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Interaction between humus form and herbicide toxicity to Collembola (Hexapoda)

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1 **1. Introduction**

2

3 Numerous studies have assessed the impact of herbicides on soil fauna, but
4 contradictory results have been obtained, depending on animal groups studied, chemical nature
5 of the herbicide and additives, soil type and rate of application (Rapoport and Cangiolli, 1963;
6 Edwards, 1965; Edwards and Lofty, 1969; Curry, 1970; Van der Drift, 1970; Fratello et al., 1985;
7 Mallow et al., 1985; Prasse, 1985; Chalupský, 1989; Krogh, 1991). Before standardized
8 laboratory tests were developed some authors claimed that there was no direct effect of
9 herbicides on soil animals and that most increases or decreases of populations were indirect
10 effects, mostly caused by vegetation changes (Curry, 1970; Edwards and Thompson, 1973;
11 Chalupský, 1989). Nevertheless, under standardized conditions without interference from
12 vegetation, herbicides differ strongly in toxic as well as stimulatory effects when applied at field
13 doses (Eijsackers, 1978; Subagja and Snider, 1981; Eijsackers, 1991; Van Gestel et al., 1992).
14 Despite fruitful efforts to standardize methods (Riepert and Kula, 1996; Crouau et al., 1999)
15 some uncertainty is inherent in the representativeness of ecotoxicological studies for field
16 conditions, given what we know about avoidance and dispersion behaviour of Collembola
17 (Ulber, 1979; Duelli et al., 1990; Mebes and Filser, 1997; Alvarez et al., 2000). Acute toxicity
18 levels given by standardized indices such as LOEC or EC₅₀ (Reinecke 1992; Forbes and
19 Forbes, 1994; Riepert and Kula, 1996; Crouau et al., 1999) may be irrelevant for risk
20 assessment if field animals are killed by moving to untreated but unfavourable micro-sites at
21 doses far below recommended levels. The reversibility of local changes in habitat use, induced
22 by pesticides, can also be questioned, given the large variation in recovery processes from one
23 species to another (Alvarez et al., 2000). Given what we know about the behaviour of whole
24 animal communities compared to single species facing experimental stresses, and strong
25 interactions between animal species (Haukka, 1987; Hågvar, 1990; Ponge, 1999; Salmon and
26 Ponge, 1999), community-level effects must be suspected, which are not taken into account in
27 standardized tests using mass cultures of single species (Van Gestel et al., 1992). Thus there is
28 a need for field- and laboratory-based tests using communities (Frampton, 1997; Urzelai et al.,
29 2000; Cortet and Poinot-Balaguer, 2000) if we want to become more realistic in ecological risk

1 assessment (Van Straalen and Løkke, 1997; Van Straalen and Van Rijn, 1998; Suter et al.,
2 2000).

3
4 From our knowledge of the biochemical properties of soils at varying levels of acidity
5 and organic matter content (Coulson et al., 1960; Davies et al., 1964; Lindqvist, 1983; Petersen
6 and Persson, 1987; White, 1994), it may be hypothesized that organisms living in acid organic
7 soils are more tolerant of phenolic and terpenic compounds than organisms living in neutral
8 organo-mineral soils (Hågvar and Abrahamsen, 1984; Poinot-Balaguer et al., 1993; Ponge,
9 1993; Loranger et al., 2001). Thus, the effects of pesticides on non-target organisms can be
10 expected to vary according to soil features, in particular acidity, organic matter, clay and water
11 content, not only because of the impact of these factors on the fate of organic compounds
12 (Mortland et al., 1986; Müller-Wegener, 1987; Laszlo, 1987; Stehouwer et al., 1993; Akhouri et
13 al., 1997), but also because of different tolerance levels of different soil biocenoses. The latter
14 point has remained unstudied until now.

15
16 Springtails (Class Collembola, Phylum Arthropoda) were chosen, due to their
17 abundance and diversity in most soils (Petersen and Luxton, 1982; Ponge et al., 1997; Hopkin,
18 1997) and marked shifts in species composition caused by changes in acidity (Hågvar and
19 Abrahamsen, 1984; Ponge, 1993; Chagnon et al., 2000; Loranger et al., 2001).

20
21 In addition to laboratory bio-assays in semi-natural conditions, using two undisturbed
22 acid and neutral soils, attraction or avoidance of a herbicide by Collembola was assessed on
23 impregnated filter paper, using two different species coming from the same soils.

24

25 **2. Materials and methods**

26

27 *2.1. Laboratory tests using complete communities*

28

29 Experiments were performed on natural soils, with undisturbed animal communities, to
30 which a herbicide (Madit D®, with isoproturon as the active molecule) was applied at doses and

1 in the same way as in conventional agriculture. In order to test simultaneously the effects of
2 herbicide application and of acid humus inoculation, two different soils, the hemorganic A
3 horizon from a neutral (pH 7.5) Eumull and the holorganic O horizon from an acid (pH 4.3)
4 Dysmoder (Brêthes et al., 1995), were put together in two-compartmented boxes, with or
5 without the addition of herbicide to one or both compartments. Other experiments used the
6 same soil in both compartments, with and without herbicide.

7

8 The neutral hemorganic Eumull was considered to be a reference for agricultural soils,
9 harbouring more complete faunal communities due to organic matter input and the absence of
10 pesticide use and deep ploughing (Ponge, 2000b). Previous studies had shown that agricultural
11 soils and forest soils did not differ fundamentally when soil-dwelling communities were
12 considered (Ponge, 1993). The acid organic Dysmoder was used as a possible source for the
13 introduction of more tolerant strains of soil animals in agricultural soils.

14

15 Boxes made of moulded polystyrene (175 x 115 x 65 mm LxWxH) were used for these
16 experiments. A 2 mm thick wall made of polymethylmethacrylate was perforated (400 holes, 2
17 mm diameter each) then inserted in the central part of each box, dividing it into two connected
18 compartments 650 mL each. Small arthropods (including springtails) and worms (nematodes,
19 enchytraeids, small epigeic earthworms) were expected to cross the wall easily, following
20 preliminary experiments using defaunated soil (data not shown). There was no contact between
21 the soils present in the two compartments. Thus only animals and gases could move between
22 compartments.

23

24 OF (fragmented) and OH (humified) organic horizons of a Dysmoder humus profile (10
25 cm deep) were collected in a mixed forest stand (Senart forest, 20 km southwest of Paris),
26 made of sessile oak (*Quercus petraea* (Mattus.) Liebl. and Scots pine (*Pinus sylvestris* L.), then
27 gently homogenized by hand in a plastic sheet before being added to the appropriate
28 compartments. Stones, large roots and large pieces of wood were removed during the
29 homogenizing process. The same method was used for collecting the A (organo-mineral)
30 horizon of a calcic Eumull profile in a hornbeam stand (*Carpinus betulus* L.) in the park adjacent

1 to the laboratory (close to the Senart forest). Compartments were filled with humus, leaving only
2 the top 1cm free of soil, thus each compartment held ca. 500 mL of soil.

3

4 The herbicide Madit D® comprised 50% (w/v) isoproturon. It was applied at a rate of 3
5 L. ha⁻¹, which is the rate prescribed for the current control of annual grasses and broad-leaved
6 weeds. For that purpose each compartment receiving the herbicide (1 square decimeter) was
7 sprayed with 1.5 mL of a diluted solution containing 3 µL of the herbicide. Thus 1.5 mg of
8 isoproturon was applied to each compartment, corresponding to a nominal concentration of 5.6
9 mg.kg⁻¹ dry weight for the Eumull and 23 mg.kg⁻¹ dry weight for the Dysmoder. Boxes were then
10 closed and randomly placed in a dark chamber at constant temperature (15°C) for two weeks.

11

12 The following ten treatments were applied, with five replicates each, representing all
13 possible combinations of herbicide treatment (with or without) and humus type (Eumull or
14 Dysmoder):

15

- 16 • Eumull/Eumull (E/E)
- 17 • Dysmoder/Dysmoder (D/D)
- 18 • Eumull+Herbicide/Eumull+Herbicide (EH/EH)
- 19 • Eumull+Herbicide/Eumull (EH/E and E/EH)
- 20 • Dysmoder+Herbicide/Dysmoder+Herbicide (DH/DH)
- 21 • Dysmoder+Herbicide/Dysmoder (DH/D and D/DH)
- 22 • Eumull/Dysmoder (E/D and D/E)
- 23 • Eumull+Herbicide/Dysmoder+Herbicide (EH/DH and DH/EH)
- 24 • Eumull+Herbicide/Dysmoder (EH/D and D/EH)
- 25 • Eumull/Dysmoder+Herbicide (E/DH and DH/E)

26

27 The experiment allowed several comparisons to be made, which were treated
28 separately for the sake of clarity. Untreated collembolan communities (E/E and D/D) were used
29 for comparisons between the two animal communities. Soils treated with isoproturon but with
30 the same soil in both compartments (EH/EH and DH/DH) were compared with untreated soils

1 (E/E and D/D, respectively) to assess the effects of herbicide application alone. Experimental
2 boxes with the two compartments having received different treatments (herbicide or humus
3 type) were used to study more complex interactions, involving either the same humus type
4 (EH/EH, EH/E, DH/DH, DH/D) or two different humus types (E/D, EH/DH, EH/D, E/DH) in the
5 same box.

6

7 At the end of the experiment, the twin boxes were thoroughly voided and the soil
8 samples corresponding to the 100 compartments were separately extracted in Berlese funnels.
9 Soil samples (500 mL) were gently spread on a large size wire net (5 mm mesh size, 20 cm
10 diameter), in order to avoid possible barrier effects of surface-applied pesticides during
11 extraction (Krogh, 1991). During the 10-d extraction the soil was gently heated by 25 W bulb
12 lamps in order to avoid too rapid desiccation. Animals collected under the desiccating soil were
13 preserved in 95% ethyl alcohol before being sorted under a dissecting microscope. Collembola
14 were mounted in chloral-lactophenol (25 ml lactic acid, 50 g chloral hydrate, 25 ml phenol) and
15 identified to species under a phase contrast microscope at x400 magnification. Gisin (1960) was
16 used as a reference book but several more recent identification keys and diagnoses were used
17 additionally, including Zimdars and Dunger (1994), Jordana et al. (1997), Fjellberg (1998) and
18 Bretfeld (1999).

19

20 The basic data consisted of animal densities and number of species per compartment.
21 An additional index was calculated as the ratio between the number of species and the number
22 of individuals. It was referred to as the relative richness. Comparisons between treatments were
23 done at the species level or at the community level, using Kruskal-Wallis tests for comparisons
24 of means when replicates of compared treatments were independent (not in the same boxes) or
25 Friedman tests for paired comparisons when two compartments within the same box were
26 compared (Sokal and Rohlf, 1995). When the two compartments received the same treatment,
27 values were averaged for each box and used for comparisons with other treatments. Given that
28 extraction efficiency could vary from one humus type to another (Macfadyen, 1957),
29 comparisons between Eumull and Dysmoder should be made with care. Thus most conclusions
30 were based on comparisons between treatments applied to the same humus type. Despite the

1 (apparent) factorial design of the experiment, data could not be analysed by multi-way ANOVA,
2 since i) humus types were too different in their chemical and biological properties to expect
3 additive effects of humus type and herbicide, ii) compartments within a box were not
4 independent from each other.

5

6 2.2. Laboratory tests using single species

7

8 Two collembolan species, *Heteromurus nitidus* (Entomobryidae), living in the Eumull,
9 and *Folsomia manolachei* (Isotomidae), living in the Dysmoder, were previously reared on an
10 artificial substrate used for standardized tests (Riepert and Kula, 1996), made of a mixture of
11 10% sphagnum peat, 20% kaolinite and 70% fine quartz sand. The pH of the artificial substrate
12 was brought to 6.2 by adding 0.45% calcium carbonate. The substrate was moistened to 50% of
13 water holding capacity by adding deionized water. Cattle dung powder was given as additional
14 food when necessary. Cultures were kept in the dark at 15°C. Before each experimental run,
15 animals were conditioned for 20 min to light (artificial light) and temperature (20°C) used in the
16 experiment. Animals were individually introduced into 8 cm diameter Petri dishes, on the bottom
17 which was partially covered by two half-disks of 7 cm diameter Whatman filter paper at a
18 distance of 0.5 cm from each other. One half-disk was impregnated with deionized water and
19 used as a control, the other was impregnated with the test solution at varying concentration.
20 Fifteen Petri dishes (replicates) were placed under a Sharp® fluorescent illuminator normally
21 used for scanning documents, each with an animal placed in the space between two half-disks
22 at the beginning of the trial. Since subterranean springtails such as *H. nitidus* are highly
23 sensitive to light (Salmon and Ponge, 1998), control experiments were done with water on both
24 half-disks in order to verify the absence of light gradients under the illuminator. One hour after
25 the introduction of test animals, their position on one or the other half-disk was checked in each
26 Petri dish. Data were total numbers of animals either on water or on test solution. The
27 significance of attractive or repulsive effects of test solutions was assessed by a sign-test,
28 based on binomial distribution (Rohlf and Sokal, 1995). Animals used for an experimental run
29 were kept for further experiments with at least 48 h interval between two successive runs with

1 the same animal. In the meantime animals were kept on uncontaminated artificial substrate with
2 food added.

3

4 **3. Results**

5

6 *3.1. Untreated collembolan communities*

7

8 Thirty-nine species were identified in the material extracted at the end of the experiment
9 (Table 1). Ten were common to both soils (ubiquitous species), nine were found in the neutral
10 Eumull (pH 7.5) only (Eumull species), 16 in the acid Dysmoder (pH 4.3) only (Dysmoder
11 species), and six could not be attributed unambiguously to one or other humus type, since they
12 were found only in boxes with the two different soils (dubious species). Based on our extraction
13 results, five times as many animals and twice as many species were present in the acid than in
14 the neutral soil (Table 2, Fig. 1). Thus the relative richness of the Eumull was higher than that of
15 the Dysmoder. Abundance and number of ubiquitous species were higher in the Dysmoder than
16 in the Eumull. Among the common species (species present in more than 10 compartments)
17 ubiquitous relative to humus type, all but one either did not express significant differences in
18 their densities between humus types or were more abundant in the Dysmoder, the exception
19 being *Dicyrtoma fusca* which was more abundant in the Eumull (Table 2). *Parisotoma notabilis*,
20 although classified as ubiquitous, was nearly absent in the Eumull although it was the second
21 most abundant species in the Dysmoder, after *Isotomiella minor*, which dominated both
22 communities.

23

24 *3.2. Collembolan communities with herbicide and the same humus in both compartments*

25

26 Laboratory effects of Madit D® on collembolan communities can be assessed by
27 comparing between untreated experimental boxes with those in which the herbicide was added
28 to both compartments (Table 2, Fig. 1). There were no significant effects of the herbicide on the
29 abundance as well as the species richness of collembolan communities, whatever the humus
30 type, but two species, namely *Megalothorax minimus* and *Sphaeridia pumilis*, reacted positively

1 to the addition of the herbicide in the Dysmoder. Both species were found exclusively in
2 herbicide-treated boxes.

3

4 Possible avoidance or attraction effects could be tested when the herbicide was applied
5 to only one compartment. No such effect was detected in Eumull (Table 3), but a small although
6 significant effect was perceived in Dysmoder (Table 4). In Dysmoder, *Friesea truncata*
7 decreased in abundance in the treated compartment (DH/D) compared to the control (D/D),
8 while its abundance in the untreated compartment (D/DH) was not different from the control.
9 The case of the ubiquitous species *Sphaeridia pumilis* was somewhat different, since it was
10 absent in the control (D/D), but present in both treated (DH/D) and untreated (D/DH)
11 compartments (Table 4). This resulted in an increase by one in the number of ubiquitous
12 species, as well as in the relative richness index.

13

14 3.3. Interaction between humus type and herbicide in Eumull communities

15

16 The combination of Dysmoder with Eumull caused an increase in the relative richness
17 of the collembolan Eumull community (Table 5). This increase was due to the addition of
18 Dysmoder species to the Eumull population (Fig. 1). This addition was counterbalanced by a
19 strong decrease in the abundance and number of Eumull species, from 5.5 and 2.5,
20 respectively, to only one individual (and thus one species) per compartment. The net result was
21 a decrease in the total abundance and an increase in the total number of species of Collembola
22 per compartment. The relative richness index increased accordingly. At the species level (Table
23 5), *Isotomurus palustris*, an Eumull species, was negatively affected by the presence of
24 Dysmoder, its population collapsing to less than one individual per compartment. The observed
25 decrease in the total abundance of Collembola was mainly due to a collapse in the population of
26 *Isotomurus palustris*, the second most abundant species of the Eumull after *Isotomiella minor*.
27 The decrease in the number of Eumull species was due, not only to the collapse of the
28 *Isotomurus palustris* population, but also to the disappearance of several other less abundant
29 Eumull species, among them *Heteromurus nitidus* (data not shown).

30

1 The observed collapse in Eumull species (both in abundance and number) under the
2 influence of the presence of Dysmoder was less pronounced when the herbicide was added,
3 regardless of the compartment chosen for this addition (Table 5, Fig. 1). Nevertheless the
4 abundance of *Isotomurus palustris* remained always at a very low level, compared to Eumull
5 alone (with or without herbicide, see Table 2). An increase of the number of ubiquitous species
6 was observed in Eumull when it was combined with Dysmoder plus herbicide. As already
7 mentioned Dysmoder species appeared, too, in Eumull when this was combined with
8 Dysmoder, irrespective of the application of the herbicide.

9 10 3.4. Interaction between humus type and herbicide in Dysmoder communities

11
12 An increase in the total number of species was observed in Dysmoder combined with
13 Eumull, compared to Dysmoder alone (Table 6, Fig. 1). At the species level, the only effect of
14 the presence of Eumull was a strong decrease in the abundance of *Neanura muscorum*, a
15 Dysmoder species (Table 1).

16
17 The herbicide interacted with the humus type by increasing the number of ubiquitous
18 species in Dysmoder combined with Eumull when the application occurred in both
19 compartments (Fig. 1, Table 6). The abundance of Dysmoder species in Dysmoder combined
20 with Eumull decreased by 50% when the herbicide was applied to the Dysmoder compartment.
21 At the species level, the abovementioned decrease in the abundance of *Neanura muscorum*
22 when Dysmoder was combined with Eumull disappeared in the presence of herbicide, whatever
23 the compartment chosen for the application (Table 6). *Sphaeridia pumilis*, which was absent
24 from Dysmoder in the absence of Eumull (Table 6) or of herbicide (Table 2), was present when
25 the acid humus was combined with Eumull, and the abundance of this species increased in the
26 presence of herbicide, whatever the compartment chosen for its application. Another stimulatory
27 effect of the herbicide was observed also on *Lepidocyrtus lignorum*, the population of which
28 doubled when the herbicide was applied to both compartments.

29 30 3.5. Laboratory assays on single species

1

2 Experiments with *Heteromurus nitidus*, a typical Eumull species (Ponge, 1993; Salmon
3 and Ponge, 1999), showed it to be indifferent to the presence of isoproturon until a
4 concentration of 0.5 mg.L^{-1} was reached (Fig. 2). Above this threshold, the animals avoided the
5 herbicide, but the departure from indifference was significant only above 5 mg.L^{-1} . The other
6 species, *Folsomia manolachei*, coming from Dysmoder soil, exhibited a weak (insignificant)
7 attraction to the herbicide at concentrations below 0.05 mg.L^{-1} , then the response abruptly
8 turned to avoidance, which became significant above 0.5 mg.L^{-1} .

9

10 At the beginning of the experiment with complete collembolan communities, the
11 concentration of isoproturon in the soil solution varied from 2.7 mg.L^{-1} for Eumull to 4.4 mg.L^{-1}
12 for Dysmoder, as ascertained from the amount of herbicide applied at the beginning of the
13 experiment and the amount of water present in the soil. Compared to filter paper experiments
14 this corresponded to a concentration where *Heteromurus nitidus* shifted from indifference to
15 avoidance (Fig. 1) and to a range of concentration where *Folsomia manolachei* clearly avoided
16 the herbicide.

17

18 4. Discussion

19

20 The two-week laboratory experiment on complete collembolan communities did not
21 reveal effects of the application of isoproturon on the Eumull population. On the contrary, in
22 several treatments the Dysmoder population showed an increase in the abundance of two
23 species, the Symphypleone *Sphaeridia pumilis* and the Neelipleone *Megalothorax minimus*.
24 Both were totally absent from the untreated soil; thus the herbicide can be suspected of
25 favouring egg hatching, for instance by terminating diapause, or by decreasing egg predation.
26 Although no clear-cut explanation can be found, it should be noted that *Sphaeridia pumilis* is
27 known for its temporary disappearance, eggs being the only resting stage during unfavourable
28 seasons (Blancquaert et al., 1982). A higher predation pressure can be suspected in Dysmoder
29 compared to Eumull (Salmon and Ponge, 1999), which could explain why such effects were not
30 shown in Eumull. Thus direct as well as indirect effects of the herbicide could explain the

1 observed phenomenon, although literature data cannot support either one or the other
2 hypothesis.

3

4 Avoidance effects were revealed by choice experiments on filter paper, at the same
5 concentration as that employed for the community experiment with natural soils. Such a
6 phenomenon was only poorly revealed in soil when animals were allowed to cross a perforated
7 wall to reach a compartment without herbicide. Among the more abundant species only the
8 predator *Friesea truncata* was suspected of having escaped from the herbicide-treated
9 Dysmoder compartment. This species decreased in density in the treated Dysmoder soil when
10 combined with Eumull, but in this case no corresponding increase was observed in the Eumull
11 counterpart, pointing to the ability of the Dysmoder population of *F. truncata* to cross the
12 perforated wall to escape from the herbicide-treated compartment, but its inability to survive in
13 Eumull.

14

15 Most marked effects were displayed by the Eumull community when Dysmoder was
16 present in the neighbouring compartment. A strong depressive effect was observed on the
17 epigeic species *Isotomurus palustris*, although it was not affected at all by the herbicide. At first
18 sight this could be due to attraction to Dysmoder as well as to toxicity. Attraction to the
19 Dysmoder compartment can be ruled out since only a few individuals of this Eumull species
20 were found in Dysmoder when adjacent to Eumull, thus no compensatory increase occurred in
21 the Dysmoder. Since *Isotomurus palustris* normally lives aboveground (Ponge, 1993), we can
22 suspect that it did not withstand the Dysmoder smell in our experimental boxes, where volatile
23 compounds (fungal odours, terpenes) probably abound. It has been demonstrated that the
24 odour of the micromycete *Trichoderma* was avoided by the collembolan *Onychiurus sinensis*
25 (Sadaka-Laulan et al., 1998), and that some compounds isolated from fungal odours could be
26 repellent to Collembola, too (Bengtsson et al., 1991), but no toxic effect mediated by olfactory
27 compounds has been demonstrated so far.

28

29 Reverse effects of Eumull upon the Dysmoder community were quite different. No toxic
30 effect of Eumull was observed, except a decrease in the abundance of the neanurid *Neanura*

1 *muscorum*. Colonization of the Eumull compartment by animals coming from the Dysmoder was
2 demonstrated. In the Dysmoder compartment, the population was stimulated to a great extent,
3 probably above numbers actually found at the end of the experiment if Dysmoder animals found
4 in the Eumull compartment (colonizing individuals) are added.

5
6 Despite weak effects of the herbicide alone, the combination of herbicide and humus
7 treatments exhibited non-additive effects. The disappearance of toxic effects of Dysmoder upon
8 herbicide application could result from an inactivation of the toxic components of the Dysmoder
9 smell (if any) by isoproturon or adjuvant compounds. In the absence of any knowledge on the
10 formulation of Madit D®, this information being not given by the producer, no clear hypotheses
11 can be drawn. If we take into account the rapid transformation of isoproturon in the soil
12 (Verschueren, 2001), mainly resulting from demethylation, hydrolysis and hydroxylation of the
13 phenylurea moiety within a few weeks, a number of different chemicals, each with its own
14 sorptive properties, may have appeared within the two weeks of our experiment. When
15 Dysmoder was combined with Eumull, Dysmoder species were not eliminated by the herbicide,
16 which otherwise would have resulted in a decrease in their number. Nevertheless, we observed
17 a decrease in the abundance of species commonly but exclusively living in acid soils, such as
18 the epigeic *Lipothrix lubbocki* and the endogeic *Proisotoma minima* (Ponge, 1993; Ponge,
19 2000a), in addition to the already mentioned depressive effect on the ubiquitous *Friesea*
20 *truncata*. Since *L. lubbocki* and *P. minima* were never retrieved in the adjacent Eumull
21 compartment, it appears that either i) they were directly or indirectly affected by the herbicide
22 without being able to escape it or ii) they escape Dysmoder compartments but were killed in
23 Eumull compartments. Such an effect was not displayed by the application of herbicide to
24 Dysmoder in the absence of Eumull, which could give support to the second hypothesis.

25

26 Methods used in the present study allow the measurement of subtle effects of
27 herbicides on motile non-target organisms, such as soil microarthropods, in particular when
28 toxicity, attraction and avoidance are combined. Doses at which the herbicide was applied are
29 well below the thresholds given for the toxicity of isoproturon. For instance, nitrification is not
30 inhibited below 300 mg.L⁻¹ (Verschueren, 2001, nominal data per unit of soil not given), which is

1 not far from the concentration of the undiluted herbicide (500 mg.L⁻¹). Despite low concentration
2 of the herbicide, perturbations of soil animal communities were displayed, especially when two
3 distinct humus types were put together in the same boxes, pointing on non-additive effects of
4 humus type and herbicide application. At the low doses used for our experiment on collembolan
5 communities, avoidance rather than toxic effects can be suspected, supported by experimental
6 results with single species, but toxic effects of one humus type upon the other, as well as
7 detoxifying effects of the herbicide were registered, too, pointing to complex relationships
8 between pesticides and soils when living organisms are involved (Torstensson, 2000). We
9 conclude that further experiments are necessary before the inoculation of organisms living in
10 acid soils, suggested as a trade-off for the negative impact of pesticides on biodiversity (Forbes
11 and Forbes, 1994), could be applied successfully to agricultural soils.

12

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14

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17

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1 **7. Figure captions**

2

3 **Fig. 1.** Species richness of Collembola in the adjacent compartments of experimental twin
4 boxes. E = Eumull soil. EH = Eumull soil treated with isoproturon. D = Dysmoder soil.
5 DH = Dysmoder soil treated with isoproturon. Bars indicate standar errors (five
6 replicates).

7

8 **Fig. 2.** Results of choice experiments with *Heteromurus nitidus* (Eumull population) and
9 *Folsomia manolachei* (Dysmoder population), showing the number of animals found on
10 impregnated filter paper after one hour (15 replicates with one individual each) plotted
11 as a function of the concentration of the herbicide (logarithmic scale). Arrows (E for
12 Eumull and D for Dysmoder) indicate the concentration of the soil solutions in
13 experiments with complete collembolan communities. Horizontal lines indicate absence
14 of choice (7.5 individuals on each side) and its confidence interval at the 95% threshold
15 level.

16

Table 1. List of collembolan species found in the experiments with complete communities. 0: absence, 1: presence

	Eumull	Dysmoder	Ubiquitous	Dubious
<i>Allacma fusca</i> (Linné, 1758)	0	0	0	1
<i>Allacma gallica</i> (Carl, 1899)	0	1	0	0
<i>Arrhopalites caecus</i> (Tullberg, 1871)	1	0	0	0
<i>Arrhopalites sericus</i> Gisin, 1947	0	1	0	0
<i>Dicyrtoma fusca</i> (Lucas, 1842)	0	0	1	0
<i>Dicyrtomina minuta</i> (Fabricius, 1783)	0	0	0	1
<i>Entomobrya nivalis</i> (Linné, 1758)	0	1	0	0
<i>Folsomia candida</i> (Willem, 1902)	1	0	0	0
<i>Folsomia manolachei</i> Bagnall 1939	1	0	0	0
<i>Friesea truncata</i> Cassagnau, 1958	0	0	1	0
<i>Heteromurus major</i> (Monniez, 1889)	0	1	0	0
<i>Heteromurus nitidus</i> (Templeton, 1835)	1	0	0	0
<i>Isotomiella minor</i> (Schäffer, 1896)	0	0	1	0
<i>Isotomurus palustris</i> (Müller, 1776)	1	0	0	0
<i>Kalaphorura burmeisteri</i> (Lubbock, 1873)	1	0	0	0
<i>Lepidocyrtus lanuginosus</i> (Gmelin, 1788)	0	0	1	0
<i>Lepidocyrtus lignorum</i> (Fabricius, 1781)	0	0	1	0
<i>Lipothrix lubbocki</i> (Tullberg, 1872)	0	1	0	0
<i>Megalothorax minimus</i> (Willem, 1900)	0	1	0	0
<i>Mesaphorura betschi</i> Rusek, 1979	0	1	0	0
<i>Mesaphorura jevanica</i> Rusek, 1996	0	0	1	0
<i>Mesaphorura leitzaensis</i> Jordana, 1993	0	0	1	0
<i>Mesaphorura macrochaeta</i> Rusek, 1976	1	0	0	0
<i>Mesaphorura yosii</i> (Rusek, 1967)	0	1	0	0
<i>Micranurida pygmaea</i> (Börner, 1901)	0	1	0	0
<i>Neanura muscorum</i> (Templeton, 1835)	0	1	0	0
<i>Oncopodura crassicornis</i> Shoebbotham, 1911	0	0	0	1
<i>Onychiurus jubilaris</i> Gisin, 1957	0	0	0	1
<i>Orchesella cincta</i> (Linné, 1758)	0	0	1	0
<i>Paratullbergia callipygos</i> (Börner, 1902)	0	1	0	0
<i>Parisotoma notabilis</i> (Schäffer, 1896)	0	0	1	0
<i>Pogonognathellus flavescens</i> (Tullberg, 1871)	0	0	0	1
<i>Proisotoma minima</i> (Absolon, 1901)	0	1	0	0
<i>Pseudosinella alba</i> (Packard, 1873)	0	1	0	0
<i>Sminthurinus aureus</i> (Lubbock, 1862)	1	0	0	0
<i>Sphaeridia pumilis</i> (Krausbauer, 1898)	0	0	1	0
<i>Stenaphorura denisi</i> (Bagnall, 1935)	1	0	0	0
<i>Tomocerus minor</i> (Lubbock, 1862)	0	1	0	0
<i>Willemia anophthalma</i> Börner, 1901	0	1	0	0
<i>Xenylla tullbergi</i> Börner, 1903	0	1	0	0
1 <i>Xenyllodes armatus</i> (Axelson, 1903)	0	0	0	1

2

Table 2. Results of treatments in which both 550 mL compartments of experimental boxes received or not the herbicide. Data are numbers of animals per compartment, averaged over five replicates, with standard errors. Significant differences among treatments ($P < 0.05$) are indicated by different letters

	Eumull	Eumull+Herbicide	Dysmoder	Dysmoder+Herbicide
<i>Dicyrtoma fusca</i>	1.9±0.7a	2.3±0.3a	0b	0.1±0.1b
<i>Folsomia manolachei</i>	0.6±0.3	0.3±0.1	0	0
<i>Friesea truncata</i>	1.5±0.3b	1.3±0.3b	14.6±0.9a	18.4±3.4a
<i>Heteromurus major</i>	0b	0b	1.7±0.7a	3.2±0.5a
<i>Isotomiella minor</i>	10.7±1.6b	9.9±1.3b	46.8±6.3a	56.7±10.0a
<i>Isotomurus palustris</i>	3.7±1.6a	4.5±2.2a	0b	0b
<i>Lepidocyrtus lanuginosus</i>	0b	0.1±0.1b	7.0±1.0a	3.9±1.3a
<i>Lepidocyrtus lignorum</i>	0b	0.2±0.2b	2.8±0.6a	3.3±1.1a
<i>Lipothrix lubbocki</i>	0b	0b	2.8±0.4a	2.7±0.3a
<i>Megalothorax minimus</i>	0b	0b	0b	0.9±0.2a
<i>Mesaphorura leizaensis</i>	0	0.1±0.1	0.1±0.1	0.7±0.3
<i>Micranurida pygmaea</i>	0	0	0.2±0.2	0.4±0.2
<i>Neanura muscorum</i>	0b	0b	3.3±1.0a	3.4±2.4ab
<i>Orchesella cincta</i>	0.1±0.1	0	0.6±0.4	0
<i>Paratullbergia callipygos</i>	0	0	0.2±0.1	0.9±0.4
<i>Parisotoma notabilis</i>	0.2±0.2b	0.2±0.2b	16.7±0.9a	14.4±2.6a
<i>Proisotoma minima</i>	0b	0b	7.9±1.6a	8.7±1.9a
<i>Sphaeridia pumilis</i>	0b	0.1±0.1b	0b	3.4±1.9a
<i>Stenaphorura denisi</i>	0.4±0.2	0.3±0.2	0	0
<i>Tomocerus minor</i>	0b	0b	1.2±0.3a	1.3±0.4a
Total abundance	19.9±2.2b	19.9±3.8b	106.3±7.5a	122.8±13.0a
Total number of species	5.0±0.6b	4.9±0.6b	10.3±0.3a	11.7±0.7a
Relative richness	0.27±0.08a	0.28±0.03a	0.10±0.01b	0.10±0.01b
Abundance of Eumull species	5.5±1.9a	5.5±2.5a	0b	0b
Number of Eumull species	2.5±0.4a	1.7±0.2a	0b	0b
Abundance of ubiquitous species	14.4±1.8b	14.3±1.8b	88.7±6.3a	100.9±12.7a
Number of ubiquitous species	2.5±0.3b	3.1±0.4b	5.5±0.3a	5.9±0.4a
Abundance of Dysmoder species	0b	0b	17.6±1.7a	21.9±4.1a
Number of Dysmoder species	0b	0b	4.8±0.4a	5.8±0.3a

1

2

Table 3. Experiments with Eumull in the two compartments of experimental boxes. Data are numbers of animals per compartment averaged over five replicates, with standard errors. The slash sign separates the considered compartment (left) and the adjacent compartment (right). When both compartments were given the same treatment, corresponding data were pooled, otherwise they were considered as distinct treatments. Differences between treatments are not significant ($P > 0.05$)

	Eumull/Eumull	Eumull/Eumull+Herbicide	Eumull+Herbicide/Eumull
<i>Dicyrtoma fusca</i>	1.9±0.7	1.4±0.5	1.8±0.6
<i>Folsomia manolachei</i>	0.6±0.3	0.8±0.4	1.6±0.5
<i>Friesea truncata</i>	1.5±0.3	1.6±0.7	1.8±0.9
<i>Heteromurus major</i>	0	0	0
<i>Isotomiella minor</i>	10.7±1.6	10.0±2.1	8.2±3.6
<i>Isotomurus palustris</i>	3.7±1.6	13.6±12.4	20.4±17.9
<i>Lepidocyrtus lanuginosus</i>	0	0	0
<i>Lepidocyrtus lignorum</i>	0	0	0
<i>Lipothrix lubbocki</i>	0	0	0
<i>Megalothorax minimus</i>	0	0	0
<i>Mesaphorura leitzaensis</i>	0	0	0
<i>Micranurida pygmaea</i>	0	0	0
<i>Neanura muscorum</i>	0	0	0
<i>Orchesella cincta</i>	0.1±0.1	0	0
<i>Paratullbergia callipygos</i>	0	0	0
<i>Parisotoma notabilis</i>	0.2±0.2	0	0
<i>Proisotoma minima</i>	0	0	0
<i>Sphaeridia pumilis</i>	0	0.2±0.2	0.2±0.2
<i>Stenaphorura denisi</i>	0.4±0.2	0	0
<i>Tomocerus minor</i>	0	0	0
Total abundance	19.9±2.2	28.8±13.7	35.6±22.4
Total number of species	5.0±0.6	4.6±0.4	4.6±0.9
Relative richness	0.27±0.08	0.28±0.08	0.31±0.09
Abundance of Eumull species	5.5±1.9	15.4±12.4	23.4±17.8
Number of Eumull species	2.5±0.4	1.6±0.2	1.6±0.5
Abundance of ubiquitous species	14.4±1.8	13.4±2.4	12.0±4.8
Number of ubiquitous species	2.5±0.3	3.0±0.3	2.8±0.5
Abundance of Dysmoder species	0	0	0
Number of Dysmoder species	0	0	0

1

2

Table 4. Experiments with Dysmoder in the two compartments of experimental boxes. Data are numbers of animals per compartment averaged over five replicates, with standard errors. The slash sign separates the considered compartment (left) and the adjacent compartment (right). When both compartments were given the same treatment, corresponding data were pooled, otherwise they were considered as distinct treatments. Significant differences between treatments ($P < 0.05$) are indicated by different letters

	Dysmoder/Dysmoder	Dysmoder/Dysmoder+Herbicide	Dysmoder+Herbicide/Dysmoder
<i>Dicyrtoma fusca</i>	0	0	0
<i>Folsomia manolachei</i>	0	0	0
<i>Friesea truncata</i>	14.6±0.9a	18.6±6.5ab	7.4±1.9b
<i>Heteromurus major</i>	1.7±0.7	3.0±1.0	2.8±0.4
<i>Isotomiella minor</i>	46.8±6.3	40.6±6.4	32.6±7.3
<i>Isotomurus palustris</i>	0	0	0
<i>Lepidocyrtus lanuginosus</i>	7.0±1.0	5.8±1.0	5.2±1.5
<i>Lepidocyrtus lignorum</i>	2.8±0.6	2.8±0.7	4.2±1.2
<i>Lipothrix lubbocki</i>	2.8±0.4	2.2±0.7	2.2±1.0
<i>Megalothorax minimus</i>	0	2.2±2.2	1.0±0.5
<i>Mesaphorura leitzaensis</i>	0.1±0.1	0.6±0.6	0.4±0.2
<i>Micranurida pygmaea</i>	0.2±0.2	0.2±0.2	0.2±0.2
<i>Neanura muscorum</i>	3.3±1.0	1.0±0.3	2.2±1.7
<i>Orchesella cincta</i>	0.6±0.4	1.0±0.4	0.6±0.4
<i>Paratullbergia callipygos</i>	0.2±0.1	0.4±0.2	0.8±0.4
<i>Parisotoma notabilis</i>	16.7±0.9	16.6±3.9	14.6±4.0
<i>Proisotoma minima</i>	7.9±1.6	6.2±1.6	5.4±2.7
<i>Sphaeridia pumilis</i>	0b	3.2±2.0a	2.8±1.2a
<i>Stenaphorura denisi</i>	0	0	0
<i>Tomocerus minor</i>	1.2±0.3	1.2±0.8	1.8±0.7
Total abundance	106.3±7.5	106.6±6.5	85.2±16.6
Total number of species	10.3±0.3	11.8±0.5	12.8±1.0
Relative richness	0.10±0.01b	0.11±0.01ab	0.19±0.05a
Abundance of Eumull species	0	0	0
Number of Eumull species	0	0	0
Abundance of ubiquitous species	88.7±6.3	89.2±5.5	67.8±12.8
Number of ubiquitous species	5.5±0.3b	6.6±0.2a	6.6±0.2a
Abundance of Dysmoder species	17.6±1.7	17.4±3.5	17.4±4.4
Number of Dysmoder species	4.8±0.4	5.2±0.6	6.2±1.0

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Table 5. Experiments with Eumull communities adjacent to Dysmoder. Data are means of five replicates with standard errors. The slash sign separates the considered compartment (left) and the adjacent compartment (right). When both compartments were given the same treatment, corresponding data were pooled, otherwise they were considered as distinct treatments. Significant differences between treatments ($P < 0.05$) are indicated by different letters

	Eumull/Eumull	Eumull/Dysmoder	Eumull/Dysmoder+Herbicide	Eumull+Herbicide/Dysmoder+Herbicide	Eumull+Herbicide/Dysmoder
<i>Dicyrtoma fusca</i>	1.9±0.7	1.2±0.4	1.2±0.5	1.4±0.5	1.0±0.3
<i>Folsomia manolachei</i>	0.6±0.3ab	0.0±0.0b	1.0±0.0a	0.4±0.2ab	1.0±0.8ab
<i>Friesea truncata</i>	1.5±0.3	1.8±0.8	1.8±0.7	1.4±0.4	1.2±0.5
<i>Heteromurus major</i>	0	0.2±0.2	0	0.2±0.2	0.4±0.2
<i>Isotomiella minor</i>	10.7±1.6	8.4±1.5	10.8±2.6	9.8±2.4	7.4±2.1
<i>Isotomurus palustris</i>	3.7±1.6a	0.6±0.2b	1.0±0.8ab	0.8±0.2b	0.4±0.2b
<i>Lepidocyrtus lanuginosus</i>	0	0.2±0.2	0.2±0.2	0.2±0.2	0.2±0.2
<i>Lepidocyrtus lignorum</i>	0	0.2±0.2	0.2±0.2	0.2±0.2	0
<i>Lipothrix lubbocki</i>	0	0	0	0.2±0.2	0.2±0.2
<i>Megalothorax minimus</i>	0	0	0.4±0.4	0	0
<i>Mesaphorura leitzaensis</i>	0	0	0	0.4±0.2	0
<i>Micranurida pygmaea</i>	0	0	0	0	0
<i>Neanura muscorum</i>	0	0.2±0.2	0	0.2±0.2	0.2±0.2
<i>Orchesella cincta</i>	0.1±0.1	0.2±0.2	0	0	0.2±0.2
<i>Paratullbergia callipygos</i>	0	0.2±0.2	0.4±0.4	0	0
<i>Parisotoma notabilis</i>	0.2±0.2	0.6±0.4	0.2±0.2	0	0.4±0.2
<i>Proisotoma minima</i>	0	0	0	0	0
<i>Sphaeridia pumilis</i>	0	0.4±0.4	0.2±0.2	0.8±0.6	0
<i>Stenaphorura denisi</i>	0.4±0.2	0.4±0.2	0.2±0.2	0.4±0.2	1.0±0.4
<i>Tomocerus minor</i>	0	0	0	0	0
Total abundance	19.9±2.2	15.2±2.6	18.2±3.0	17.0±2.6	16.8±5.0
Total number of species	5.0±0.6	5.8±0.7	6.0±0.3	6.6±0.9	5.8±0.7
Relative richness	0.27±0.04b	0.40±0.03a	0.36±0.05ab	0.41±0.06ab	0.44±0.10ab
Abundance of Eumull species	5.5±1.9a	1.0±0.0b	2.6±1.1ab	2.2±0.6ab	5.6±3.6ab
Number of Eumull species	2.5±0.4a	1.0±0.0b	2.0±0.5ab	2.2±0.6ab	1.8±0.4ab
Abundance of ubiquitous species	14.4±1.8	13.0±2.4	14.6±2.3	14.2±2.4	10.4±2.4
Number of ubiquitous species	2.5±0.3b	3.6±0.7ab	3.4±0.2a	3.8±0.7ab	3.2±0.5ab
Abundance of Dysmoder species	0b	0.6±0.2a	0.8±0.5ab	0.6±0.2a	0.8±0.4ab
Number of Dysmoder species	0b	0.6±0.2a	0.4±0.2ab	0.6±0.2a	0.8±0.4ab

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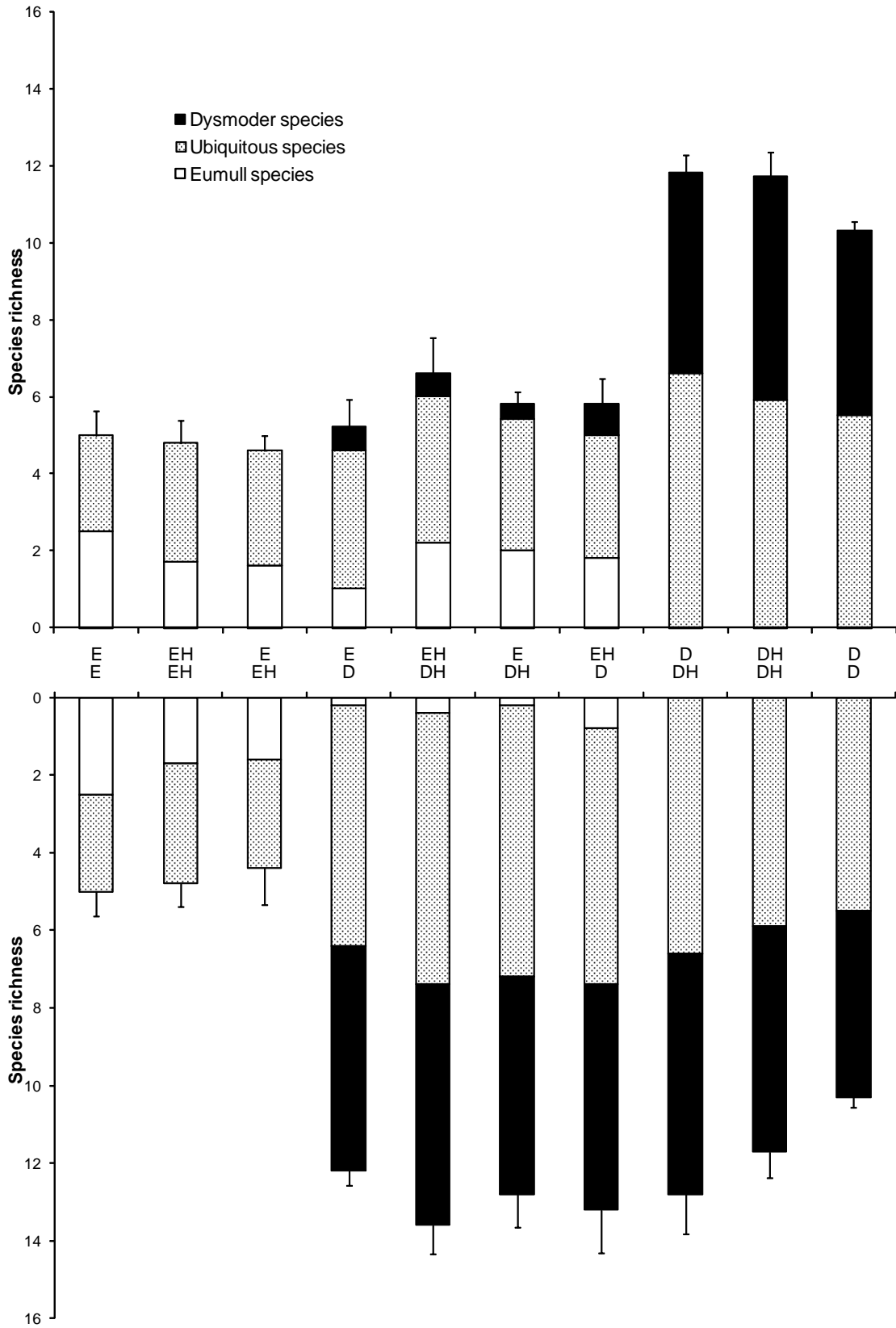
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Table 6. Experiments with Dysmoder communities adjacent to Eumull. Data are means of five replicates with standard errors. The slash sign separates the considered compartment (left) and the adjacent compartment (right). When both compartments were given the same treatment, corresponding data were pooled, otherwise they were considered as distinct treatments. Significant differences between treatments ($P < 0.05$) are indicated by different letters

	Dysmoder/Dysmoder	Dysmoder/Eumull	Dysmoder/Eumull+Herbicide	Dysmoder+Herbicide/Eumull+Herbicide	Dysmoder+Herbicide/Eumull
<i>Dicyrtoma fusca</i>	0	0	0.4±0.4	0	0.2±0.2
<i>Folsomia manolachei</i>	0	0	0.2±0.2	0.2±0.2	0
<i>Friesea truncata</i>	14.6±0.9a	15.0±4.8ab	14.8±3.6ab	16.4±4.8ab	8.4±1.9b
<i>Heteromurus major</i>	1.7±0.7	2.2±0.9	3.8±0.7	3.6±0.7	2.2±0.4
<i>Isotomiella minor</i>	46.8±6.3	63.8±12.8	45.6±12.3	54.8±9.3	67.8±8.0
<i>Isotomurus palustris</i>	0	0.2±0.2	1.0±1.0	0.2±0.2	0
<i>Lepidocyrtus lanuginosus</i>	7.0±1.0	4.8±0.7	7.8±3.0	6.6±1.3	5.2±1.7
<i>Lepidocyrtus lignorum</i>	2.8±0.6b	2.6±0.4b	3.6±0.8ab	5.0±0.5a	3.6±0.9ab
<i>Lipothrix lubbocki</i>	2.8±0.4a	2.8±1.0ab	3.6±0.9a	2.4±0.7ab	1.4±0.4b
<i>Megalothorax minimus</i>	0	0	0.2±0.2	0.2±0.2	0.8±0.4
<i>Mesaphorura leizaensis</i>	0.1±0.1	0.6±0.6	0.2±0.2	0.4±0.2	0.8±0.4
<i>Micranurida pygmaea</i>	0.2±0.2	0.2±0.2	0.6±0.2	0.4±0.2	0.2±0.2
<i>Neanura muscorum</i>	3.3±1.0a	0.6±0.2b	4.6±3.1a	3.0±1.4ab	1.0±0.3ab
<i>Orchesella cincta</i>	0.6±0.4	0.4±0.2	0.8±0.8	1.0±0.4	0.2±0.2
<i>Paratullbergia callipygos</i>	0.2±0.1	1.2±0.6	0.6±0.4	0.8±0.4	0.6±0.2
<i>Parisotoma notabilis</i>	16.7±0.9	19.6±4.3	16.0±3.4	18.8±1.8	18.4±4.1
<i>Proisotoma minima</i>	7.9±1.6a	7.4±1.5ab	9.8±3.6a	7.4±1.4a	2.4±0.7b
<i>Sphaeridia pumilis</i>	0.0±0.0c	1.2±0.6bc	5.2±2.3ab	4.8±1.2a	3.4±1.0ab
<i>Stenaphorura denisi</i>	0	0	0	0	0
<i>Tomocerus minor</i>	1.2±0.3	1.2±0.6	0.4±0.4	1.2±0.4	1.0±0.4
Total abundance	106.3±7.5	127.8±18.1	121.0±29.5	127.6±13.7	118.0±14.7
Total number of species	10.3±0.3b	12.2±0.4a	13.8±1.1a	13.8±0.7a	13.0±0.8a
Relative richness	0.10±0.01	0.10±0.01	0.13±0.02	0.11±0.01	0.11±0.01
Abundance of Eumull species	0	0.2±0.2	1.6±1.1	0.4±0.2	0.2±0.2
Number of Eumull species	0	0.2±0.2	0.8±0.4	0.4±0.2	0.2±0.2
Abundance of ubiquitous species	88.7±6.3	108.0±17.6	94.4±22.7	107.8±12.7	108.0±14.0
Number of ubiquitous species	5.5±0.3c	6.2±0.2bc	6.6±0.4ab	7.0±0.0a	7.0±0.3ab
Abundance of Dysmoder species	17.6±1.7a	19.6±1.2ab	24.2±6.9a	19.2±2.3a	9.6±1.7b
Number of Dysmoder species	4.8±0.4	5.8±0.2	5.8±0.7	6.2±0.7	5.6±0.8

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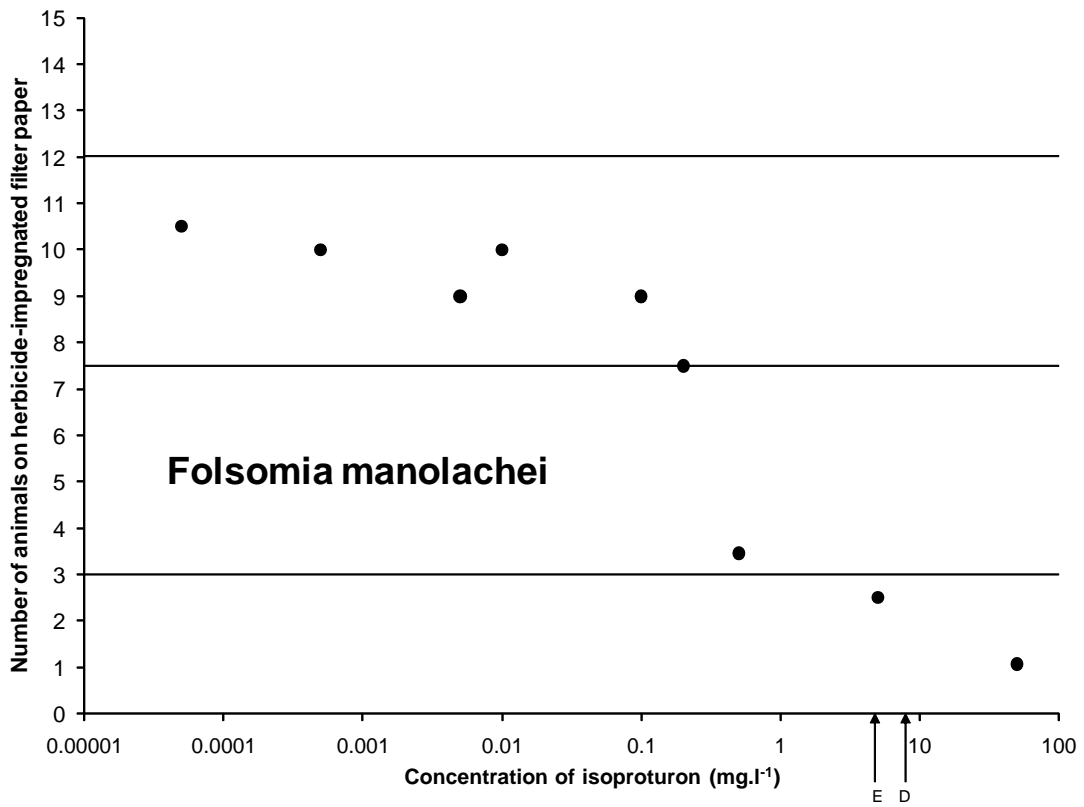
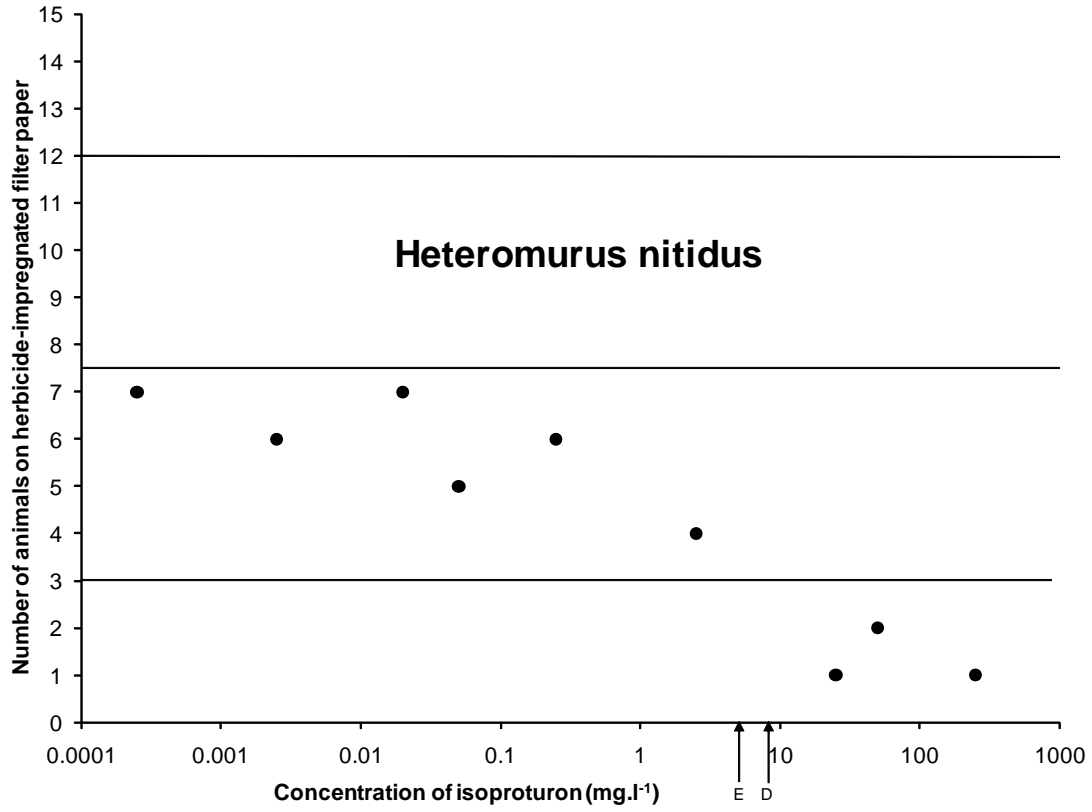
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2 Fig. 1

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2 Fig. 2