**Supporting information**

Negative effects of forest gaps on dung removal in a full-factorial experiment

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**Table S1.** Number of individuals of each dung beetle species collected per experimental treatment. Nomenclature follows Rössner (2012). Species-specific individual biomass (in g) and habitat preferences (both taken from Frank et al. 2017) are also given. Summaries of communities per treatment are included at the bottom of the table.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Species | Gap | Gap+  Deadwood | Deadwood | Control | Biomass | Habitat |
| Geotrupidae |  |  |  |  |  |  |
| *Anoplotrupes stercorosus* (Scriba, 1791) | 178 | 159 | 253 | 383 | 0.12915 | forest |
| *Trypocopris vernalis* (Linnaeus, 1758) | 25 | 32 | 15 | 21 | 0.23114 | forest |
|  |  |  |  |  |  |  |
| Scarabaeidae |  |  |  |  |  |  |
| *Aphodius depressus* (Kugelann, 1792) | 2 | 1 | 28 | 41 | 0.0059 | forest |
| *Aphodius erraticus* (Linnaeus, 1758) | 0 | 2 | 0 | 0 | 0.0153 | open land |
| *Aphodius fimetarius* (Linnaeus, 1758) | 0 | 0 | 0 | 1 | 0.00898 | indifferent |
| *Aphodius maculatus* Sturm, 1800 | 6 | 1 | 15 | 9 | 0.0032 | forest |
| *Aphodius pusillus* (Herbst, 1789) | 3 | 6 | 10 | 8 | 0.00385 | forest |
| *Aphodius rufipes* (Linnaeus, 1758) | 3 | 6 | 10 | 31 | 0.0405 | forest |
| *Aphodius rufus* (Moll, 1782) | 0 | 2 | 1 | 1 | 0.00704 | forest |
| *Aphodius* spec. | 1 | 0 | 0 | 0 | 0.0026 | NA |
| *Aphodius sticticus* (Panzer, 1798) | 1 | 2 | 4 | 3 | 0.00372 | forest |
| *Aphodius zenkeri* Germar, 1813 | 7 | 10 | 19 | 11 | 0.00295 | forest |
| *Onthophagus coenobita* (Herbst, 1783) | 0 | 2 | 1 | 1 | 0.02161 | open land |
| *Onthophagus fracticornis* (Preyssler, 1790) | 7 | 4 | 1 | 3 | 0.02046 | open land |
| *Onthophagus ovatus* (Linnaeus, 1767) | 2 | 0 | 0 | 0 | 0.00282 | open land |
| *Onthophagus similis* (Scriba, 1790) | 0 | 0 | 0 | 1 | 0.01105 | open land |
| *Onthophagus verticicornis* (Laicharting, 1781) | 1 | 0 | 0 | 2 | 0.0278 | open land |
|  |  |  |  |  |  |  |
| Number of individuals | 236 | 227 | 357 | 516 |  |  |
| Species number | 12 | 12 | 11 | 14 |  |  |
| Expected species number (Jackknife1 ± SE) | 16±2 | 16±2 | 14±2 | 18±2 |  |  |
| Biomass [g], total, mean±SD | 29.1  1.0±1.3 | 28.4  1.0±1.1 | 36.9  1.3±1.6 | 56.1  2.0±3.3 |  |  |
| Dung removal [%], mean±SD | 48.5±37.8 | 48.5±39.6 | 56.9±39.7 | 61.9±36.4 |  |  |

**Table S2.** Pairwise contrasts for comparisons of dung beetle diversity, dung beetle biomass and dung removal among experimental treatments. *P*-values are Tukey-corrected for multiple comparisons and based on Kenward-Roger-approximated degrees of freedom. Significant contrasts (*P*<0.05) are printed in bold.

|  |  |  |  |
| --- | --- | --- | --- |
| Contrast | Estimate ± SE | *t*-ratio | *P*-value |
| *Dung beetle diversity* (F=3.202, *P*(F)=0.027) | | | |
| Gap – Gap+Deadwood | -0.180 ± 0.232 | -0.774 | 0.866 |
| Gap – Deadwood | -0.286 ± 0.232 | -1.230 | 0.610 |
| **Gap – Control** | **-0.693 ± 0.232** | **-2.986** | **0.019** |
| Gap+Deadwood – Deadwood | -0.106 ± 0.232 | -0.456 | 0.968 |
| Gap+Deadwood – Control | -0.514 ± 0.232 | -2.212 | 0.129 |
| Deadwood – Control | -0.408 ± 0.232 | -1.756 | 0.302 |
|  |  |  |  |
| *Dung beetle biomass* (F=3.928, *P*(F)=0.011) | | | |
| Gap – Gap+Deadwood | -0.032 ± 0.111 | -0.291 | 0.991 |
| Gap – Deadwood | -0.149 ± 0.111 | -1.340 | 0.541 |
| **Gap – Control** | **-0.344 ± 0.111** | **-3.099** | **0.014** |
| Gap+Deadwood – Deadwood | -0.116 ± 0.111 | -1.049 | 0.721 |
| **Gap+Deadwood – Control** | **-0.312 ± 0.111** | **-2.809** | **0.031** |
| Deadwood – Control | -0.195 ± 0.111 | -1.759 | 0.300 |
|  |  |  |  |
| *Dung removal* (F=13.703, *P*(F)<0.001) | | | |
| Gap – Gap+Deadwood | -0.002 ± 0.026 | -0.060 | 0.999 |
| **Gap – Deadwood** | **-0.087 ± 0.026** | **-3.394** | **0.004** |
| **Gap – Control** | **-0.135 ± 0.026** | **-5.307** | **<0.001** |
| **Gap+Deadwood – Deadwood** | **-0.086 ± 0.026** | **-3.341** | **0.005** |
| **Gap+Deadwood – Control** | **-0.134 ± 0.025** | **-5.257** | **<0.001** |
| Deadwood – Control | -0.048 ± 0.026 | -1.883 | 0.237 |

**Table S3.** Full results of the path model (Fisher’s C=8.702, *P*=0.069) (see Figure 3). Estimates give standardized path coefficients ± SE. Significant paths are shown in bold.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Response | Predictor | Estimate ± SE | | Critical value | *P*-value |
| *Causal path* |  |  | |  |  |
| **Dung removal** | **~ Gap** | **-0.242 ± 0.067** | | **13.211** | **<0.001** |
| Dung removal | ~ Deadwood | -0.044 ± 0.063 | | 0.472 | 0.494 |
| Dung removal | ~ Dung beetle diversity | -0.059 ± 0.043 | | 1.850 | 0.178 |
| **Dung removal** | **~ Dung beetle biomass** | **0.196 ± 0.052** | | **13.422** | **<0.001** |
| Dung removal | ~ Forest cover | -0.012 ± 0.062 | | 0.037 | 0.850 |
| **Dung removal** | **~ Canopy openness** | **-0.192 ± 0.053** | | **12.870** | **0.001** |
| **Dung beetle diversity** | **~ Gap** | **-0.347 ± 0.060** | | **33.716** | **<0.001** |
| **Dung beetle diversity** | **~ Deadwood** | **-0.122 ± 0.060** | | **4.176** | **0.042** |
| **Dung beetle diversity** | **~ Precipitation** | **-0.346 ± 0.133** | | **5.347** | **0.030** |
| Dung beetle diversity | ~ Temperature | 0.005 ± 0.104 | | 0.002 | 0.964 |
| Dung beetle diversity | ~ Forest cover | -0.130 ± 0.108 | | 1.248 | 0.275 |
| Dung beetle diversity | ~ Canopy openness | 0.176 ± 0.098 | | 2.971 | 0.099 |
| **Dung beetle biomass** | **~ Gap** | **-0.276 ± 0.045** | | **37.796** | **<0.001** |
| **Dung beetle biomass** | **~ Deadwood** | **-0.097 ± 0.044** | | **4.912** | **0.027** |
| Dung beetle biomass | ~ Precipitation | 0.091 ± 0.139 | | 0.383 | 0.542 |
| **Dung beetle biomass** | **~ Temperature** | **0.425 ± 0.105** | | **16.180** | **<0.001** |
| Dung beetle biomass | ~ Forest cover | 0.134 ± 0.111 | | 1.370 | 0.254 |
| **Dung beetle biomass** | **~ Canopy openness** | **-0.233 ± 0.010** | | **5.271** | **0.032** |
| **Dung beetle biomass** | **~ Dung beetle diversity** | **0.150 ± 0.032** | | **22.620** | **<0.001** |
|  |  |  | |  |  |
| *Correlated error* |  |  | |  |  |
| **Temperature** | **~~ Precipitation** | **-0.426** | | **-11.084** | **<0.001** |
|  |  |  | |  |  |
| *D-separation test* |  |  | |  |  |
| Dung depletion ~ Gap + Deadwood + Dung beetle diversity + Dung beetle biomass + Forest cover + Canopy openness + Precipitation | | |  | 2.915 | 0.101 |
| Dung depletion ~ Gap + Deadwood + Dung beetle diversity + Dung beetle biomass + Forest cover + Canopy openness + Temperature | | |  | 2.474 | 0.128 |



**Figure S1.** Schematic illustration of dung beetle sampling and measurement of dung removal. a) Per plot (here exemplified by a *Gap*), one dung beetle trap and five dung removal measurements were placed. b) Dung beetle traps consisted of plastic cups (9 cm diameter, 13 cm height) dug into the ground, covered by a lid with a hole (4 cm diameter) serving as a funnel; a teabag filled with about 35 g cattle dung was attached with a rubber band to a wooden skewer to function as bait. c) For measuring dung removal about 170 g of frozen cattle dung were placed on cellulose paper. d) In some cases, no dung could be retrieved after 48 h as dung was completely buried by dung beetles, especially *Anoplotrupes stercorosus* (shown). All pictures by Michael Staab.



**Figure S2.** Dung removal was not related to the initial volume of deadwood (per site) before creating gaps. The dashed line indicates the non-significant prediction of a linear mixed-effects model (response: dung removal; fixed effect: initial deadwood volume; random effect: plot-in-site-in-region; *t*=0.471, *P*=0.643). Note that the x-axis is on a square-root scale.



**Figure S3.** The biomass of all dung beetles was strongly related (Spearman’s *ρ*=0.933) to the biomass of *Anoplotrupes stercorosus*, the most common species in the sampling. Note that both axes are on a square-root scale.



**Figure S4.** The creation of gaps had no influence on dung beetle community composition. a) Two-dimensional NMDS ordination based on biomass (stress=0.21). Composition overlaps (PERMANOVA; F=1.186, *P*=0.310) between open (*Gap*, *Gap+Deadwood*) and covered plots (*Deadwood*, *Control*). b) Relative contributions to species and c) biomass are dominated by species preferring forests (using the classification of Frank et al. 2017) with no difference between open and covered plots (ANOVA; proportion forest species: F=1.340, *P*=0.251; proportion biomass forest species: F=1.479, *P*=0.229). Data in b) and c) are shown as violin plots, fusing boxplots with kernel densities.

**References cited in supplementary material**

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