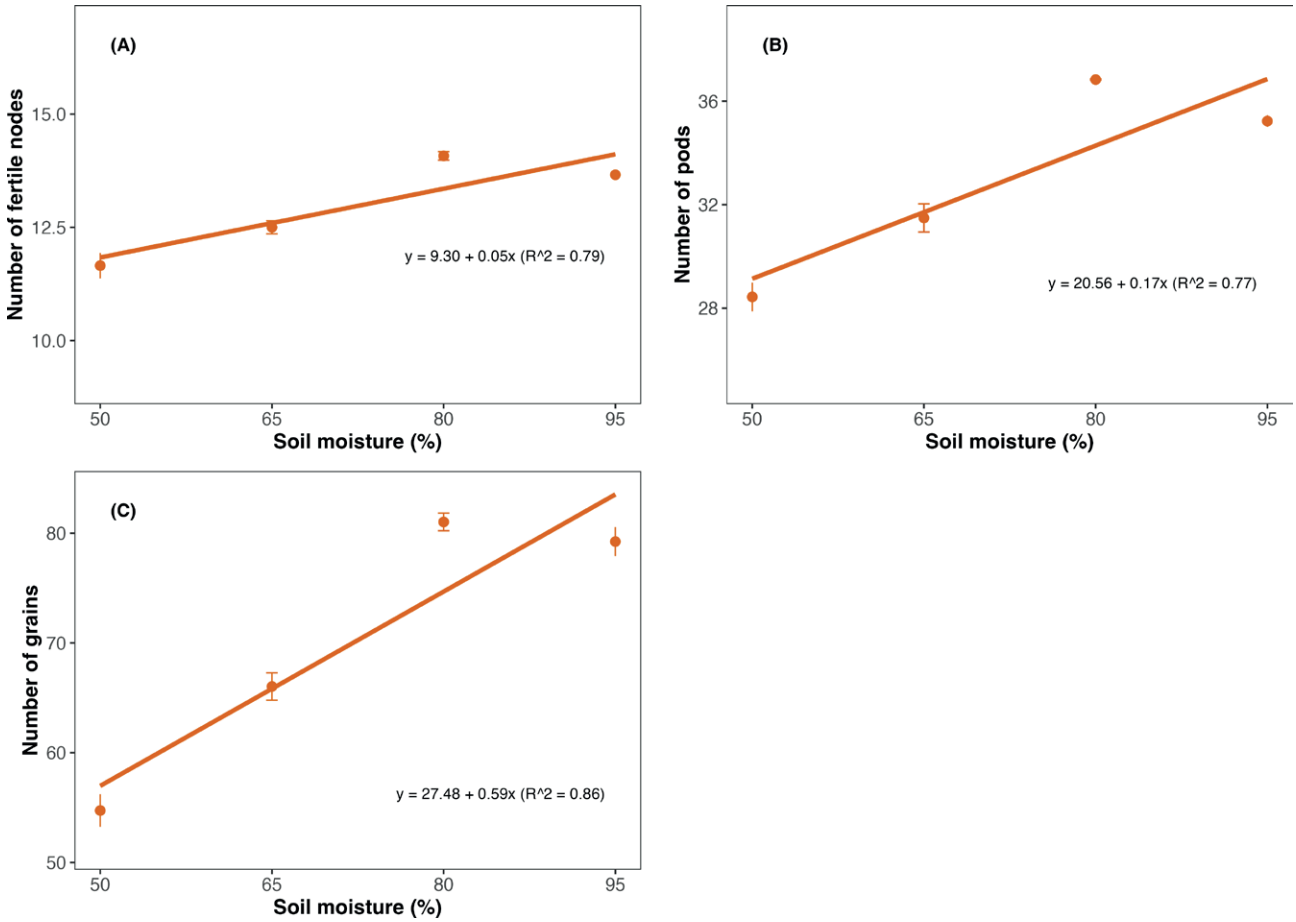


Figure 10. Mean numbers of fertile nodes (A), pods (B), and grains (c) on soybean plants grown in pots containing field soils maintained at four levels of soil moisture (% of water hold capacity). The means are averages from two experiments and the five soil types assessed in this study. Error bars indicate standard errors of means.

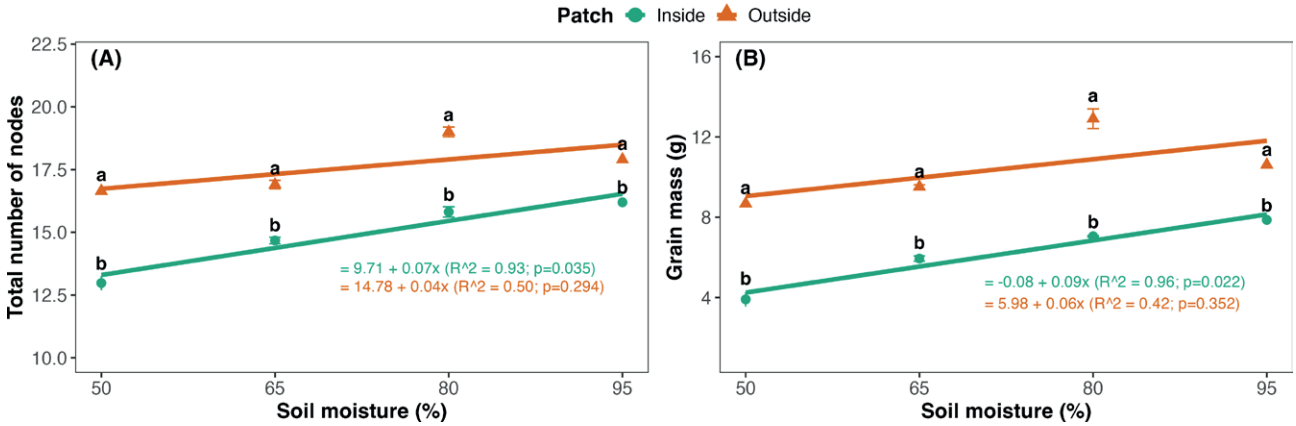


Figure 11. Mean numbers of nodes (A), and mean grain weights (B), for soybean plants grown in pots containing field soils from inside or outside RRR patches. Means accompanied by different letters are different ($P \leq 0.05$), as indicated by Tukey's HSD tests.

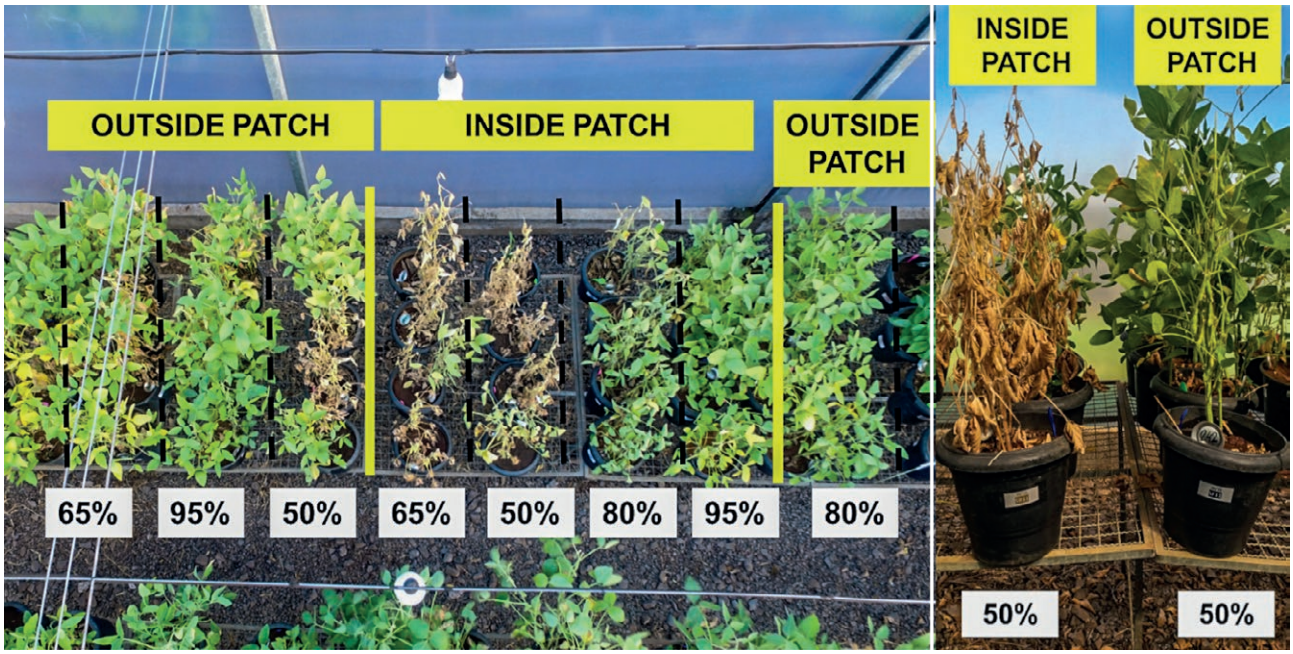


Figure 12. Soybean plants growing in pots containing field soils from outside or inside Rhizoctonia root rot patches, and maintained at four water holding capacities (50, 65, 80, or 95% WHC).

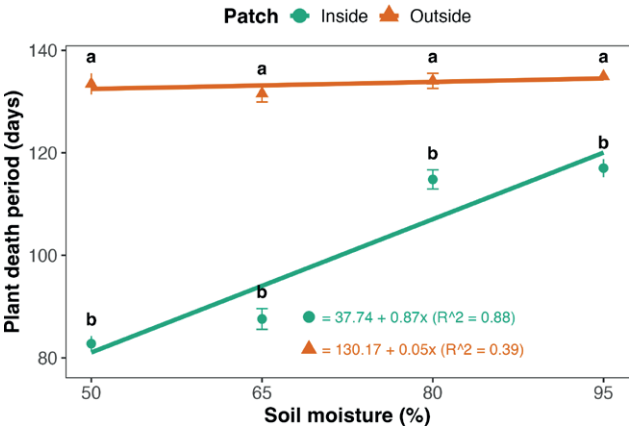


Figure 13. Mean time (days) to soybean plant death, for plants grown in pots containing field soils collected from inside or outside RRR patches and maintained at four water holding capacities (50, 65, 80, or 95% WHC). Letters accompanying means indicate differences ($P \leq 0.05$) between Inside and Outside patch soils at each moisture level (Tukey's HSD test). Error bars indicate standard errors of the means. Respective regression equations, and their coefficients of determination (R^2) are included in the Figure.

treatments were detected for the plant growth variables that were assessed (Supplementary Table S5). Analyses of variance also showed that there were no differences ($P > 0.05$) for the two grain yield components for all tested factors and their interactions, suggesting a low direct effect RRR on soybean plant architecture (Figure 15).

Soybean grain yield components were also affected by the field soil type in which they were grown, as shown by significant effects ($P \leq 0.05$) of field soil type on means of per plant number of nodes, number of grains, and grain weight (Supplementary Table S5). Plants in Acrisol and Nitisol had greater numbers of nodes compared to plants in Cambisols and Leptosol (Figure 16A). Plants cultivated in Acrisol and Cambisol Tb, however, produced the greatest numbers (Figure 16 B) and weights of grains (Figure 16 C) per plant. The least grain weights per plant were observed in Leptosol (Figure 16 C), and one of the lowest number of grains were produced from this soil (Figure 16 B). The low number of total nodes and grains for plants cultivated in Leptosol contributed for the lowest grain weight for plants in this soil. Furthermore, the highest total number of nodes of plants cultivated on Nitisol aligned with the lowest number of grains from this soil. Consequently, the grain weight per plant from Nitisol was greater than from plants in Leptosol, but was less than for plants in Acrisol or Cambisol Tb (Figure 16).

General response of disease severity and yield components

The descriptive statistical analysis of the variables related to RRR severity and soybean yield components

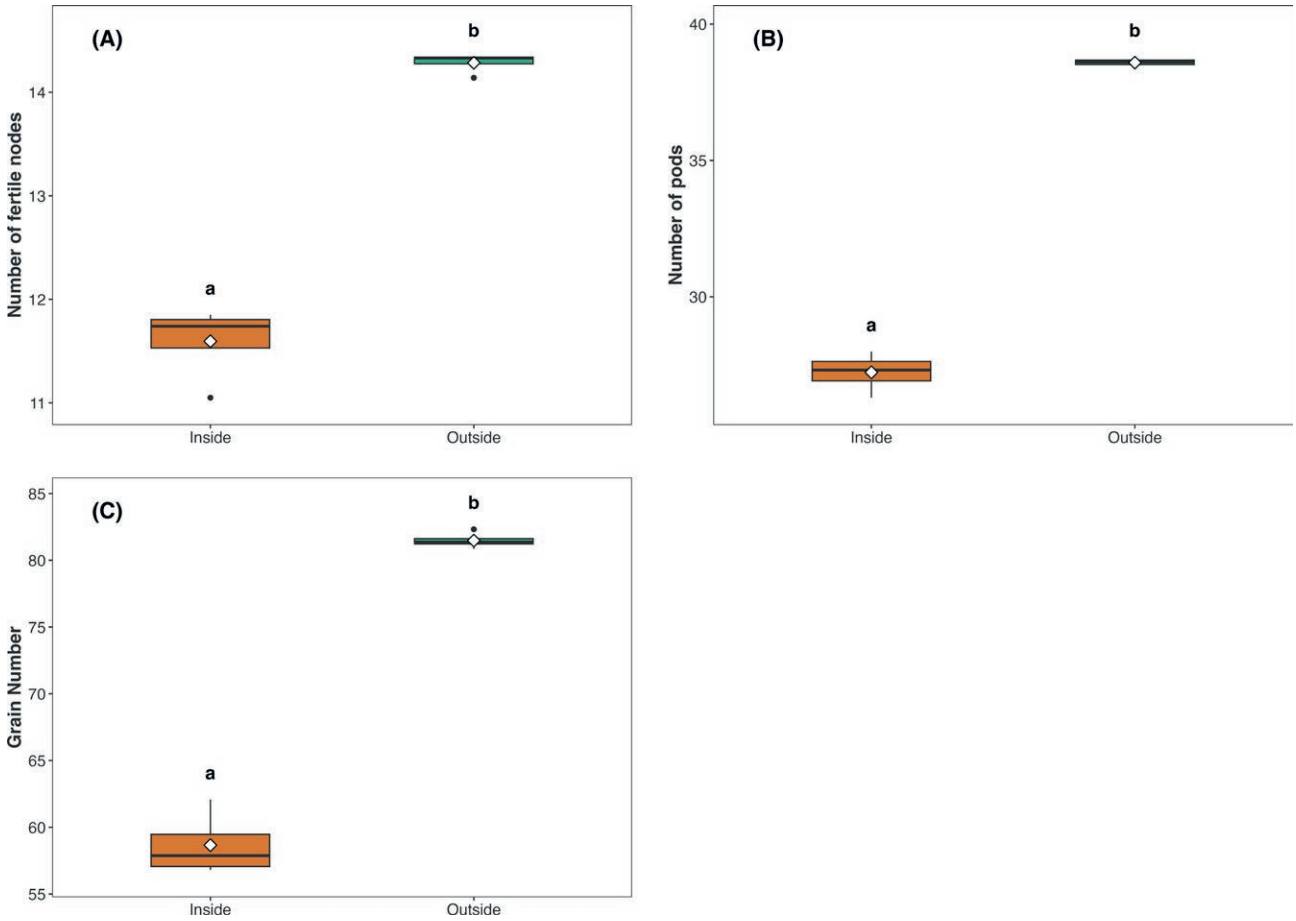


Figure 14. Mean numbers of fertile nodes (A), pods (B), or grains (C), from soybean plants grown in pots containing soil collected from Inside or Outside field Rhizoctonia root rot patches. For each median (horizontal line), the box represents data variation, and the small diamond symbol is the mean. Different letters (a or b) indicate treatment differences (Inside or Outside patch soils) ($P \leq 0.05$), as shown by Tukey's test.

evaluated in different soil types and different soil moisture levels (Supplementary Table S6), showed that the mean disease severity was 1.18, corresponding mostly to initial symptoms restricted to the stem bases. However, the high variability observed (CV = 118%) indicated that, although many plants remained symptomless or showed only mild lesions, a considerable portion developed severity scores of 3 or 4, characterizing severe RRR. This contrast highlights the typical field patch pattern for the disease, in which most plants exhibit low disease intensities, while some are severely affected (Fenille *et al*., 2002).

In contrast, the measured vegetative growth parameters (plant height, number of nodes), were more stable, indicating low direct impacts of the RRR on soybean plant architecture. However, the yield components, especially grain mass, were affected by the disease. This reinforces that RRR severely affects soybean reproductive growth stages (Balbinotti *et al*., 2025). During these stages root rots reach greatest intensity at the onset of flowering and during grain filling, increasing yield losses even when host vegetative development is maintained (Balbinotti *et al*., 2022).

DISCUSSION

Soil moisture effects on disease severity

This study has provided the first analyses, in subtropical environments, of interactive effects of soil moisture and soil types in development of root rot of soybean plants caused by *R. solani*. Among these edaphic factors, the results showed that soil moisture had considerable influence on RRR severity, plant growth and grain yields. Overall, the disease was more severe in the low

Figure 15. Soybean plants showing the progression of Rhizoctonia root rot along their phenological cycles. (A to E) Early vegetative stages with vigorous plants, no symptoms or initial symptoms at the stem bases. (F to H) Intermediate growth stages with the onset of disease and visible lesions at the plant collars. (I and J) Advanced reproductive stage where the disease manifested severely, with dead plants or intense leaf blight symptoms (I and J).

moisture soils (≤ 65% WHC) than in the wet soils (80 to 95% WHC). This was also evident in previous studies, which have reported soil moisture effects on Rhizoctonia root rot of wheat (Gill *et al*., 2000; 2001a; 2001b) and oats (Hynes, 1937), as well as for disease caused by *Fusarium graminearum* in soybean (Cruz *et al*., 2020). *Macrophomina phaseolina*, under high temperatures and low soil moisture, also caused yield losses in crops of soybean, sorghum and groundnut (Marquez *et al*., 2021). In the present study soybean plants were grown in temperatures of 22 to 28°C during the day, and 18 to 21°C at night, which favour *R. solani* disease severity when plants are cultivated at high soil moisture (Gill *et al*., 2001a; Cruz *et al*., 2020). High soil moisture condition probably affects fungus growth, because of prevailing low extent of air-filled pore space, or from competition from soil microorganisms, which may be associated with pathogen suppression through competition (Gill *et al*., 2001b). Compacted, poorly drained, or very moist soils provide conditions that favour *R. solani* proliferation (Höper and Alabouvette, 1996; Dixon and Tilston, 2010), and decrease host plant defense capacity by reducing oxygen availability (Stamford *et al*., 2005; Ghorbani *et al*., 2008).

Soil moisture effects on soybean plant growth and yield components

Soil moisture favours plant growth and grain yield, as shown in the present study by effects of this edaphic factor on numbers of soybean fertile nodes, pods and grains (Figure 10), and on total number of nodes and on grain weights (Figure 11), for plants growing in soils from inside, as well as outside, of *R. solani* root rot patches. High soil water availability reduced disease severity, prolonged plant growth duration, and increased the main soybean yield components. This response confirms that maintaining adequate soil moisture helps to mitigate the effects of Rhizoctonia root rot, and enhances the physiological and productive performance of soybean plants.

During this study, it was observed that control of soil moisture levels at sowing was important for the initial development of RRR. High moisture levels immediately after sowing favored the germination of *R. solani* microsclerotia and the initial infection by the pathogen into soybean plants. This showed that, even under water deficit conditions, infection by the pathogen can occur, and that subsequent water stress intensified disease effects throughout the host plant growth cycle. Monitoring fields of soybean crops, in years of water deficit (drought), present authors have commonly observed Rhizoctonia patches in soybean fields, whereas in years with normal or high rainfall, these patches have not been evident. This pattern was observed and quantified in the present study experiments: at 50% soil WHC, water-holding capacity and at 24 h after rehydration, soybean plants showed wilting, leading to increased disease severity with plant leaf blades and main stems

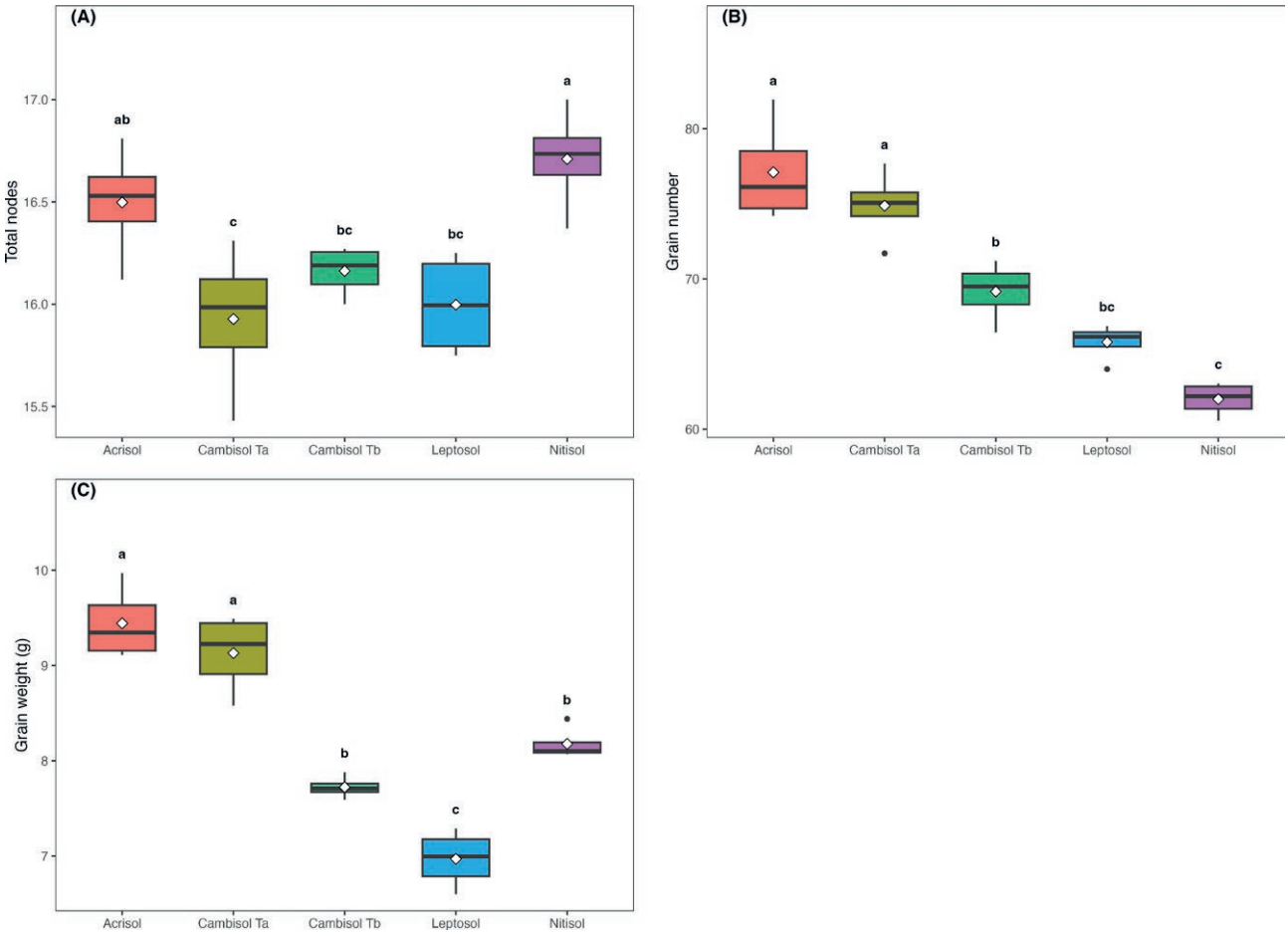


Figure 16. (A) Means of numbers of nodes per soybean plant, (B) numbers of grains per plant, or (C) and grain weights, averaged across two experiments (Experiment 1 and 2) and four different soil moisture contents, for soybean plants grown in pots containing five different soils. Boxes each represent the interquartile range, the central line is the median value, and the white diamond indicates the mean. Different letters accompanying the means indicate significant differences among the five soils (Tukey's test; $P \leq 0.05$).

wilting and collapsing. When water was replenished to restore the soil moisture content to 50% WHC, the plants rehydrated, regained turgor, and resumed growth. The leaf blades returned to normal form and recovered green colour, although necrotic lesions caused by RRR remained visible.

Lechner (2008) demonstrated that plant regrowth and recovery of turgor after rehydration of leaves that had apparently reached their final size can be widespread among dicotyledonous plants. In *Arabidopsis thaliana* and *Helianthus annuus*, rehydration increased by up to 186% and leaf area increased by 88%, compared to plants maintained under water deficit, effects that were attributed to cell expansion. Soybean regrowth observed in the present study probably represented reversible change in turgor, rather than leaf growth. These results emphasize that soybean plants, even when infected by *R. solani*, maintain their capacity for leaf expansion and recovery under conditions of replenished water availability, explaining the lower disease severities that were observed at high soil moisture levels.

When soil is wet, plant roots can still translocate water and photosynthates, allowing plants to remain alive (Taiz and Zeiger, 2006). This explains why disease severity was less at 95% water holding capacity. Despite root infection by the pathogen, water availability around roots favours absorption, since close contact between root surfaces and soil is essential for maximum water uptake, enhanced by root growth and root hair development. This ensures water translocation to vascular tissues, enabling plant survival even under disease pressure (Taiz and Zeiger, 2013). This behaviour was also consistent with field observations, where RRR patches were more visible in dry years, and were almost absent

in years with high rainfall. These observations reinforce the hypothesis that although water availability affects pathogens, it is probably also important for plant tolerance to soilborne disease. Plant susceptibility is not fixed but results from the activation of physiological responses modulated by pathogens (*R. solani* in the present case). Under water deficit, these responses are intensified, increasing oxidative stress and hormone imbalances, which favour disease progression. Under high water availability, the lower induction of these responses reduces the pathogen's advantage, and promotes activation of plant tolerance mechanisms (Gorshkov and Tsers, 2021). Even when infected, soybean plants can extend their life cycles in environments with high moisture. This result is consistent with studies that relate maintenance of turgor to delays in expression of severe disease symptoms (Datta *et al*., 2022; Nasimi *et al*., 2024). The present study results showed increased periods until plant death for the wet soil treatments, demonstrating that water availability reduced soybean stress and delayed death caused by *R. solani*. Water uptake occurs mainly in the youngest roots, near root apices, where root hairs maximize contact with soil solutions. Older roots, become less permeable due to the formation of exodermis tissues, and are the roots most attacked by the pathogens (Taiz and Zeiger, 2013; Liu and Kreszies, 2023). The exodermis of older roots is impregnated with suberin, which reduces their permeability, whereas younger roots remain active for water and nutrient absorption (Taiz and Zeiger, 2013).

Soybean yields increased linearly with increasing soil moisture, with major yield components showing increased numbers of fertile nodes, pods, and grains, and grain weight. Soybean plants with low disease severity under higher soil moisture conditions had increased biomass accumulation and, consequently, increased grain filling. This relationship between water availability and productivity is linked to critical stages of soybean development, especially at grain filling, which is highly dependent on water availability. Reduction of RRR severity under wet soil conditions is likely to help in maintaining high yield potential in soybean crops. Similar results have been observed in management systems under different climatic conditions, where high rainfall years resulted in greater plant biomass, numbers of pods, grain yields, compared with dry years (Toleikiene *et al*., 2021).

Differences in soybean plants in soil from inside or outside field RRR patches were also distinctive. For soil from inside patches, plants grown at 95% WHC had increased growth cycles and produced fuller pods than plants at lower soil moisture contents. In the outside patch soil, excessive water promoted greater vegetative growth than for inside patch soil, but reduced allocation to reproductive structures. These results also show that the interaction between *R. solani* and soil moisture availability is decisive. In areas with established inoculum (as for the inside patch soils) low moisture aggravated RRR and reduced yield potential. In pathogen- and infection-free areas, excess water compromised the balance between soybean growth and reproduction.

Soil effects

Moisture stress conditions that may favour development of root rots caused by *Rhizoctonia solani* can be modulated by soil physiochemical characteristics, since these influence water and nutrient availability for plants and microorganisms. Variability in soil type may alter disease severity in different ways. However, the present study results showed that, overall, soil type did not greatly influence on RRR severity. At higher (80 and 95%) and lower (50%) WHCs, soil moisture levels had greater effects on disease severity than soil type (Figure 9). In Experiment 1, at 65% WHC, RRR severity was less in Leptosol than in Acrisol, but there were no differences between these two soils and the other soil types. In Experiment 2, soil type did not affect RRR severity in all the four soil moisture treatments evaluated. The lower disease severity observed in Leptosol compared to Acrisol, and Nitisol compared to Cambisol Tb (in Experiment 1, at 80% WHC) may be due increased disease pressure from RRR in Acrisol and Cambisol, since disease in these soils was observed four years before than in Leptosol and Nitisol. In addition, soybean yields were greatest in the fields from which the Acrisol and Cambisol Tb soils were taken, as was also the case in the present study experiments (Figure 15). In field soybean crops, increased shoot biomass increases grain yields and also increases amounts of crop residues on soil surfaces. In no tillage soils, *R. solani* colonizes and overwinters on crop residues, providing sources of inoculum for subsequent crop growing seasons (Kurm *et al*., 2023). The increased severity of root diseases caused by this and other soilborne pathogenic fungi is associated with increased residue on the soil surface, lack of soil disturbance, and cooler, wetter soil conditions in the spring in no tillage soils with cereals crops in the Pacific Northwest of USA (Paulitz *et al.,* 2002). In this way, the *R. solani* growth index was especially high in presence of maize or *Medicago* litter which increased the probability of seed and seedling infection by this fungus in *Lactuca sativa* (Bonanomi *et al*., 2020). Furthermore, Höper and Alabouvette (1996),

and Dixon and Tilston (2010), reported that compacted and poorly drained soils are also conditions that favour proliferation of *R. solani*. These soil conditions decrease host plant defense capacity by reducing oxygen availability (Stamford *et al*., 2005; Ghorbani *et al*., 2008). In this way, the greater RRR severity observed in Cambisol Tb than for Nitisol, at 80% WHC, can be attributed to their drainage capacities, which was moderately drained for Cambisol Tb, but well drained for Nitisol (Supporting Table S1).

In the conditions of the present study, where most of the soils were acidic clays, soil moisture levels alone mostly accounted for severity of RRR, and effects of the different soil types on severity were secondary. In contrast, soil type influenced plant growth (total number of nodes) and yield (grain number and weight). Grain yields were probably limited by the acidic condition of these soils, because the most relevant soil chemical properties influencing N fixation in soybean plants are pH and aluminum saturation (Alves *et al*., 2021). The pHs in most of the present study soils was less than 5.0 and, consequently, aluminum saturation was in the toxicity range (> 10%). The exception was Cambisol Tb, where weak acidity was found (2.6 – 3.6%; Supporting Table S2). Soil acidity possibly limited the grain yields, even in the best scenario (outside RRR patch soil and the 95% WHC treatment) where grain yield was approx. 11 g plant^{-1} (average from both Experiments and all five soil types; Figure 11). Extrapolating to 300,000 plants ha^{-1}, this grain yield is equivalent to 3.3 t ha^{-1}; or approx. half of the yield from plants grown in soil samples collected from outside RRR patches. This indicates intermediate soybean grain yield from outside RRR patches, and low grain yield from inside the patches, although the plants assessed were grown in controlled glasshouse conditions.

Soil acidity possibly limited the effect of soil types on RRR severity by limiting plant growth, which can decrease plant defense mechanisms (Balbinotti *et al*., 2025). Lime application improved soybean grain yields for crops cultivated in acidic soils (Balbinotti *et al*., 2022). The present study results showed that the greatest grain yields were measured from Acrisol and Cambisol Tb, while in Cambisol Ta and in Nitisol the yield were intermediate, and yield was least in Leptosol (Figure 15C). Of the five soils, Cambisol Tb had lowest exchangeable and saturation aluminum, calcium, magnesium, base saturation, zinc, and sulphur, and the highest organic matter content and phosphorus availability (Supplementary Table S2), indicating that these soil chemical attributes may have favoured soybean plant growth and grain yield in Cambisol Tb.

Further considerations

The study has integrated edaphic, hydric, and pathogen history factors within one experimental design, aiming to elucidate the conditions that favour development of RRR patches in soybean crops during drought years. This research has integrated edaphic and hydric variables under controlled conditions, and has assessed effects of soil moisture and soil types on RRR severity and soybean yields. To date, only the studies by Balbinotti *et al*. (2022; 2023; 2025) have directly addressed these interactions, demonstrating the relevance of soil pH, calcium, and base saturation on dynamics of soybean disease caused by *R. solani*. However, reports from studies combining multiple soil types and different soil moisture levels within a single experimental framework are scarce in the literature. Therefore, the results presented here provide new knowledge to assist understanding edapho-climatic factors that influence the severity of Rhizoctonia root rot in soybean, cultivated on no tillage soils and in a subtropical environment. This study is a methodological and conceptual advance providing a knowledge base for future studies.

The results of this study have shown that water availability reduces severity of Rhizoctonia root rot, is likely to prolong soybean crop cycles, and improve yield components. Interactions between edaphic factors and presence of RRR patches create complex crop environments. Soil and water management strategies can guide practices that mitigate RRR impacts across different soil types. Combination of edaphic management with biological control agents and disease resistant soybean cultivars, alongside recent advances such as the use of CRISPR-based gene-editing tools, as well as inclusion of disease resistant host genotypes, will assist provision of effective and sustainable integrated strategies for managing RRR (Balbinotti *et al*., 2025). Adjustments to soil preparation that optimize water retention and promote uniform moisture distribution can help prevent excessive accumulation and localized water deficits in specific soil zones. Identifying the moisture levels that favour *R. solani* will assist implementation of management practices that minimize activity of this pathogen, thereby reducing damage and yield losses in soybean crops.

The results of this study help to explain conflicting results reported in previous research, and provide new knowledge explaining how severity of root rot of soybean caused by *R. solani* is influenced by soil moisture, especially in no tillage and acid subtropical soils under water deficit conditions.

ACKNOWLEDGMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, by the University of Passo Fundo (UPF) the MB Consultoria Agrícola and by the Pedaço de Chão Farm. The authors extend their appreciation to the Cezar Luiz Alves Ferreira, Dianez Teresinha Balbinotti Ferreira, Rosemiro Balbinotti, and Junior César Balbinotti, and the Agricultural Microbiology Laboratory of UPF through the research group (Kelen Bordignon, Matheus Durigon, Maurício Barbieri, Eduarda Steffens, and Cáren Verginassi) for supporting this work.

AUTHOR CONTRIBUTIONS

Conceptualization: Maicon Balbinotti; **Methodology:** Maicon Balbinotti; **Investigation:** Maicon Balbinotti, Júlia dos Santos de Britto, Milena Balbinotti Ferreira; **Writing - original draft preparation:** Maicon Balbinotti, José Luís Trevizan Chiomento, Pedro Alexandre Varella Escosteguy, Mateus Possebon Bortoluzzi, Jaqueline Huzar-Novakowiski; **Writing - review and editing:** Laura Mugnai, Pedro Alexandre Varella Escosteguy, José Luís Trevizan Chiomento, Mateus Possebon Bortoluzzi, Nadia Canali Lângaro, Maicon Balbinotti: Luciane Maria Colla; **Supervision:** Jaqueline Huzar-Novakowiski, Laura Mugnai, Nadia Canali Lângaro; **Data curation - formal analyses:** Jaqueline Huzar-Novakowiski, Maicon Balbinotti.

LITERATURE CITED

Abbas A., Khan S.U., Khan W.U., Saleh T.A., Khan M.H.U., ... Ikram M., 2019. Antagonist effects of strains of *Bacillus* spp. against *Rhizoctonia solani* for their protection against several plant diseases. *Comptes Rendus Biologies* 342: 124–135. https://doi.org/10.1016/j.crvi.2019.05.002

Abbas A., Mubben M., Sohail M.A., Solanki M.K., Hussain B., Nosheen S., 2022. Root rot: a silent alfalfa killer in China-distribution, fungal and oomycete pathogens, impact of climatic factors, and its management. *Frontiers in Microbiology* 13: 961794. https://doi.org/10.3389/fmicb.2022.961794

Agrios G.N., 1997. *Plant Pathology*. Academic Press, San Diego.

Alves L.A., Ambrosini V.G., Denardin L.G.O., Flores J.P.M., Martins A.P., ... Tiecher T., 2021. Biological N2 fixation by soybeans grown with or without liming on acid soils in a no-till integrated crop-livestock system. *Soil and Tillage Research* 209:104923. https://doi.org/10.1016/j.still.2020.104923

Ajayi-Oyetunde O.O., Bradley C.A., 2018. *Rhizoctonia solani*: taxonomy, population biology, and management of *Rhizoctonia* seedling disease of soybean. *Plant Pathology* 67: 3–17. https://doi.org/10.1111/ppa.12733

Akber M.A., Mubeen M., Sohail M.A., Khan S.W., Solanki M.K., ... Zhou L., 2023. Global distribution, traditional and modern detection, diagnostic, and management approaches of *Rhizoctonia solani* associated with legume crops. *Frontiers in Microbiology* 13: 1091288. https://doi.org/10.3389/fmicb.2022.1091288

Balbinotti M., Molin C., Britto J.S., Bordignon K., Barbieri M., Huzar-Novakowiski J., 2022. Effect of limestone dose on the incidence of *Rhizoctonia* root rot and soybean yield in four soil types. *Plant Pathology* 72: 407–650. https://doi.org/10.1111/ppa.13677

Balbinotti M., Escosteguy P.A.V., Klein V.A., Molin C., Britto J.S., ... Huzar-Novakowiski J., 2023. Soil chemical and physical attributes associated with *Rhizoctonia* root rot of soybean in southern Brazil. *Plant and Soil* 493: 221–235. https://doi.org/10.1007/s11104-023-06227-9

Balbinotti M., Schneider J.R., Forcelini C.A., Lângaro N.C., Huzar-Novakowiski J., 2025. Perspectives on plant nutrition and soil fertility in *Rhizoctonia* management in soybean. *Journal of Soil Science and Plant Nutrition* 25: 5983–6000. https://doi.org/10.1007/s42729-025-02512-x

Bates D., Maechler M., Bolker B., Walker S., Christensen R.H.B., ... Jagan M., 2024. lme4: linear mixed-effects models using 'Eigen' and S4. Version 1.1-35.5. *R package documentation*. https://doi.org/10.32614/CRAN.package.lme4

Bonanomi G., Zotti M., Idbella M., Di Silverio N., Carrino L., ... Incerti G., 2020. Decomposition and organic amendments chemistry explain contrasting effects on plant growth promotion and suppression of *Rhizoctonia solani* damping-off. *PLoS One* 15: e0230925. https://doi.org/10.1371/journal.pone.0230925

Brooks M., Bolker B., Kristensen K., Maechler M., Magnusson A., ... Agronah M., 2024. glmmTMB: generalized linear mixed models using Template Model Builder. Version 1.1-10. *R package documentation*. https://doi.org/10.32614/CRAN.package.glmmTMB

Carling D.E., 1996. Grouping in *Rhizoctonia solani* by hyphal anastomosis reaction. In: (Sneh B., Jabaji-Hare S., Neate S., Dijst G., ed.), *Rhizoctonia Species: Taxonomy, Molecular Biology, Ecology, Pathology and*

Disease Control. Dordrecht, Kluwer Academic Publishers, pp. 37-47.

Christensen R.H.B., 2024. A tutorial on fitting cumulative link mixed models with clmm2 from the ordinal package. *R package vignette*. https://cran.r-project.org/web/packages/ordinal/vignettes/clmm2_tutorial.pdf

Clevinger E.M., Biyashev R., Schmidt C., Song Q., Robertson A.E., … Saghai Maroof M.A., 2025. Mapping of *Phytophthora sojae* resistance in soybean genotypes PI 399079 and PI 408132. *Crop Science*. https://doi.org/10.1002/csc2.70027

Coque J.J.R., Álvarez-Pérez J.M., Cobos R., González-García S., Ibáñez A.M., … Calvo-Peña C., 2020. Advances in the control of phytopathogenic fungi that infect crops through their root system. *Advances in Applied Microbiology* 111: 123–170.

Cruz D.R., Leandro L.F.S., Mayfield D.A., Meng Y., Munkvold G.P., 2020. Effects of soil conditions on root rot of soybean caused by *Fusarium graminearum*. *Phytopathology* 110:1523–1533. https://doi.org/10.1094/PHYTO-02-20-0052-R

Datta S., Sarkar M., Chowdhury A., Rakwal R., Agrawal G.K., Sarkar A., 2022. A comprehensive insight into the biology of *Rhizoctonia solani* AG1-IA Kühn, the causal organism of the sheath blight disease of rice. *Journal of Plant Pathology* 104: 79–98. https://doi.org/10.1007/s42161-021-00974-3

Dixon G.R., Tilston E.L., 2010. Soil-borne pathogens and their interactions with the soil environment. In: (Dixon G., Tilston E., ed.), *Soil Microbiology and Sustainable Crop Production*. Dordrecht, Springer, pp. 79-105. https://doi.org/10.1007/978-90-481-9479-7_6

Dorrance A.E., Kleinhenz M.D., McClure S.A., Tuttle N.T., 2003. Temperature, moisture, and seed treatment effects on *Rhizoctonia solani* root rot of soybean. *Plant Disease* 87: 533–538. https://doi.org/10.1094/PDIS.2003.87.5.533

Fehr W.R., Caviness C.E., 1977. *Stages of soybean development*. Special Report 80. Ames, Iowa State University of Science and Technology.

Fenille R.C., Souza N.L. de, Kuramae E.E., 2002. Characterization of *Rhizoctonia solani* associated with soybean in Brazil. *European Journal of Plant Pathology* 108: 783–792. https://doi.org/10.1023/A:1020811019189

Ghorbani R., Wilcockson S., Koocheki A., Leifert C., 2008. Soil management for sustainable crop disease control: a review. *Environmental Chemistry Letters* 6: 149–162. https://doi.org/10.1007/s10311-008-0147-0

Gill J.S., Sivasithamparam K., Smettem K.R.J., 2000. Soil types with different texture affect development of *Rhizoctonia* root rot of wheat seedlings. *Plant and Soil* 221: 113–120.

Gill J.S., Sivasithamparam K., Smettem K.R.J., 2001a. Effect of soil moisture at different temperatures on Rhizoctonia root rot of wheat seedlings. *Plant and Soil* 231: 91–96.

Gill J.S., Sivasithamparam K., Smettem K.R.J., 2001b. Soil moisture affects disease severity and root colonization of wheat by *Rhizoctonia solani* AG-8. *Soil Biology and Biochemistry* 33: 1363–1370. https://doi.org/10.1016/S0038-0717(01)00041-4

Gorshkov V., Tsers I., 2021. Plant susceptible responses: the underestimated side of plant-pathogen interactions. *Biological Reviews*. https://doi.org/10.1111/brv.12789

Goulart A.C.P., 2018. Setting a rating scale for assessing *Rhizoctonia solani* lesions on cotton, soybean and common bean seedlings. *Bioscience Journal* 34: 1632–1639. https://doi.org/10.14393/BJ-v34n6a2018-42657

Hynes H.J., 1937. Studies on *Rhizoctonia* root rot of wheat and oats. *Science Bulletin, Department of Agriculture, New South Wales* No. 58.

Homet P., González M., Matías L., Godoy O., Pérez-Ramos I.M., … Gómez-Aparicio L., 2019. Exploring interactive effects of climate change and exotic pathogens on *Quercus suber* performance: damage caused by *Phytophthora cinnamomi* varies across contrasting scenarios of soil moisture. *Agricultural and Forest Meteorology* 276: 107605.

Höper H., Alabouvette C., 1996. Importance of physical and chemical soil properties in the suppressiveness of soils to plant diseases. *European Journal of Soil Biology* 32: 41–48.

Hothorn T., Bretz F., Westfall P., Heiberger R.M., Schuetzenmeister A., Scheibe S., 2024. multcomp: simultaneous inference in general parametric models. Version 1.4-26. *R package documentation*. https://doi.org/10.32614/CRAN.package.multcomp

Jayaraman S., Naorem A.K., Lal R., Dalal C.R., Sinha N.K., … Chaudhari S.K., 2021. Disease-suppressive soils -beyond food production: a critical review. *Journal of Soil Science and Plant Nutrition* 21: 1437–1465. https://doi.org/10.1007/s42729-021-00451-x

Kurm V., Schilder M.T., Haagsma W.K., Bloem J., Scholten O.E., Postma J., 2023. Minimum tillage increases soil biological properties but not suppression against *Rhizoctonia solani* and *Streptomyces scabies*. *Applied Soil Ecology* 181: 104646. https://doi.org/10.1016/j.apsoil.2022.104646

Lechner L., Pereyra-Irujo G.A., Granier C., Aguirrezábal L.A.N., 2008. Rewatering plants after a long water-

deficit treatment reveals that leaf epidermal cells retain their ability to expand after the leaf has apparently reached its final size. *Annals of Botany* 101: 1007–1015. https://doi.org/10.1093/aob/mcn029

Lenth V.R., 2018. lsmeans: least-squares means. Version 2.30-0. *R package documentation*. https://doi.org/10.32614/CRAN.package.lsmeans

Liu T., Kreszies T., 2023. The exodermis: a forgotten but promising apoplastic barrier. *Journal of Plant Physiology* 290: 154118. https://doi.org/10.1016/j.jplph.2023.154118

Marquez N., Giachero M.L., Declerck S., Ducasse D.A., 2021. *Macrophomina phaseolina*: general pathogenicity characteristics and control methods. *Frontiers in Plant Science* 12: 634397. https://doi.org/10.3389/fpls.2021.634397

Mello S.C.M. de., Ecktein B., Marques E., Carvalho D.D.C., 2020. Controle de doenças de plantas. In: Fontes E.M.G., Valadares-Inglis M.C. (eds.), *Controle biológico de Pragas da Agricultura*. Brasília, Embrapa.

Molin C., Ribeiro N.R., Matsumoto M.N., Brollo J., Bordignon K., ... Huzar-Novakowiski J., 2022. Soybean cultivars adapted to southern Brazil differ in their reaction to *Globisporangium irregulare*, *G. ultimum* var. *sporangiiferum* and *Pythium conidiophorum*. *Plant Pathology*. https://doi.org/10.1111/ppa.13631

Naqvi S.A.H., Abbas A., Farhan M., Kiran R., Hassan Z., ... Baloch F.S., 2024. Unveiling the genetic tapestry: exploring *Rhizoctonia solani* AG-3 anastomosis groups in potato crops across borders. *Plants* 13: 715. https://doi.org/10.3390/plants13050715

Nasimi Z., Barriuso J., Keshavarz T., Zheng A., 2024. Molecular, physiological, and biochemical properties of sclerotia metamorphosis in *Rhizoctonia solani*. *Fungal Biology Reviews* 48: 100351. https://doi.org/10.1016/j.fbr.2023.100351

Navi S.S., Huynh T., Mayers C.G., Yang X.-B., 2019. Diversity of *Pythium* spp. associated with soybean damping-off, and management implications by using foliar fungicides as seed treatments. *Phytopathology Research* 1: 8. https://doi.org/10.1186/s42483-019-0015-9

Otten W., Gilligan C.A., Watts C.W., Dexter A.R., Hall D., 1999. Continuity of air-filled pores and invasion thresholds for a soil-borne fungal plant pathogen, *Rhizoctonia solani*. *Soil Biology and Biochemistry* 31: 1803–1810. https://doi.org/10.1016/S0038-0717(99)00099-1

Otten W., Gilligan C.A., 2006. Soil structure and soil-borne diseases: using epidemiological concepts to scale from fungal spread to plant epidemics. *European Journal of Soil Science* 57: 26–37. https://doi.org/10.1111/j.1365-2389.2006.00766.x

Paulitz T.C., Smiley, R.W., Cook, R.J., 2002. Insights into the prevalence and management of soil-borne cereal pathogens under direct seeding in the Pacific Northwest, U.S.A. *Canadian Journal of Plant Pathology* 24:416–428. https://doi.org/10.1080/07060660209507029

R Core Team, 2022. *R: a language and environment for statistical computing*. Vienna, R Foundation for Statistical Computing. Available at: https://www.r-project.org/

Rahman M.T., Rubayet M.T., Bhuiyan M.K., 2020. Integrated management of *Rhizoctonia* root rot disease of soybean caused by *Rhizoctonia solani*. *Nippon Journal of Environmental Science* 1: 1018. https://doi.org/10.46266/njes.1018

Ritchie S.W., Hanway J.J., Thompson H.E., Benson G.O., 1977. *How a soybean plant develops*. Special Report 53. Ames, Iowa State University of Science and Technology.

Sallam N., Ali E.F., Seleim M.A.A., 2021. Endophytic fungi associated with soybean plants and their antagonistic activity against *Rhizoctonia solani*. *Egyptian Journal of Biological Pest Control* 31: 54. https://doi.org/10.1186/s41938-021-00402-9

Spurlock T.N., Rothrock C.S., Monfort W.S., Griffin T.W., 2016. The distribution and colonization of soybean by *Rhizoctonia solani* AG11 in fields rotated with rice. *Soil Biology and Biochemistry* 94: 29–36. https://doi.org/10.1016/j.soilbio.2015.11.002

Stamford N.P., Rodrigues J.J.V., Heck R.J., Andrade D.E.G.T., 2005. Propriedades físicas e químicas dos solos. In: (Michereff S.J., Andrade D.E.G.T., Menezes M., ed.), *Ecologia e manejo de patógenos radiculares em solos tropicais*. Recife, Universidade Federal Rural de Pernambuco, pp. 41-60.

Taiz L., Zeiger E., 2006. *Plant Physiology*, 4th edition. Sunderland, MA, Sinauer Associates.

Taiz L., Zeiger E., 2013. Capítulo 4 – Balanço hídrico das plantas. In: *Fisiologia Vegetal*, 5ª edição, tradução A.M. Divan Junior, revisão técnica P.L. de Oliveira. Porto Alegre, Artmed, p. 85.

Toleikiene M., Slepetys J., Sarunaite L., Lazauskas S., Deveikyte I., Kadziuliene Z., 2021. Soybean development and productivity in response to organic management above the northern boundary of soybean distribution in Europe. *Agronomy* 11: 214. https://doi.org/10.3390/agronomy11020214

Wickham H., Chang W., Henry L., Pedersen T.L., Takahashi K., ... Brand T.V.D., 2024. ggplot2: create elegant data visualisations using the grammar of graphics. Version 3.5.1. *R package documentation*. https://doi.org/10.32614/CRAN.package.ggplot2

Yan H., Nelson B. Jr., 2022. Effects of soil type, temperature, and moisture on development of *Fusarium* root rot of soybean by *Fusarium solani* (FSSC 11) and *Fusarium tricinctum*. *Plant Disease* 106: 2974–2983. https://doi.org/10.1094/PDIS-12-21-2738-RE

Supplementary Table S1. Characterization of the soil types of the fields sampled in the study.

Site/Soil profile	Characteristic	Rhodic	Dystric-Haplic	Eutric-Haplic	Dystric-Lithic	Dystrophic Red
		Acrisol Ac)	Cambisol CaTa)	Cambisol CaTb)	Leptosol (Lep)	Nitisol (Nit)
Environmental characteristics	Geographical coordinates	28º 45' 28.9" S 52º 26' 20.0" W	28º 45' 40.1" S 52º 26' 20.2" W	28º 45' 34.3" S 52º 26' 07.0" W	28º 44' 45.11" S 52º 28' 1.44" W	28º 45' 42.1" S 52º 28' 38.3" W
	Altitude (m)	580	584	586	566	575
	Climate	Subtropical	Subtropical	Subtropical	Subtropical	Subtropical
	Regional relief	Soft wavy	Soft wavy	Soft wavy	Soft wavy	Soft wavy
	Current relief	Flat	Soft wavy	Soft wavy	Strong wavy	Flat
	Stonyness	Non-stony	Slightly stony	Slightly stony	Very stony	Not stony
	Rockiness	Not rocky	Slightly rocky	Slightly rocky	Extremely rocky	Not rocky
	Primary vegetation	Native field	Native forest	Native field	Native forest	Native field
	Current vegetation	Crop plants	Crop plants	Crop plants	Crop plants	Crop plants
	Drainage	Well drained	Moderately drained	Moderately drained	Well drained	Well drained
	Erosion	Not apparent	Not apparent	Slightly apparent	Not apparent	Not apparent
A Horizon[1]	Thickness (cm)	75	30	50	35	20
	Gravel	Little gravel	Very gravelly	Gravel	Very gravelly	Little gravel
	Waxiness/Grade	Little/Weak	Abundant/Strong	Little/Weak	Little/Weak	Abundant/Moderate
	Cohesion	Moderately cohesive	Strongly cohesive	Strongly cohesive	Moderately cohesive	Strongly cohesive
	Collor *	(D) 2,5YR – 3/4 Dark reddish brow (W) 10R 3/1 Dark reddish gray (WK) 10R 2/3 Duskyred	(D) 7.5YR 5/2 Brown (W) 2.5YR 4/2 Weak red (WK) 5YR 4/3 Reddish brown	(D) 10R 3/6 Dark red (W) 7.5R 2.5/1 Reddish black (WK) 5YR 4/2 Dark reddish gray	(D) 5 YR- 5/1 Gray (W) 7.5 YR N2/ Black (WK) 7.5 YR 3/2 Dark brown	(D) 10R 5/4 Weak red (W) 10R 5/8 Red (WK) 7.5R 5/8 Red
	Grade structure	No aggregation	Moderate	Moderate	Weak moderate	Strong
	Structure size	Very small, small, medium	Very small, small, medium, large	Very small, small, medium, large	Very small, small, medium, large	Small, medium, large
	Structure type	Granular, single grains	Angular blocks, subangular blocks, simple grains	Angular blocks, subangular blocks, simple organs	Granular, angular blocks, single grains	Granular, angular blocks, subangular blocks
	Consistency	Dry = Loose Wet = Loose Wet = Non plastic	Dry = Very hard Moist = Firm Wet = Very plastic	Dry = Very hard Moist = Firm Wet = Very plastic	Dry = Soft Moist = Loose Wet = Firm	Dry = Extremely Hard Moist = Soft Wet = Plastic
	Pores/Quantity	Large/Abundant	Medium/Common	Small/Abundant	Large/Abundant	Medium/Common
	Texture	Clay Loam	Clay-silty loam	Clay-silty loam	Clay loam	Clay
	Transition/Contrast	Flat/Gradual	Flat/Abrupt	Irregular/Abrupt	Broken/Gradual	Flat/Gradual
	Surface	Compression = Matte Amount = Little Degree = Moderate	Compression = Dull Quantity = Little Degree = Weak	Compressão = Fosca Quantidade = Comum Grau = Moderada	Compression = Dull Quantity = Little Degree = Weak	Compression = Bright Quantity = Abundant Degree = Strong

(Continued)

Table S1. (Continued).

Site/Soil profile	Characteristic	Rhodic	Dystric-Haplic	Eutric-Haplic	Dystric-Lithic	Dystrophic Red
		Acrisol Ac)	Cambisol CaTa)	Cambisol CaTb)	Leptosol (Lep)	Nitisol (Nit)
	Sand (%)	45	22	20	37	28
	Clay (%)	37	40	55	32	52
	Silt (%)	18	38	25	31	20
B Horizon[1]	Thickness (cm)	140	120	110	30	120
	Gravel	Little	Very	Very	Little	Average
	Waxiness/Grade	Abundant/Strong	Abundant/Strong	Common/Moderate	Common/Moderate	Abundant/Strong
	Cohesion	Moderadamente coeso	Moderado coeso	Moderado coeso	Moderadamente coeso	Fortemente coeso
	Collor*	(D) 2.5YR – 3/6 Dark red (W) 10R 3/6 Dark red (WK) 10R 4/6 Red	(D) 5YR – 5/2 Reddish brown (W) 2.5YR 4/8 Red (WK) 10R 4/6 Red	(D) 7.5R 7/8 Light red (W) 10R 2.5/2 Very dusky red (WK) 10R 3/4 Dusky red	(D) 10 YR- 6/3 pale brown (W) 5 YR 4/4 reddish brown (WK) 10 YR 4/4 dark yellowish brown	(D) 10R 7/8 Light red (W) 10R 3/6 Dark red (WK) 10R 5/8 Red
	Structure development	Weak	Weak	Weak	Moderate Strong	Strong
	Structure size	Small, medium, very large	Small, medium, large, very large	Small, medium, large, very large	Very small, small, medium, large	Medium, large, very large
	Structure type	Angular blocks, subangular blocks	Granular, angular blocks, subangular blocks, prismatic, columnar	Subangular, prismatic, columnar blocks	Granular, angular blocks, subangular blocks, wedge-shaped, prismatic	Angular blocks, subangular blocks, prismatic, columnar
	Consistency	Dry = Extra Hard Moist = Firm Wet = Plastic/Sticky	Dry = Very hard Moist = Friable Wet = Plastic/Very sticky	Dry = Very hard Moist = Crumbly Wet = Plastic/Very sticky	Dry = Extra hard Moist = Firm Wet = Slightly plastic/ sticky	Dry = Extremely hard Moist = Firm Wet = Very plastic/Very sticky
	Pores/Quantity	Medium/Abundant	Medium/Common	Large/Abundant	Medium/Common	Medium/Common
	Texture	Very clayey	Very clayey	Very clayey	Silty clay	Very clayey
	Transition/Contrast	Flat/Abrupt	Wavy/Light	Irregular/Gradual	Broken/Graduate	Flat/Clear
	Surface	Compression = Bright Amount = Common Degree = Strong	(presents FRICTION) Compression = Bright Quantity = Abundant Degree = Strong	Compression = Bright Amount = Common Degree = Moderate	Compression = Matte Amount = Average Degree = Moderate	Compression = Bright Quantity = Abundant Degree = Strong
	Sand (%)	20	7	6	25	120
	Clay (%)	67	76	74	44	65
	Silt (%)	13	17	20	31	17

D: Dry; W: Wet; WK: Wet Kneaded.
*Munsell's colour system (Munsell, 2009). Morphological characterization IBGE (2015).
[1] Characterization of the soil diagnostic horizons.

Literature cited

IBGE (Instituto Brasileiro de Geografia e Estatística), 2015. *Manual técnico de pedologia*, 3rd edition. Rio de Janeiro, Coordenação de Recursos Naturais e Estudos Ambientais, 430 pp.
Munsell A.H., 2009. *Munsell soil color charts*. Grand Rapids, MI.

Supplementary Table S2. Chemical analysis of soils (0-20 cm) inside and outside patches with a history of Rhizoctonia root rot occurrence in soybean.

Characteristic	Units	Acrisol		Cambisol Ta		Cambisol Tb		Leptosol		Nitisol	
		Patch	Outside	Patch	Outside	Patch	Outside	Patch	Outside	Patch	Outside
Clay content[a]	%	52.00	51.00	59.20	53.20	62.10	60.10	51.93	56.18	57.50	57.20
pH	-	4.75	5.00	4.90	5.01	4.94	4.60	4.89	4.93	4.41	4.87
pH SMP[b]	-	5.60	5.70	5.90	5.80	5.70	5.30	5.83	6.03	5.30	5.60
Phosphorus (P)	mg dm^{-3}	17.7	17.1	55.8	54.0	24.2	21.3	31.5	48.8	43.8	31.0
Potassium (K)	mg dm^{-3}	340.68	260.69	386.29	369.73	311.24	280.35	387.19	390.24	384.53	372.46
Organic matter	%	3.23	3.08	4.60	4.28	3.64	3.61	4.01	3.76	3.53	3.88
Aluminium (Al^{3+})	$cmol_c$ dm^{-3}	1.08	0.96	0.41	0.34	2.03	0.92	0.73	0.41	1.96	1.17
Calcium (Ca^{2+})	$cmol_c$ dm^{-3}	4.54	5.09	8.03	9.51	5.90	6.73	5.58	6.56	3.06	5.18
Magnesium (Mg^{2+})	$cmol_c$ dm^{-3}	1.98	2.25	3.52	3.23	2.33	3.19	2.67	2.88	1.60	2.54
H + Al	$cmol_c$ dm^{-3}	7.43	6.54	5.29	4.88	9.44	6.53	6.03	4.48	10.24	7.94
Cation exchange capacity	$cmol_c$ dm^{-3}	14.81	14.54	18.86	17.47	17.23	18.39	15.25	14.88	15.88	16.60
Base saturation	%	50.76	55.43	69.62	74.06	49.90	61.96	61.40	69.68	37.41	53.18
Al saturation	%	14.54	14.02	3.61	2.63	15.03	9.96	8.93	4.63	28.62	15.68
K saturation	%	5.91	4.64	5.25	5.41	4.63	3.95	6.58	6.68	6.26	5.77
Zinc	mg dm^{-3}	2.03	2.08	7.11	4.50	2.76	2.56	4.70	4.00	2.62	4.19
Copper	mg dm^{-3}	6.43	3.39	4.82	2.23	5.33	2.30	3.88	2.59	4.01	3.38
Manganese	mg dm^{-3}	14.73	13.56	17.58	14.02	16.12	16.96	17.48	12.59	18.41	25.00
Boron	mg dm^{-3}	0.29	0.32	0.34	0.36	0.29	0.32	0.34	0.31	0.34	0.33
Sulphur	mg dm^{-3}	13.90	12.29	33.37	23.80	13.90	18.22	26.01	30.35	27.76	27.32

Methods for soil analysis described in Walkley and Black (1934), Tedesco et al. (1995), Toledo et al. (2012) e Embrapa (2017).
[a] Clay content was estimated using the hydrometer method.
[b] pH SMP is the pH of the soil measured using a buffer solution at pH 7.

Literature cited

Embrapa (Empresa Brasileira de Pesquisa Agropecuária), 2017. In: Teixeira P.C., Donagemma G.K., Fontana A., Teixeira W.G. (eds.), *Manual de métodos de análise de solo*, 3rd edition. Brasília, DF, Embrapa. Available at: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1085209/manual-de-metodos-de-analise-de-solo
Tedesco J.M., Gianello C., Bissani A.C., Bohnen H., Volkeweiss S.J., 1995. *Análise de solo, plantas e outros materiais*, 2ª edição. Porto Alegre, Departamento de Solos, UFRGS.
Toledo J.A., Kaminski J., Santanna M.A., Santos D.R. dos, 2012. Tampão Santa Maria (TSM) como alternativa ao tampão SMP para medição da acidez potencial de solos ácidos. *Revista Brasileira de Ciência do Solo* 36: 427-435. https://doi.org/10.1590/S0100-06832012000200012
Walkley A., Black I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* 37: 29-38.

Supplementary Table S3. Gravimetric water content (g g^{-1}) at field capacity of the 0-20 cm soil layer, previously determined using porous plate funnels at a tension of -10 kPa, and at different levels of water holding capacity determined from pot weighing in Experiment 1 and 2.

	Water holding capacity (%)					Field capacity
Soil type	50	65	80	95	100	-10 kPa
	g g^{-1}					
Experiment 1						
Acrisol	0.162	0.211	0.349	0.309	0.325	0.29
Cambisol Ta	0.144	0.187	0.23	0.273	0.288	0.297
Cambisol Tb	0.143	0.186	0.229	0.272	0.286	0.313
Leptosol	0.075	0.097	0.12	0.143	0.150	0.301
Nitisol	0.143	0.187	0.23	0.273	0.287	0.304
Experiment 2						
Acrisol	0.169	0.22	0.271	0.322	0.339	0.29
Cambisol Ta	0.157	0.205	0.266	0.299	0.315	0.297
Cambisol Tb	0.152	0.198	0.243	0.289	0.304	0.313
Leptosol	0.165	0.215	0.265	0.314	0.331	0.301
Nitisol	0.162	0.211	0.26	0.308	0.324	0.304

Supplementary Table S4. Acaricides, fungicides, and insecticides used in the experiments.

Growth stage	Commercial product	Class	Active ingredient	Dose (L or kg ha^{-1})
Seed treatment	Apron RFC	Fungicide	Fludioxonil + Metalaxyl-M	0.12
Seed treament	Terra Forte	Inseticide	Fipronil	0.12
V3	Premio	Inseticide	Chlorantraniliprole	0.04
V6				
V6	Ativum	Fungicide	Epoxiconazol + Fluxapiroxade + Piraclostrobina	0.5
R1				
R3	Orkestra	Fungicide	Piraclostrobina + Fluxapiroxade	0.3
R5.1	Versatilis	Fungicide	Fenpropimorph	0.5
R1	Unizebe Gold	Fungicide	Mancozeb	1.5
R3				
R5.1				
V6				
R3	Abamectin 72 EC	Acaricide	Abamectin	0.3
R5.1	Talisman	Inseticide	Bifenthrin + Carbosulfan	0.25

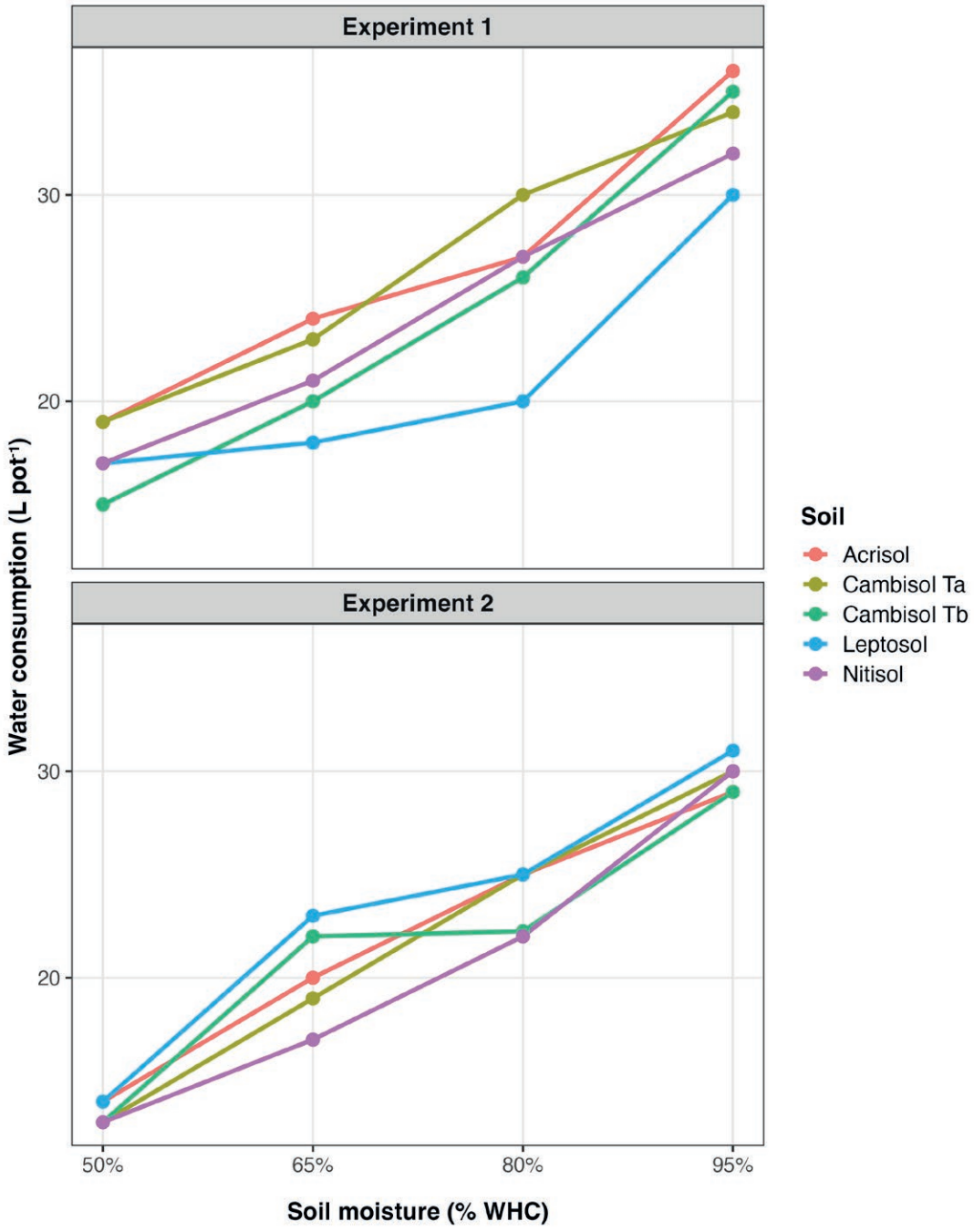
Supplementary Table S5. Summary of the analysis of variance indicating the effect of the tested factors on Rhizoctonia root rot severity (score) and on plant growth and yield variables.

Source	DF	Chi-square and significance level (*P*, in parentheses)								
		Severity	Plant death	Plant height	First node*	Total nodes	Fertile nodes	Pods	Grain	
			Number of days	cm	cm	Number per plant				g per plant
Moisture (M)	3	**126.69 (*P* ≤ 0.01)**	24.16 (***P* ≤ 0.01**)	3.89 (*P* = 0.27)	5.18 (*P* = 0.15)	62.22 (***P* ≤ 0.00**)	**10.66 (*P* = 0.01)**	**8.81 (*P* = 0.03)**	**25.85 (*P* ≤ 0.00)**	37.43 (***P* ≤ 0.00**)
Experiment (E)	1	1.30 (*P* = 0.25)	0.00 (*P* = 0.98)	0.65 (*P* = 0.41)	0.30 (*P* = 0.58)	0.35 (*P* = 0.61)	2.40 (*P* = 0.12)	0.00 (*P* = 0.93)	0.00 (*P* = 0.95)	1.73 (*P* = 0.84)
Soil (S)	4	**16.89 (*P* ≤ 0.01)**	1.23 (*P* = 0.87)	2.37 (*P* = 0.66)	3.78 (*P* = 0.43)	19.80 (***P* ≤ 0.00**)	4.85 (*P* = 0.89)	2.08 (*P* = 0.71)	**10.07 (*P* = 0.03)**	**22.52 (*P* ≤ 0.00)**
Patch (P)	1	-	29.06 (***P* ≤ 0.01**)	2.96 (*P* = 0.08)	0.79 (*P* = 0.37)	73.43 (***P* ≤ 0.00**)	**39.11 (*P* ≤ 0.00)**	**10.09 (*P* ≤ 0.01)**	**9.46 (*P* ≤ 0.01)**	45.90 (***P* ≤ 0.00**)
E x M	3	6.81 (*P* = 0.07)	5.49 (*P* = 0.13)	1.27 (*P* = 0.73)	0.53 (*P* = 0.91)	6.34 (*P* = 0.09)	4.24 (*P* = 0.23)	0.09 (*P* = 0.99)	2.78 (*P* = 0.42)	3.27 (*P* = 0.43)
S x M	12	14.89 (*P* = 0.25)	16.66 (*P* = 0.16)	4.44 (*P* = 0.97)	10.30 (*P* = 0.58)	15.98 (*P* = 0.19)	18.74 (*P* = 0.64)	2.71 (*P* = 0.99)	12.85 (*P* = 0.37)	19.89 (*P* = 0.39)
P x M	3	-	**11.39 (*P* ≤ 0.01)**	0.76 (*P* = 0.85)	3.93 (*P* = 0.26)	**12.95 (*P* ≤ 0.01)**	3.15 (*P* = 0.36)	3.29 (*P* = 0.34)	2.34 (*P* = 0.50)	**20.57 (*P* ≤ 0.00)**
E x S	4	4.60 (*P* = 0.33)	2.14 (*P* = 0.70)	1.77 (*P* = 0.77)	1.92 (*P* = 0.74)	1.34 (*P* = 0.67)	2.14 (*P* = 0.70)	0.11 (*P* = 0.99)	7.23 (*P* = 0.12)	5.30 (*P* = 0.72)
E x P	1	-	1.91 (*P* = 0.16)	0.16 (*P* = 0.68)	0.59 (*P* = 0.44)	2.25 (*P* = 0.27)	0.72 (*P* = 0.39)	0.00 (*P* = 0.99)	1.70 (*P* = 0.19)	1.47 (*P* = 0.25)
S x P	4	-	1.66 (*P* = 0.79)	3.80 (*P* = 0.43)	3.20 (*P* = 0.52)	9.81 (*P* = 0.76)	7.36 (*P* = 0.11)	0.59 (*P* = 0.96)	3.22 (*P* = 0.52)	7.61 (*P* = 0.10)
E x S x M	12	**21.86 (*P* = 0.03)**	19.98 (*P* = 0.67)	4.38 (*P* = 0.97)	4.86 (*P* = 0.96)	13.54 (*P* = 0.33)	14.61 (*P* = 0.26)	2.61 (*P* = 0.99)	7.53 (*P* = 0.82)	8.79 (*P* = 0.86)
E x P x M	3	-	4.53 (*P* = 0.20)	2.07 (*P* = 0.55)	0.30 (*P* = 0.95)	2.97 (*P* = 0.39)	2.35 (*P* = 0.50)	0.19 (*P* = 0.97)	2.84 (*P* = 0.41)	5.40 (*P* = 0.07)
S x P x M	12	-	9.50 (*P* = 0.65)	3.41 (*P* = 0.99)	6.04 (*P* = 0.91)	18.71 (*P* = 0.09)	13.57 (*P* = 0.32)	2.05 (*P* = 0.99)	7.29 (*P* = 0.83)	13.49 (*P* = 0.76)
E x S x P x M	12	-	20.37 (*P* = 0.06)	3.76 (*P* = 0.98)	2.23 (*P* = 0.99)	20.02 (*P* = 0.06)	11.89 (*P* = 0.45)	2.09 (*P* = 0.99)	10.21 (*P* = 0.59)	18.17 (*P* = 0.61)
E x S x P	4	-	3.37 (*P* = 0.49)	4.40 (*P* = 0.35)	1.45 (*P* = 0.83)	8.84 (*P* = 0.82)	1.57 (*P* = 0.81)	0.64 (*P* = 0.95)	6.51 (*P* = 0.16)	5.79 (*P* = 0.23)

* height of insertion of the first productive node. Bold values of *p* indicate factor significance ($p \leq 0{,}05$). The experiment was conducted in two locations, encompassing five soil types (Acrisol, Cambisol Ta, Cambisol Tb, Leptosol and Nitisol), two field positions (inside and outside patches with Rhizoctonia root rot), and four soil moisture levels (50%, 65%, 80%, and 95% of the soil's water-holding capacity).

Supplementary Table S6. Descriptive statistics of Rhizoctonia root rot severity and soybean yield component variables evaluated under different soil types and moisture levels.

Variable	Rhizoctonia root rot severity	Number of days until plant death	Plant height	Height of the first node insertion	Total number of nodes per plant	Number of fertile nodes per plant	Number of podes per plant	Number of grains per plant	Grain weight (dry) per plant
Variable type	Ordinal qualitative	Discrete quantitative	Continuous quantitative	Continuous quantitative	Discrete quantitative	Discrete quantitative	Discrete quantitative	Discrete quantitative	Continuous quantitative
Unit	Score (0 a 4)	Count	cm	cm	Count	Count	Count	Count	g
Mean	1.18	117.02	63.78	10.33	16.32	12.97	33.00	70.31	8.31
Standard error	0.08	1.33	0.47	0.12	0.11	0.12	0.45	1.07	0.16
Median	0.75	132.00	64.00	10.00	16.00	13.00	33.00	69.00	8.27
Mode	0.00	139.00	61.00	10.00	17.00	13.00	26.00	60.00	4.69
Standard deviation	1.39	23.81	8.44	2.13	2.02	2.03	7.92	18.96	2.89
Variância	1.94	567.04	71.18	4.55	4.06	4.12	62.71	359.54	8.36
Minimum	0	70	38	3	10	5	15	19	1.82
Maximum	4	139	87	17	21	20	56	126	15.29
Number of observations (*n*)	320	320	317	316	311	311	312	312	308
Coefficient of variation (%)	118.2	20.3	13.2	20.6	12.4	15.6	24.0	27.0	34.8



Supplementary Figure S1. Total irrigation (L) during the experimental period for experiment 1 (a) and experiment 2 (b) at 50, 65, 80, and 95% of water holding capacity (WHC) for different soil types.