Physiologically-Mediated Self/NonSelf Root Discrimination in *Trifolium repens* has Mixed Effects on Plant Performance

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**ABSTRACT**

Recent studies suggest that plant roots can avoid competition with other roots of the same plant, but the mechanism behind this behavior is yet largely unclear and their effects on plant performance hardly studied. We grew combinations of two ramets of *Trifolium repens* in a single pot that were either intact, disconnected for a shorter or longer time, or that belonged to different genotypes. Interconnected ramets developed lower root length and mass than any other combination of ramets, supporting the notion that self/nonself discrimination in *T. repens* was based entirely on physiological coordination between different roots that develop on the same plant, rather than biochemical allorecognition. These responses were consistent among eight field-collected genotypes, suggesting that self/nonself discrimination is a common feature in wild populations of white clover. There were no significant treatment × genotype interactions suggesting that genetic variation for self/nonself discrimination may be limited. Self-interactions resulted in lower to similar shoot biomass and number of ramets, but higher flowering probabilities, compared to nonself interactions. Thus, our results demonstrated that the performance consequences of self/nonself discrimination may be more complicated than previously thought.

**INTRODUCTION**

Competition is one of the most prominent determinants of plant performance. The most successful competitors are those individuals that capture the greatest proportion of shared resources. However, increased allocation to resource capturing organs may come at a cost of reduced reproduction and fitness. Accordingly, selection should favor mechanisms that minimize competition between parts of the same genetic individual or “self-competition” (e.g. refs. 12 and 13).

While the potential to minimize self-competition has been considered to be relatively limited in plants, recent evidence has shown that plant roots are able to differentially respond according to the identity of their neighbors. Mahall and Callaway found that roots of the desert shrub *Ambrosia dumosa* responded to contacts with roots of different *Ambrosia* plants by decreasing their rate of elongation, but showed no such response when contacting other roots of the same individual plant. By contrast, Falik et al. have shown that roots of *Pisum sativum* decreased root growth in the presence and in the direction of their own roots compared to roots of other plants. These kinds of responses have now been demonstrated for a number of species, including *Glycine max*; *Phaseolus vulgaris*; *Fragaria chiloensis*; *Miscanthus sinensis* and *Buchloe dactyloides*.

The mechanism behind self/nonself (S/NS) root discrimination is still obscure. In *Pisum sativum*, *Fragaria chiloensis* and *Buchloe dactyloides* the mechanism is largely or wholly based on physiologically coordinated responses among different roots that develop on the same plant, but the responses of *Miscanthus sinensis* could be interpreted as being based on biochemical allorecognition, i.e., immunological-like recognition.

The few studies that have looked at shoot biomass or fruit production as fitness measures emphasized reduced plant performance under nonself as compared to self interactions, which was interpreted as a cost of an enhanced root allocation under nonself interactions. These results suggest that reduced root growth under self interactions might save resources under competition with self, a reduction that is not evolutionary stable under competition with nonself neighbors. It is yet unknown how widespread the effects of S/NS root discrimination on plant performance are among plant species, and among different genotypes of the same species.
Here we present the results of experiments designed to study the nature and consequences of S/NS root discrimination in the widely-studied white clover (*Trifolium repens* L.). Using *T. repens* ramets of known genotypic identities collected from wild populations, we pursued the following three objectives. First, we investigated the ability of *T. repens* to discriminate between self and nonself roots. Using two different genotypes allowed us to assess whether root discrimination in this species is based on physiological coordination between different roots of the same plant or biochemical allorecognition. Second, we tested how common self/nonself discrimination was among a wider variety of field-collected *T. repens* genotypes. Finally, by measuring shoot biomass, number of ramets and number of flowers we tested the hypothesis that the cost of enhanced root proliferation under nonself interactions compromised plant performance, as compared to self interactions.

**MATERIALS AND METHODS**

**Plant material.** White clover, *Trifolium repens* L., is a short-lived perennial legume, native to Eurasia. It has been deliberately introduced worldwide as a forage crop. It is very common in pasture and forage mixes but also occurs as a significant weed of lawns, turfgrass, and orchards. *T. repens* can colonize bare soil patches and gain local dominance by clonal spread. Genotypes of *T. repens* were collected from natural populations in floodplains of the main tributary of the River Rhine, east and west of Nijmegen in the summer of 2001. Stock plants of each of the genotypes were grown under uniform conditions in a garden (in summer) or in an unheated greenhouse (in winter) at the Radboud University Nijmegen, The Netherlands. Plants were propagated in early 2002 to create a number of different mother plants for each of the genotypes. Experimental ramets were then selected from these mother plants based on size uniformity of their shoots and roots.

**Experiment 1: Testing for self/nonself discrimination and its effects.** Connected ramet pairs of *T. repens* with shoots and roots of similar sizes were planted in pots so that each pot contained two ramets from either the same mother plant (SELF), or from two different mother plants belonging to the same (NONSELF) or different (ALIEN) genotypes (Fig. 1). The stolons connecting the ramet pairs were either left intact (INTACT SELF, INTACT NONSELF, INTACT ALIEN) or severed (SEVERED SELF, SEVERED NONSELF, SEVERED ALIEN), producing two genetically identical but physiologically separate individuals. Throughout, experimental ramet severing was carried out immediately before the onset of the experiment. Differences in root growth between INTACT SELF and INTACT NONSELF indicate that the discrimination has a physiological basis. Differences between INTACT ALIEN and INTACT NONSELF plants may suggest the involvement of biochemical allorecognition, i.e., S/NS discrimination that is based on the genetic identity of the competing plants. If all three treatments are different from each other both physiological and genetic mechanisms could be involved.

In *Buchloe dactyloides*, Gruntman and Novoplansky showed that cuttings originating from adjacent nodes become progressively alienated from each other and eventually relate to each other as genetically alien. By comparing INTACT SELF and SEVERED SELF we test whether disconnecting ramets results in S/NS discrimination, as compared to INTACT NONSELF in which the two experimental plants originated from different but genetically identical mother plants, separated a few months before the experiment started. Furthermore, comparing INTACT NONSELF and INTACT ALIEN to SEVERED NONSELF and SEVERED ALIEN, respectively, allowed us to trace down and control for possible effects of plant severing (due to wounding) that are unrelated to root discrimination.

All these tests (all six treatments in Fig. 1) were carried out on one *T. repens* genotype (genotype A) using a second genotype (genotype B) as a competitor in the ALIEN treatments (Fig. 1). The SELF treatments were also conducted on genotype B. This design allowed us to (a) investigate whether genotype B also exhibited self/nonself discrimination, and (b) to control for potential inherent differences in ramet sizes and growth rates between the genotypes that could have been mistakenly interpreted as caused by the main treatments. All treatments were replicated 8–16 times. The experiment started on 13 September 2002 and lasted 91 days.

Aboveground plant biomass and number of ramets, fitness measures that are commonly used in clonal plants (e.g. refs. 29 and 30), were measured at harvest.

**Experiment 2: Testing for self/nonself discrimination in a larger selection of genotypes.** In order to test the prevalence of self/nonself discrimination in *Trifolium repens*, we repeated part of the treatments of experiment 1 using eight different field-collected genotypes. The above mentioned INTACT SELF, INTACT NONSELF and INTACT ALIEN treatments were used to test whether root discrimination was based on physiological coordination or biochemical allorecognition. Because the first experiment showed some severing effects, we also included the SEVERED SELF and SEVERED ALIEN treatments. In the ALIEN treatments four unique genotype pairs were tested: A–B, C–D, E–F and G–I, with genotypes A and B as a repetition of the first experiment. Each treatment was replicated 3–10 times. The second experiment, carried out under identical conditions as the first experiment, started on 6 January 2003 and lasted 88 days.

**Growth conditions, plant processing and statistical analyses.** The experiments were carried out in a controlled growth chamber (Geerlings Koeltechniek, Rijswijk, The Netherlands). Supplemental
Self/Nonself Discrimination in Trifolium repens

Lighting with fluorescent tubes and additional high pressure sodium lamps yielded 250 μmol m⁻² s⁻¹ for 16 h per day and a constant temperature of 20°C. Ramet pairs with 25 mm long shoots (petioles) and 5 mm long roots were cut from the mother plants. They were rooted in pots by pinning them down to the soil medium using plastic-coated metal wires. We used square 10 x 10 x 10 cm plastic pots filled with a 1:1 mixture of fine vermiculite and sieved potting soil. When plants were grown in pot pairs (Fig. 1), the relative positions of the pots were fixed by gluing them to each other. Special care was given to ensure that the position of the two ramets in relation to the pot's rim and their neighbors was similar in all treatments, irrespective of whether the ramets were connected or not. A 1 cm thick layer of black polyethylene beads covered the pot's surface in order to avoid the rooting of daughter ramets. T. repens stolons grow out laterally and were arranged in such a way that leaf overtopping and hence above-ground competition was avoided. The pots containing the ramet pairs were randomly arranged on benches in the growth chamber. The plants were irrigated by tap water every 3–4 days. To increase the probability of effective root competition no additional nutrients were supplemented.

The plants were harvested following initial leaf senescence. Since no meaningful shading developed among neighboring plants during the experiments it is assumed that leaf senescence developed mainly due to nutrient limitation. The substrate was carefully washed and the roots of the two ramets were separated. Total root length was estimated from scans of fresh roots using DT-scan software (Delta-T, Cambridge, UK). Shoot and root biomasses were determined after drying the plants at 70°C for at least three days. Statistical analyses were conducted using SYSTAT 10.0. All dependent variables were tested for normality and log-transformed when they did not meet the assumptions of parametric statistics. We used one-way ANOVA's to test for treatment effects in Experiment 1, and two-way ANOVA's (treatment x genotype) in experiment 2. Differences between individual treatment averages were further assessed by Tukey HSD comparisons.

RESULTS

Self/nonself discrimination. By the end of experiment 1, INTACT NONSELF plants had on average 30% greater root length and 53% greater root biomass than INTACT SELF plants (Fig. 2). Physiological integration among intercon- nected ramets thus had a significant effect on root responses. Severing the connection produced interactions similar to NONSELF interactions: SEVERED SELF and SEVERED NONSELF plants developed similar root length and biomass as INTACT NONSELF. In addition, root responses in INTACT ALIEN were similar to INTACT NONSELF, suggesting that biochemical allorecognition had no significant role in the observed discrimination. However, there was an interaction between alien and severing effects in genotype B (Fig. 2): in SEVERED ALIEN, plants developed greater root length and biomass than in INTACT ALIEN. A similar trend in Genotype A was not significant.

Shoot growth. While only genotype B produced significantly greater shoot biomass in SEVERED ALIEN than in INTACT SELF, shoot growth increased rather than decreased under all nonself and
The responses of the eight genotypes to the treatments as expressed by root and shoot variables are able to discriminate between for Tests of effects of self/nonself discrimination in Our results before the experiment or separated months in advance, as well as of ramets of the same genotype severed from each other immediately presence of other roots of the same physiological individual. Roots self and nonself neighbors and develop smaller root systems in the presence of ramets of the same genotype. In contrast to the results of the first experiment, no additional root growth could not be segregated according to their self-nonself discrimination. Interactions for these variables (Table 1), indicating that genotypes showed similar trends as shoot biomass, and the NONSELF and the SEVERED ALIEN interactions resulted in significantly larger geno- types. Our results thus support the notion that coordination among roots of the same physiological individual plant rather than biochemical allorecognition, was responsible for S/NS root discrimination in T. repens. We are the first to demonstrate the effects of self/nonself root discrimination in this species, despite the enormous attention it enjoyed in ecology and agronomy, and the first to show that the responses were consistent among eight different field-collected genotypes. Our results thus suggest that self/nonself discrimination is a widespread phenomenon in wild populations of T. repens. Nonself interactions may lead to considerably higher rooting densities (and less flowering—see below) in white clover populations, especially where they consist of intermingled genotypes and fragmented clones. Our results are consistent with recent work with Pisum sativum and Buchloe dactyloides showing that inhibitory effects among roots of the same plant are rapidly lost when the connection between the roots is terminated by severing, though more rapidly than in Buchloe. Modular integration, also regarding root responses, has been observed before, but the surprising effect of s/ns discrimination as reported here is that physiological integration is a prerequisite for the discriminatory root responses to occur. This communication may be mediated by hormones such as auxin and cytokinins, with the shoot as an intermediary. A resource-based signal seems unlikely as discriminatory effects are demonstrated well before resources are limiting, and because the restricted root growth has led to reduced rather than increased shoot growth in our experiments (see below). Falik et al. and Gruntman and Novopslansky speculated that oscillations of hormones and/or electricity underlie the physiological identity of individual plants and their discriminatory responses toward self/nonself neighbors but the nature of these signals is still obscure and in an urgent need of further investigation. Only few studies allowed a systematic comparison between effects of physiological coordination and biochemical allorecognition, and such a comparison suggests a near consensus that self/nonself discrimination is based on coordination among roots that develop on the same physiological individual. Only in the rhizomatous grass Miscanthus sinensis, self/nonself discrimination couldn’t safely be assigned to either mechanistic category. Consistent among four different genotypes, root growth was more strongly inhibited upon encounters with roots of a genetically identical but physiologically separate individual than with roots of a different genotype. Either the s/ns mechanism in Miscanthus is physiological and the time of separation (that was done just before the experiment started; Nishiwaki A, personal communication) was not sufficient to alienate the individuals from each other (sensu), or the mechanism was based on biochemical allorecognition. A similar apparent discrepancy was demonstrated in our first experiment, where severing connections...alien interactions in Experiment 1 (Fig. 2C). The number of ramets showed similar trends as shoot biomass, and the NONSELF and the SEVERED ALIEN treatments resulted in significantly larger genotype A plants than the INTACT SELF treatment. The markedly enhanced root growth under nonself and alien interactions resulted only in a marginally higher allocation of biomass to roots (Fig. 2D). This allocation response was not significant with the exception of the SEVERED ALIEN treatment. **Prevalence of self/nonself discrimination among T. Repens genotypes.** The responses of the eight genotypes to the treatments were largely consistent with the results of the first experiment (Fig. 3). Across all genotypes, NONSELF, SEVERED and ALIEN interactions resulted in significantly greater root length and biomass compared to INTACT SELF. Although genotypes differed in root lengths and root biomass, there were no significant treatment x genotype interactions for these variables (Table 1), indicating that genotypes could not be segregated according to their self-nonself discrimination. In contrast to the results of the first experiment, no additional root biomass was produced under SEVERED ALIEN over all genotypes, even though genotype B demonstrated the same trend as in experiment 1 (Fig. 3B). Overall, there were no treatment effects on plant performance in the second experiment (Figs. 3C and E). Trends in experiment 1 of enhanced shoot biomass and number of ramets under NONSELF, SEVERED or ALIEN interactions were not discernable, although there were some differences in response among individual genotypes (marginally significant treatment x genotype interaction for number of ramets; Table 1). The number of flowers per plant varied an order of magnitude among genotypes (Fig. 3F) and was significantly different among treatments in a two-way ANOVA (Table 1). Although the Tukey grouping in Figure 3F (in which these genotypic differences were not incorporated) did not reveal differences among individual treatments, NONSELF, SEVERED and ALIEN interactions all resulted in 30% fewer flowers compared to INTACT SELF. These shifts in flowering were not due to (small) changes in number of ramets among treatments. An analysis of number of flowers with number of ramets as a covariate still revealed a significant treatment effect (p < 0.01), with INTACT ALIEN significantly lower than INTACT SELF (results not shown).

**DISCUSSION**

Self/nonself root discrimination in Trifolium Repens. Our results show that roots of Trifolium repens are able to discriminate between self and nonself neighbors and develop smaller root systems in the presence of other roots of the same physiological individual. Roots of ramets of the same genotype severed from each other immediately before the experiment or separated months in advance, as well as roots of different genotypes elicited similarly higher root growth compared to roots that encountered roots of connected ramets (Fig. 2A and B). Our results thus support the notion that coordination among roots of the same physiological individual plant rather than biochemical allorecognition, was responsible for S/NS root discrimination in T. repens. We are the first to demonstrate the effects of self/nonself root discrimination in this species, despite the enormous attention it enjoyed in ecology and agronomy, and the first to show that the responses were consistent among eight different field-collected genotypes. Our results thus suggest that self/nonself discrimination is a widespread phenomenon in wild populations of T. repens. Nonself interactions may lead to considerably higher rooting densities (and less flowering—see below) in white clover populations, especially where they consist of intermingled genotypes and fragmented clones.

**Table 1.** Tests of effects of self/nonself discrimination in Trifolium repens as expressed by root and shoot variables in Experiment 2

<table>
<thead>
<tr>
<th>Root length</th>
<th>Root biomass</th>
<th>Shoot biomass</th>
<th>Proportion of roots</th>
<th>Number of ramets</th>
<th>Number of flowers</th>
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<td>F</td>
<td>P</td>
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<td>F</td>
<td>P</td>
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<td>5.188</td>
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<tr>
<td>Genotype</td>
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<td>8.25</td>
<td>&lt;0.001</td>
<td>7</td>
<td>13.08</td>
</tr>
<tr>
<td>T x G</td>
<td>21</td>
<td>1.27</td>
<td>0.208</td>
<td>21</td>
<td>1.26</td>
</tr>
<tr>
<td>Error</td>
<td>217</td>
<td></td>
<td></td>
<td>217</td>
<td></td>
</tr>
</tbody>
</table>
Self/Nonself Discrimination in *Trifolium repens*

enhanced root growth more strongly upon encounters with roots of a different than of the same genotype (Fig. 2A and B). Nevertheless, here too, variability in the alienation time of recently-severed ramets could account for this discrepancy. Further work is necessary in order to totally rule out the possible role of biochemical allorecognition in S/NS root discrimination.

Whatever the precise mechanism, it is remarkable that none of the measured plant characteristics showed a difference in response among the eight *T. repens* genotypes in Experiment 2 (Table 1), despite large differences in genotypic means, as significant Genotype x Environment effects are ubiquitous for ecologically relevant plastic traits. If more generally true, this result will have profound consequences for the evolution and ecological significance of this type of interaction. It would suggest that additive genetic variation for S/NS discrimination is lacking and that benefits and costs are equally shared among competing individuals, effectively prohibiting the evolution of these traits. However, whether this lack of genotypic differentiation in self/nonself discrimination has wider validity (see ref. 19) is in urgent need of further investigation.

**Implications of self/nonself discrimination for growth and reproductive allocation.** We expected that enhanced root proliferation under nonself encounters would compromise shoot growth and reproduction, but this expectation was not borne out by the results. In both experiments, enhanced root proliferation under nonself interactions resulted in similar or higher shoot mass and number of ramets. This lack of cost of root growth occurred despite of the apparent intense belowground competition demonstrated by the leaf senescence that suggested strong nutrient limitation towards the end of the experiments. Yield density curves revealed that both *T. repens* genotypes interacted strongly when grown with a single neighbor under the conditions of our experiments (results not shown). The total shoot mass of two neighboring ramets was 70–94% that of four neighboring ramets growing under the same conditions in the same pots.

Our results seemingly challenge the evolutionary arguments rationalizing self/nonself discrimination and are in a potential conflict with the conclusions of a number of other experimental studies.11,18,19 However, a closer inspection of the results sheds light on the discrepancy with these results. Similar to our experiments, shoot mass at harvest was equal for plants experiencing self and nonself competition in both *Glycine max* and *Phaseolus vulgaris*,11,18 in spite of the smaller root systems produced under self interactions. Maina et al18 harvested plants at regular time intervals and showed that up to day 40, shoot mass was greater in plants interacting with roots of a different individual compared to plants interacting with their own roots. It was not until the last 20 d of the experiment that the shoot biomasses became equal. These results suggest that in the initial process of competition, when self/nonself discrimination has already begun, the larger roots take up more nutrients and enhance...
plant growth. Over longer periods, as competition for soil resources intensifies, costs of the larger root systems may become apparent and effects on plant performance may turn negative, as shown by Holzapfel and Alpert in *Fragaria chiloensis*. Nevertheless, further investigation will have to concentrate on studying the cumulative fitness effects of S/NS discrimination over realistic competitive regimes in the field and over much longer periods.

In support of the hypothesis that self/nonself discrimination yields ecological benefits and in contrast to the results on shoot biomass and number of ramets, the number of flowers per plant was higher under intact self interactions than in all other treatments in our second experiment (Fig. 3f). This result was consistent for most genotypes, despite a ten-fold difference in flowering percentage. Gersani et al. and Maina et al. also found a higher number of fruits and greater pod mass under self- rather than nonself competition, as in our experiment largely due to a higher propensity of meristems to flower. However, it remains to be demonstrated that meristic response is entirely or even partly due to resource shortage. In *Phaseolus vulgaris* a higher nutrient supply hardly increased the number of pods per unit of plant size, while the number of pods was 53% higher in similar-sized plants under self-than under nonself-competition, suggesting that nutrient availability and self/nonself discrimination affect flowering differently. There are no indications in this study, nor in ours, that resource shortage due restricted root production under self interaction was less severe than under nonself, severed, and alien interactions, explaining the flowering differences. Nevertheless, further research is necessary to confirm these results.

**References**