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Assessing the impact of human trampling on vegetation: a systematic review and meta-analysis of experimental evidence

Vegetation trampling resulting from recreation can adversely impact natural habitats, leading to the loss of vegetation and the degradation of plant communities. A considerable primary literature exists on this topic, therefore it is important to assess whether this accumulated evidence can be used to reach general conclusions concerning vegetation vulnerability to inform conservation management decisions. Experimental trampling studies on a global scale were retrieved using a systematic review methodology and synthesised using random effects meta-analysis. The relationships between vegetation recovery and each of initial vegetation resistance, trampling intensity, time for recovery, Raunkiaer life-form (perennating bud position), and habitat were tested using random effects multiple meta-regressions and subgroup analyses. The systematic search yielded 304 studies; of these, nine reported relevant randomized controlled experiments, providing 188 vegetation recovery effect sizes for analysis. The synthesis indicated there was significant heterogeneity in the impact of trampling on vegetation recovery. This was related to resistance and recovery time, and the interactions of these variables with Raunkiaer life-form, but was not strongly dependent on the intensity of the trampling experienced. The available evidence suggests that vegetation dominated by hemicryptophytes and geophytes recovers from trampling to a greater extent than vegetation dominated by other life-forms. Variation in effect within the chamaephyte, hemicryptophyte and geophyte life-form sub-groups was also explained by the initial resistance of vegetation to trampling, but not by trampling intensity. Intrinsic properties of plant communities appear to be the most important factors determining the response of vegetation to trampling disturbance. Specifically, the dominant Raunkiaer life-form of a plant community accounts for more variation in the resilience of communities to trampling than the intensity of the trampling experienced, suggesting that simple assessments based on this trait could guide decisions concerning sustainable access to natural areas. Methodological

and reporting limitations must be overcome before more disparate types of evidence can be synthesised; this would enable more reliable extrapolation to non-study situations, and a more comprehensive understanding of how assessments of intrinsic plant traits can be used to underpin conservation management decisions concerning access.

1 **Assessing the impact of human trampling on vegetation: a**

2 **systematic review and meta-analysis of experimental evidence**

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9 Resilience, Raunkiaer life-form.

10 **1. Introduction**

11 Recreational pressure can cause many problems for managers of nature reserves, countryside and
12 wilderness (Leung & Marion 2000). Effective management is essential if the recreational usage
13 of natural habitats is to be balanced with the retention of the nature conservation value of a site.
14 In this context, biodiversity managers and researchers in the UK have identified the need for
15 increased knowledge about the impact of recreational activities on biodiversity as one of the 100
16 most policy-relevant ecological questions (Sutherland et al. 2006); recent differences of opinion
17 regarding open access policies on England's National Nature Reserves underscores the need for
18 robust evidence in this area (Marren 2013). Human trampling, and the response of vegetation to
19 this disturbance, have been a main focus of research on sustainable use of natural habitats for
20 recreation, and have been investigated in many different habitat types around the world. Studies
21 investigating vegetation responses to trampling impacts have utilised various methodologies,
22 including descriptive surveys, site comparisons, before-after control-impact (BACI) designs, and
23 experimental approaches (Sun & Walsh 1998). A standard randomised, controlled experimental
24 design has been described by Cole & Bayfield (1993), and is often used by workers in this field.
25 Standardised procedures should allow for greater comparability between studies, especially

26 where scale-dependent variables affect the measurement of impacts significantly (Taylor, Reader,
27 & Larson 1993). Work on the impact of trampling on vegetation has been reviewed on several
28 occasions (Liddle 1975a; Kuss 1986; Yorks et al. 1997); however, for a transparent and
29 comprehensive synthesis of the available evidence, a systematic methodology should be
30 employed for the retrieval, critical appraisal and pooling of studies (Pullin & Knight 2003;
31 Sutherland et al. 2004; Pullin & Stewart 2006; Stewart 2010).

32 The relevance of trampling studies for conservation managers and practitioners depends on the
33 nature of the managed site, the plant communities contained within, and the type of access in use
34 or being considered (Burden & Randerson 1972; Cole 1987). Some sites may be essentially open
35 access, whilst others may guide or restrict users to paths or delimited areas. Workers studying
36 trampling have divided community responses to trampling into various categories and series with
37 the intention of producing indicators or indices representing the responses of plant communities
38 (Leung & Marion 2000). Resistance, the intrinsic capacity of vegetation to withstand the direct
39 effect of trampling (Liddle 1975b), and resilience, the intrinsic capacity of vegetation to recover
40 from trampling (Kuss & Hall 1991), are most often used as indicators of impact. They allow
41 ecological data to be distilled into categories with biological relevance and conceptually
42 straightforward links to management practice.

43 Studies on trampling have examined the impacts on physiological & morphological vegetation
44 characteristics (Kuss & Graefe 1985), soil fauna (Chappell et al. 1971) and a range of edaphic
45 variables (e.g. Andersen 1995; Ros et al. 2004). However, the response reported most frequently
46 is vegetation cover, which can be used to quantify the vulnerability of vegetation types using
47 measures of resistance and resilience (Cole & Bayfield 1993). Primary studies often present data
48 on vegetation cover as 'relative vegetation cover' (RVC); this is the cover on a trampled plot

49 relative to its initial cover, adjusted for changes in cover on control plots during an experiment
50 (supplemental material 1; Cole & Bayfield 1993).

51 The responses of vegetation to trampling have been reported to be affected by trampling intensity
52 (number of human trampling passes; e.g. Cole 1987, 1995a), frequency (trampling passes per
53 time period; Cole & Monz 2002), distribution (whether trampling passes are dispersed or
54 clumped for a particular trampling frequency; Gallet, Lemauviel, & Rozé 2004), season (Gallet &
55 Rozé 2002), weather (Gallet & Roze 2001), habitat (Liddle 1975b), species (Gallet et al. 2004),
56 Raunkiaer life-form (i.e. perennating bud position) and growth-form (Cole 1995b), and soil type
57 (Talbot, Turton, & Graham 2003). Here, we consider variation in trampling intensity, vegetation
58 resistance, recovery time, Raunkiaer life-form of the community dominant and broad habitat type
59 as potential reasons for heterogeneity in experimental results across primary studies.

60 To our knowledge, no attempt has been made at a formal systematic evaluation of the effect of
61 trampling on vegetation, or at a meta-analytical synthesis of available data. Therefore, the aims of
62 this study were to systematically assess and review the evidence for the effects of human
63 trampling on plant communities, to synthesise experimental data via an appropriate meta-
64 analytical technique, and to investigate variables associated with significant variation in study
65 outcomes. Clearly, robust synthesis relies on robust data, and much relevant data on the effects of
66 human trampling on plants may not be suitable for quantitative synthesis (Yorks et al. 1997). The
67 nature of the available data constrained the specific questions that we were able to address to: (1)
68 Does resilience (i.e. vegetation recovery) differ with respect to trampling intensity, initial
69 resistance of the vegetation, recovery time, Raunkiaer life-form of the community dominant, or
70 habitat? And, (2), how is resilience affected by these covariates and their interactions? We also

71 present tables and lists of relevant primary studies to promote the future synthesis of the
72 considerable amount of observational and mensurative ecological work performed in this area.

73 Practical implications and guidance may be able to be derived where the relationships between
74 resilience and covariates (e.g. trampling intensity or time allowed for recovery) can be
75 manipulated by management decisions. We also comment on the limitations imposed on this
76 systematic review by the original papers, and assess the utility of experimental trampling studies
77 for improving the scientific basis of the management of human trampling impacts in areas of
78 conservation importance. Given the large number of studies that have now investigated the
79 impact of human trampling on plant communities (Yorks et al. 1997; supplemental materials 3
80 and 4), it is important to assess whether the accumulated data available in the primary scientific
81 literature can be effectively mined for ecological patterns providing reliable across-study
82 evidence that can be used to support conservation management decisions (Sutherland et al. 2004;
83 Pullin & Stewart 2006).

84 **2. Methods**

85 *2.1 Identification of relevant studies*

86 Our methodology follows the approach of Pullin & Stewart (2006). Relevant studies were
87 identified via systematic searches of electronic databases, including: JSTOR, ISI Web of
88 Knowledge, ScienceDirect, Google Scholar, DOAJ, Copac, Scirus and Agricola. English
89 language search terms reflecting elements of the review question were used in mining the
90 databases. The references of relevant articles were hand-searched for further studies. To be
91 included in the meta-analysis, a study had to meet the following criteria: (1) The subject of the
92 study must include plant species or assemblages; (2) the experimental treatment must consist of
93 human trampling; (3) the study outcomes must include relative vegetation cover (RVC), or allow

this metric to be derived; (4) the study must include controls and replication in randomized experimental designs linking cause and effect, with high strength of inference to non-study situations (Cole & Bayfield 1993; Sun & Walsh 1998). Studies which only met criteria (1) and (2) were also retrieved and summarised (supplemental materials 3 & 4). Articles were assessed for relevance by one reviewer reading article titles and abstracts; a random subset of 40 from 304 identified articles was independently assessed for relevance by a second reviewer. Cohen's Kappa test showed the selection of relevant articles to have high inter-reviewer agreement ($K = 0.818$).

2.2 Data extraction and analysis

One reviewer extracted data from graphs or tables; where data were not presented, or could not be derived, attempts were made to contact authors for the original data. Data retrieved from authors within twelve months of the enquiries being made were included in the meta-analysis. In one instance, data were converted from absolute cover to RVC (Ikeda 2003). Due to the presentation of vegetation cover data as RVC, certain aspects of the effect of trampling on vegetation could not be directly investigated. Effect sizes used in meta-analysis usually summarise the effect of a treatment or intervention by comparing treatment and control means and variability before and after the treatment in question (Egger, Smith, & Altman 2001). However, data presented as RVC are relative to mean initial vegetation cover: measures of initial variability prior to trampling, necessary for effect size calculation, are not generally presented by the authors of primary studies. This means that the immediate post-trampling impact on vegetation (a typical measure of resistance) cannot be used as the dependent variable in meta-analyses, because appropriate data summarising the pre-trampling state of the vegetation cannot be extracted from the RVC metric. Therefore, we investigated differences in RVC between the period immediately after trampling and the time-point farthest from the trampling application recorded in each study, thus increasing the predictive power and increasing independence where

there was a choice of time ranges in a study. Because primary studies often investigated more than one habitat, trampled at more than one intensity, single effect size estimates (hereafter referred to as ‘trials’) were extracted for any given habitat and trampling intensity pair within a single study. Investigating the presence of a recovery period, irrespective of length, as the main effect also increased the independence of trials within studies, giving each trial its own comparator rather than comparing several trampling intensities to a single control. Thus, as other reviewers have found practical (Yorks et al. 1997), we investigated vegetation recovery as the dependent variable on a per trial basis, and defined this as the resilience of the vegetation. It should be noted that the terms resilience and resistance have been used elsewhere to refer to indices that combine data on both vegetation response and trampling intensity to produce a metric estimating what has been defined as the ‘vulnerability’ of any given site or vegetation type (Cole & Bayfield 1993).

The main effect of the presence of a recovery period on trampled vegetation, calculated as the mean RVC at the final monitoring point of all replicates within a trial, minus the mean RVC immediately after trampling for the replicates, and other reasons for variability in vegetation recovery (trampling intensity, resistance, length of recovery period, Raunkiaer life-form, and habitat) were explored using meta-analysis and meta-regression (Deeks, Altman, & Bradburn 2001; Gurevitch & Hedges 2001). Cohen’s *d* effect sizes (Deeks et al. 2001) representing the change in vegetation cover between initial post-trampling monitoring and the final monitoring time-point were derived from the two RVC means with standard deviations and sample sizes (where the sample size is the number of experimental replicates, not the number of sub-sampled plots within replicates). Cohen’s *d* uses a pooled estimate of standard deviation, allowing for the paired nature of the data points. Data were pooled and combined across trials using DerSimonian & Laird random effects meta-analysis based on standardised mean difference (SMD;

DerSimonian & Laird 1986; Cooper & Hedges 1994). Meta-analysis combines the main effects from individual trials into a single estimate, whilst also taking the precision of each estimate into account (Gurevitch & Hedges 2001). Meta-analysis also increases statistical power and allows the quantification and, where possible, exploration of variation between trials (Deeks et al. 2001; Gurevitch & Hedges 2001). The random effects model assumes that there is variation amongst the true trial effects, and the aim of the analysis is to quantify such variation in the effect parameters; it is therefore appropriate for ecological questions where the true effect is likely to vary between trials (Gurevitch & Hedges 2001; Stewart 2010).

The effect of a post-trampling recovery period on plant growth as quantified by changes in RVC (i.e. vegetation resilience) was examined via the visual inspection of the forest plot of the estimated main effects from the trials, along with their 95% confidence intervals, and by formal tests of heterogeneity undertaken prior to meta-analysis (Thompson & Sharp 1999). Publication bias was investigated by examination of funnel plot asymmetry and the Egger test (Egger et al. 1997). The relationships between the effect of a recovery period and the explanatory variables (length of recovery period, resistance and trampling intensity) were tested using random effects SMD meta-regressions in Stata v. 8.2 (Stata Corporation 2003) using the program Metareg (Sharp 1998). Meta-regression investigates the explanatory power of covariates for the observed pattern of main effect sizes; the random effects model acknowledges the potential for residual heterogeneity not explained by the covariate(s) between trials, therefore corresponding to random effects meta-analysis in assuming that the between-trial variance is not zero (Thompson & Higgins 2002). Meta-regressions were limited to continuous trial-level variables taking a range of values, and, to avoid data-dredging, were specified *a priori* (Thompson & Higgins 2002) as resistance, length of the recovery period, and trampling intensity. Resistance was coded for meta-regressions as the mean RVC across replicates for each trial immediately after trampling had been

166 applied. Collinearity between independent variables was investigated prior to performing the
167 multiple meta-regressions (Zuur, Ieno, & Elphick 2010).

168 The use of subgroup analyses allows the investigation of variation in the main effect amongst
169 particular groups of trials that are hypothesised to be biologically significant (Brookes et al.
170 2001). We used subgroup analyses to explore variation in the effect of a recovery period amongst
171 plant communities of different Raunkiaer life-forms and different habitats. Raunkiaer life-form
172 subgroups, delineated by the position of the perennating buds (Kent 2012), were: (juvenile)
173 phanerophytes; chamaephytes; hemicryptophytes; geophytes; helophytes (where vulnerable to
174 trampling); and therophytes. The life-form category of the plant species with the highest mean
175 percentage cover, i.e. the community dominant, was taken as the category for a trial. Broad
176 habitat categories were: alpine or tundra; temperate coniferous forest; temperate deciduous forest;
177 subalpine and montane grass or shrubland; temperate shrubland; and temperate grassland. *Post*
178 *hoc* within-subgroup multiple meta-regressions were also used to investigate the differential
179 explanatory power of our *a priori* potential effect modifiers (resistance, length of the recovery
180 period, and trampling intensity) for each life-form; collinearity between independent variables
181 was also checked for all within-subgroup multiple meta-regressions (Zuur et al. 2010).

182 To investigate the potential effects of non-independence between trials on our results, due to, for
183 example, individual studies conducting multiple trials testing different trampling intensities in
184 similar habitat types, we also performed sensitivity analyses for all meta-regressions using robust
185 variance estimation (Hedges, Tipton, & Johnson 2010). Robust variance estimation was
186 performed according to (Hedges et al. 2010) on DerSimonian & Laird random effects meta-
187 regressions conducted using the metafor package (Viechtbauer 2010) for the statistical software R
188 v. 3.0.2 (R Core Team 2005).

3. Results

3.1 Systematic search results

Searching and retrieval were conducted between October 2005 and July 2006. Three hundred and four articles were judged relevant at the title level; 145 articles remained in the systematic review after the title and abstract filter stage. Of the 145 only 24 were randomised controlled experiments eligible for inclusion in the final meta-analysis. Of these 24, nine presented data that could be extracted, or which were provided by the authors (Table 1). These nine contributed 188 trials to the meta-analysis. A methodological overview of articles not included in the meta-analysis, but which used a comparator or control in their experimental design, is provided in supplemental material 3. Lists of studies not using a comparator or control, and of those studies which could not be retrieved within the resource constraints of the project, are also provided for the benefit of future reviewers (supplemental material 4).

3.2 Meta-analyses

3.2.1 Post-trampling vegetation recovery

The 95% confidence intervals (horizontal arms) of the 188 trial effect sizes estimating post-trampling recovery of vegetation cover (resilience), via changes in RVC, are shown in a forest plot (Fig. 1); the weighted central point estimates have been omitted for clarity. An enlargeable PDF version of Figure 1 with trial identifiers, trampling intensities and Cohen's d effect sizes (with 95% confidence intervals) is also provided for closer inspection (supplemental material 2). The broken vertical line shows a positive, significant change in RVC after a period of recovery across all trials ($SMD = 1.357$, $z = 11.13$, $p < 0.001$; Fig. 1). The range of variation in the contributing trials gave significant variation in effect size ($\chi^2 = 576.83$, d.f. = 187, $p < 0.001$), with trials located both sides of the line of no effect (no recovery), and with some trials exhibiting

212 wide confidence intervals. Funnel plot asymmetry (Fig. 4) and the Egger test (Egger et al. 1997)
213 suggest that there is potential bias in the data set, as there are fewer small negative trials than
214 would be expected by chance (Egger bias = 4.7, $p < 0.001$).

215 3.2.2 Multiple meta-regressions and subgroup analyses: effects of covariates

216 The multiple meta-regression found that significant heterogeneity in vegetation recovery was
217 explained by initial vegetation resistance (coeff. = -0.357, $z = -8.77$, $p < 0.001$), and the length of
218 the recovery period (coeff. = 0.246, $z = 2.00$, $p < 0.045$); however, there was less evidence for an
219 effect of trampling intensity (coeff. = -0.001, $z = -1.74$, $p = 0.082$). Correlations (Pearson's r)
220 between independent variables were all below 0.35.

221 Subgroup analyses were conducted on Raunkiaer life-form categories based on the dominant
222 field layer vegetation of each trial (Fig. 2). Vegetation dominated by phanerophytes ($n = 40$; SMD
223 = -0.033, $z = 0.63$, $p = 0.528$), chamaephytes ($n = 47$; SMD = 0.288, $z = 1.15$, $p = 0.248$),
224 helophytes ($n = 4$; SMD = 1.918, $z = 1.63$, $p = 0.102$) or therophytes ($n = 4$; SMD = -0.737, $z =$
225 1.71, $p = 0.087$), did not show a significant effect of the presence of a recovery period on RVC
226 (95 % CIs cross zero; Fig. 2); however, all of these life-form groupings displayed significant
227 within-subgroup heterogeneity ($p < 0.01$). Hemicryptophytes ($n = 72$; SMD = 1.955, $z = 12.59$, p
228 < 0.001) and geophytes ($n = 21$; SMD = 1.660, $z = 4.59$, $p < 0.001$) both showed a positive,
229 significant main effect of a recovery period on RVC (95 % CIs do not cross zero; Fig. 2), but also
230 displayed significant heterogeneity ($p < 0.01$).

231 For chamaephytes, hemicryptophytes and geophytes, *post hoc* within-group meta-regressions
232 examined the effects of resistance, length of a recovery period and trampling intensity on
233 vegetation recovery. Across the meta-regressions, correlations (Pearson's r) between independent

234 variables were all below 0.52. The meta-regressions found the initial resistance of the vegetation
235 to have a small but strong negative correlation with resilience for chamaephytes and
236 hemicryptophytes (Table 2); the length of the recovery period was less important, but positive for
237 chamaephytes and negative for hemicryptophytes (Table 2). Recovery time could not be included
238 in the geophyte meta-regression due to all data points being reported one year after trampling;
239 however, resistance was found to have a small, but significant, negative correlation for geophytes
240 (Table 2). Trampling intensity was non-significant for chamaephytes, hemicryptophytes and
241 geophytes (Table 2); the residual variation was significant for all three life-forms (chamaephytes:
242 $p = 0.044$; hemicryptophytes: $p < 0.001$; geophytes: $p = 0.001$). Simple meta-regressions for
243 trampling intensity within these subgroups also found no effect for hemicryptophytes ($p = 0.638$)
244 and chamaephytes ($p = 0.883$), suggesting that the finding of no effect of trampling intensity was
245 not being confounded by other covariates; however, trampling intensity had a significant effect
246 on geophytes ($p = 0.001$), suggesting a stronger relationship (i.e. confounding variation) between
247 trampling intensity and vegetation resistance in this subgroup. Habitat-based subgroup analyses
248 revealed positive and significant main effects ($p < 0.05$; Fig. 3) and significant heterogeneity ($p <$
249 0.01) for all habitats, except temperate grassland, for which power was very low ($n = 4$).

250 3.2.3. Sensitivity analyses

251 The use of robust variance estimation to account for the potential non-independence of trials
252 within studies reduced the significance of all covariates tested. For the main multiple meta-
253 regression, initial vegetation resistance (coeff. = -0.039; $t = -8.16$, $p < 0.001$) remained
254 significant, whilst both length of the recovery period (coeff. = 0.262; $t = 1.80$, $p = 0.13$) and
255 trampling intensity (coeff. = -0.001; $t = -1.38$, $p = 0.226$) became non-significant. The effects of
256 robust variance estimation on the Raunkiaer life-form within-subgroup meta-regressions could
257 only be investigated for chamaephytes; robust standard errors for the hemicryptophyte and

geophyte subgroups could not be produced due to the small number of studies involved (4 and 3 respectively; Hedges et al. 2010). The effect of robust standard errors on the chamaephyte multiple meta-regression was to make all covariates non-significant: resistance: coeff. = -0.033; $t = -2.60$, $p = 0.122$; recovery time: coeff. = 0.478; $t = 1.18$, $p = 0.359$; trampling intensity: coeff. = -0.001; $t = -0.49$, $p = 0.672$.

4. Discussion

4.1 Meta-analyses

We have found that, over the human trampling studies synthesized, vegetation generally recovered to some extent: there is an average significant positive effect of the presence of a recovery period on relative vegetation cover (RVC). However there is also significant heterogeneity, exceptions to this trend are frequent, and the effect may be over-estimated as a result of bias. Our results suggest that the initial resistance of a plant community, and the length of the recovery period, may be better predictors of vegetation resilience than the intensity of trampling undergone; that is, intrinsic properties of vegetation appear to be some of the most important determinants of resilience, with the magnitude of the actual disturbance explaining much less of the community response. The absence of a relationship between resilience and trampling intensity within the main meta-regression may be due to confounding variation caused by the differential vulnerability of different vegetation types, therefore these results are equivocal. However, the fact that *post hoc* life-form subgroup multiple meta-regressions for chamaephytes ($n = 47$) and hemicryptophytes ($n = 72$) also showed a lack of an effect of trampling intensity on resilience, supports the interpretation that intrinsic factors, i.e. plant traits, are often likely to be of primary importance for determining the vulnerability of vegetation to trampling (Cole 1995b). The within-life-form subgroup meta-regressions confirmed that, except possibly for geophytes, life-form type was not obviously confounding the finding of no effect of trampling intensity on resilience within the main analysis. Overall, these results support a situation where particular

plant functional traits are likely to be more important than projected intensity of use when considering the siting of recreational activities involving human trampling. This somewhat surprising result has important management ramifications because it suggests that even relatively low intensity trampling could be as damaging as high intensity trampling in certain plant communities. Thus, trampling may sometimes be unsustainable for vulnerable vegetation, potentially creating conflict between even relatively limited access and plant species- or community-focused conservation objectives.

The importance of initial vegetation resistance for recovery, indicated by the multiple meta-regressions, is likely to be a partial reflection of the negative correlation expected between resistance and resilience where vegetation is able to recover, and confirms the main effect in showing that recovery is the typical response for the levels of disturbance investigated in the studies included in our meta-analysis. However, the use of the relative metric RVC means that the recovery predicted for an impacted stand of vegetation is dependent on the initial absolute vegetation cover: a stand with high absolute cover and high resistance may not have much potential for recovery (restricted to 100%); this means that our analysis may slightly underestimate the typical recovery of more heavily impacted stands. However, it is arguably the relative resilience of different vegetation communities that is of greatest importance for informing sustainable management. In this respect our subgroup analyses confirmed the importance of Raunkiaer life-form (Cole 1995b) across the 188 trials investigated, suggesting that hemicryptophytes and geophytes will be more resilient to trampling impacts relative to other life-forms. In contrast, chamaephyte-dominated vegetation did not show a main effect of recovery; indeed, chamaephyte-dominated communities have been shown to die-back after trampling disturbance, despite initially high resistance (Cole 1995b; Cole & Monz 2002). The negative relationship between resistance and resilience in the chamaephyte subgroup meta-regression

reflects vegetation die-back after initially high resistance, rather than re-growth after initially low resistance. However, the chamaephyte subgroup meta-regression also showed a positive correlation of recovery time with resilience, suggesting that limited recovery may occur after die-back, given a period free from further disturbance. The negative correlation of recovery time for the hemicryptophyte subgroup may indicate that where recovery is not observed in the shorter-term, other factors, changes to soil characteristics for example, could make full recovery less likely.

The investigation of habitat as a reason for heterogeneity did not reveal any clear differences between subgroups (Fig. 3); however, the classification system used was broad, and sample sizes were small for some categories. As the vulnerability of vegetation to trampling may be related to primary productivity (Liddle 1975b), a greater correlation between habitat and vegetation response might have been expected. The absence of a relationship in our results may be due to subtle biases relating to the distribution of trampling intensities and the length of recovery periods, confounding with life-form and the small number of replicates per habitat in our dataset. It is also possible that RVC does not reveal differences in production across habitat types as effectively as other measures, such as vegetation height or biomass.

4.2 Critical analysis

We have found that the nature of the primary data available for meta-analytical synthesis of trampling impacts on vegetation requires a cautious approach to interpretation. Because of the lack of any measure of initial cover or variability in the majority of the primary studies analysed, we have focused on the effect of the presence of a period of recovery on post-trampling vegetation change, i.e. resilience. It should be remembered that because RVC is calculated relative to initial vegetation cover, similar RVC changes may not equate to equivalent absolute

330 changes in vegetation cover. Additionally, a non-significant main effect may either represent a
 331 lack of vegetation recovery, or a plant community with high resistance and therefore little
 332 potential for recovery; this is also a problem with using RVC to measure resilience on a study-
 333 level basis (Cole & Bayfield 1993). This problem could be ameliorated by ensuring analyses of
 334 resilience refer back to primary data, possibly by investigating the absolute resistance of
 335 vegetation as an explanation for heterogeneity in recovery. The availability of raw data in
 336 supplementary material or data repositories, or higher response rates from authors of primary
 337 studies, would increase the value of trampling studies for synthetic, predictive research in
 338 conservation, and for research on the relationship between plant traits and disturbance. The
 339 availability of raw data would also allow a more powerful analysis using a hierarchical modeling
 340 approach, with increased power to detect real differences between groups, improved ability to
 341 explore interaction within and between trials, and would also allow for formal explorations of
 342 model choice (Stewart et al. 2012). Hierarchical modelling is also an alternative to robust
 343 variance estimation in accounting for the potential non-independence of trials within studies.

344 Our analysis is also limited by the characteristics of the primary studies. Most of the studies
 345 investigated several trampling intensities within single habitats, and some habitats and species
 346 were over-represented across studies. We therefore had to balance the competing biases of
 347 aggregation and non-independence in our synthesis. Non-independence can cause the
 348 overestimation of significance levels and the underestimation of confidence intervals (Gurevitch
 349 & Hedges 2001); however, pooling effects across dependent and independent variables allows the
 350 investigation of interesting ecological heterogeneity, and increases the strength of inference to
 351 non-study situations, essentially in the same way as generalizing over subjects within studies
 352 (Rosenthal 1991). The sensitivity analysis undertaken here suggests that, if non-independence is a

353 strong property of the data we have analysed, then the most robust conclusions are those for the
354 effects of recovery time and initial vegetation resistance in the main meta-regression.

355 The most important shortcoming exposed by our systematic review is possibly the lack of high-
356 quality experimental information. Clearly, as we have found, restricting accepted information to
357 randomized controlled experiments reduces the proportion of the literature which can be included
358 in a meta-analytic review. This means that certain trends are confounded; for example, Raunkiaer
359 subgroup analyses occasionally resulted in life-forms at certain time-points originating from a
360 single study. Additionally, only one of the admitted studies examined long-term, chronic
361 trampling, and then only over three years (Cole & Monz 2002). This means that our conclusions
362 are less certain for those situations in which chronic trampling impacts affect the physical,
363 chemical and biological properties of the soil, subsequently affecting vegetation growth and
364 succession over a longer period (Burden & Randerson 1972). However, it seems highly likely
365 that negative impacts are certain at high-levels of chronic trampling, and therefore potentially of
366 less importance for evidence-based management seeking to balance biodiversity conservation
367 interest and lower-intensity access to open sites. This is a key question for societies in which
368 open access to sites is becoming more common (Sutherland et al. 2006; Marren 2013). The
369 inclusion of experimental designs with lower internal validity does not necessarily increase
370 external validity, and can simply result in more uncertainty (Stewart 2010). This is a compelling
371 reason for excluding relevant but low quality data from statistical analyses, and reflects the
372 conclusions of other workers who have reviewed trampling impacts (Yorks et al. 1997). However,
373 meta-analytical techniques designed to handle variable quality data are under development, and
374 could prove useful for synthesizing such data in the future, provided that the uncertainty
375 associated with lower-quality methodologies is adequately expressed. Bayesian Belief Networks
376 have been utilised in ecology in such situations (Newton et al. 2007).

377 In attempting this synthesis we have observed that the research methodologies and reporting of
 378 existing experimental trampling studies may be inadequate for the underpinning of scientific
 379 management of plant species and communities of conservation concern under potential threat
 380 from recreational access. Changes in species composition or richness are not routinely reported,
 381 meaning that decision-making may be based on vegetation cover indicators, such as RVC, that
 382 may not approximate to full ecological recovery to pre-disturbance conditions (Hylgaard 1980).
 383 Furthermore, the measure of RVC may be misleading as it lacks information on initial absolute
 384 plant cover, which may be of increased importance for the consideration of chronic trampling
 385 impacts. Whilst the standardisation of methods reduces unexplained variation, and increases
 386 comparability between studies, presenting results in a way which precludes the efficient meta-
 387 analysis of important responses is counter-productive to the aims of synthesis; this may be
 388 especially true where such synthesis is important for disseminating ecological results to
 389 conservation practitioners managing sites with under-studied, or unstudied, vegetation
 390 communities. Researchers could address these issues by making raw data available through
 391 online supplementary material where they do not present it in manuscripts, and by increased
 392 consideration of the potential uses of their results for meta-analytical studies.

393 *4.3 Management Implications*

394 The evidence presented here, systematically accumulated across high-quality experimental
 395 studies, suggests that vulnerable vegetation of conservation value should not be trampled,
 396 irrespective of the projected intensity of use. The range of trampling intensities investigated in
 397 the primary studies synthesized here suggests that even moderate disturbance can have significant
 398 effects on plant communities. Simple indicators such as life-form of the community dominant
 399 may then be useful for rapid assessments of a community's vulnerability to recreational pressure.

400 Zonation of recreation into high and low intensity usage, with 'honey-pots' located away from
401 vulnerable vegetation, may be a more effective conservation strategy than encouraging
402 moderately intensive but more widespread recreational usage; especially given that occasional
403 use results in the development of informal path-networks which may subsequently encourage
404 further disturbance (Roovers et al. 2004).

405 Sites of conservation importance dominated by phanerophytes, chamaephytes, helophytes or
406 therophytes should not experience regular trampling disturbance if deleterious impacts are to be
407 avoided. Reducing trampling intensities may not be effective where adverse impacts are already
408 occurring, although we did find a negative relationship between initial resistance and resilience
409 for chamaephyte-dominated vegetation (i.e. high initial impacts may be followed by some
410 recovery). Conversely, the current evidence base suggests that vegetation dominated by
411 hemicryptophytes and geophytes, life-forms with more protection for their perennating buds
412 (Kent 2012), recovers to a greater extent than vegetation dominated by other life-forms, and
413 could therefore potentially be trampled more intensively, provided monitoring is undertaken to
414 provide early warning of deterioration or unsustainable use.

415 *4.4 Future Work*

416 Systematic reviews and meta-analyses should be periodically revisited in order to incorporate
417 new data and to test new hypotheses or analytical techniques (Pullin & Stewart 2006; Stewart
418 2010). Since the research reported here was undertaken, several new studies investigating
419 trampling impacts have been reported. In contrast to the work summarised here, Bernhardt-
420 Römermann et al. (2011) found no evidence for an effect of Raunkiaer life-form in their pan-
421 European experimental study of trampling disturbance; whilst other recent studies have found
422 new evidence supporting the importance of this plant trait (Andrés-Abellán et al. 2006).

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423 Bernhardt-Römermann et al. (2011) did report evidence for the importance of plant rosette-type,
424 the categories of which used by Bernhardt-Römermann et al. (2011) are classified as
425 hemicryptophyte subtypes (Kent 2012), supporting the importance of perennating bud position
426 and protection for plant responses to trampling disturbance. Increased availability of full plant
427 community data in primary studies could enable future reviewers to estimate the relative
428 abundance of plant traits within vegetation, providing further insights into the importance of
429 Raunkiaer life-form in contrast to other community-weighted plant traits (Violle et al. 2007).

430 Given that the large total number of trampling studies that our systematic review uncovered
431 (supplemental materials 3 and 4) is still almost certainly an underestimate of the evidence-base
432 (due to our only following-up studies referenced within studies to a depth of one remove) we
433 suggest that further investigation of ways to extract the maximum information from published
434 studies will be the most efficient way of confirming when life-form, or other plant functional
435 traits, are likely to be important indicators of vegetation responses to trampling. For example, a
436 risk ratio metric of the relative proportions of different plant functional groups allowed Newton et
437 al. (2009) to summarize a much larger proportion of the primary literature on north-west
438 European heathland management than would have been possible if community composition data
439 were demanded. The increasing availability of global plant trait data (Kattge et al. 2011), suggests
440 that the concepts and information presented here could be extended to test new hypotheses about
441 the relationship between trampling disturbance and plant vulnerability. We suggest that
442 conservation planners, practitioners, and ecologists with an interest in vegetation trampling,
443 should develop a global prospective collaboration to ascertain priority questions and establish
444 standards for monitoring and data reporting. These activities would facilitate future synthesis and
445 maximize the potential for scientific evidence to inform policy in the increasingly important area
446 of research into human impacts on ecosystems.

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451 **References**

- 452 Andersen UV 1995 Resistance of Danish coastal vegetation types to human trampling. *Biological*
453 *Conservation*, 71:223–230.
- 454 Andrés-Abellán M, López-Serrano FR, Morote FAG, Cerro-Barja AD 2006 Assessment of
455 trampling simulation impacts on native vegetation in Mediterranean Sclerophyllous
456 forest. *Environmental Monitoring and Assessment*, 120:93–107.
- 457 Bernhardt-Römermann M, Gray A, Vanbergen AJ et al. 2011 Functional traits and local
458 environment predict vegetation responses to disturbance: a pan-European multi-site
459 experiment. *Journal of Ecology*, 99:777–787.
- 460 Brookes ST, Whitley E, Peters TJ et al. 2001 Subgroup analyses in randomised controlled trials:
461 quantifying the risks of false-positives and false-negatives. *Health Technology*
462 *Assessment*, 5:
- 463 Burden RF, Randerson PF 1972 Quantitative studies of the effects of human trampling on
464 vegetation as an aid to the management of semi-natural areas. *Journal of Applied Ecology*,
465 9:439–457.
- 466 Chappell HG, Ainsworth JF, Cameron RAD, Redfern M 1971 The effect of trampling on a chalk
467 grassland ecosystem. *Journal of Applied Ecology*, 8:869–882.

- 468 Cole DN 1987 Effects of three seasons of experimental trampling on five montane forest
469 communities and a grassland in western Montana, USA. *Biological Conservation*,
470 40:219–244.
- 471 Cole DN 1995a Experimental trampling of vegetation. I. Relationship between trampling
472 intensity and vegetation response. *Journal of Applied Ecology*, 32:203–214.
- 473 Cole DN 1995b Experimental trampling of vegetation. II. Predictors of resistance and resilience.
474 *Journal of Applied Ecology*, 32:215–224.
- 475 Cole DN, Bayfield NG 1993 Recreational trampling of vegetation: standard experimental
476 procedures. *Biological Conservation*, 63:209–215.
- 477 Cole DN, Monz CA 2002 Trampling disturbance of high-elevation vegetation, Wind River
478 Mountains, Wyoming, USA. *Arctic, Antarctic, and Alpine Research*, 34:365–376.
- 479 Cooper HM, Hedges LV 1994 *The Handbook of Research Synthesis*. Russell Sage Foundation,
480 New York.
- 481 Deeks JJ, Altman DG, Bradburn MJ 2001 Statistical methods for examining heterogeneity and
482 combining results from several studies in meta-analysis. In: *Systematic Reviews in Health*
483 *Care: Meta-Analysis in Context* (eds Egger M, Smith GD, Altman D), pp. 285–312. John
484 Wiley & Sons, London.
- 485 DerSimonian R, Laird N 1986 Meta-analysis in clinical trials. *Controlled Clinical Trials*, 7:177–
486 188.
- 487 Egger M, Davey Smith G, Schneider M, Minder C 1997 Bias in meta-analysis detected by a
488 simple, graphical test. *British Medical Journal*, 315:629–634.
- 489 Egger M, Smith GD, Altman D 2001 *Systematic Reviews in Health Care: Meta-Analysis in*
490 *Context*. John Wiley & Sons.
- 491 Gallet S, Lemauiel S, Rozé F 2004 Responses of three heathland shrubs to single or repeated
492 experimental trampling. *Environmental Management*, 33:821–829.

- 493 Gallet S, Roze F 2001 Resistance of Atlantic Heathlands to trampling in Brittany (France):
494 influence of vegetation type, season and weather conditions. *Biological Conservation*,
495 97:189–198.
- 496 Gallet S, Rozé F 2002 Long-term effects of trampling on Atlantic heathland in Brittany (France):
497 resilience and tolerance in relation to season and meteorological conditions. *Biological*
498 *Conservation*, 103:267–275.
- 499 Gurevitch J, Hedges LV 2001 Meta-analysis: combining the results of independent experiments.
500 In: *Design and Analysis of Ecological Experiments* (eds Scheiner SM, Gurevitch J), pp.
501 347–369. Oxford University Press, New York.
- 502 Hedges LV, Tipton E, Johnson MC 2010 Robust variance estimation in meta-regression with
503 dependent effect size estimates. *Research Synthesis Methods*, 1:39–65.
- 504 Hylgaard T 1980 Recovery of plant communities on coastal sand-dunes disturbed by human
505 trampling. *Biological Conservation*, 19:15–25.
- 506 Ikeda H 2003 Testing the intermediate disturbance hypothesis on species diversity in herbaceous
507 plant communities along a human trampling gradient using a 4-year experiment in an old-
508 field. *Ecological Research*, 18:185–197.
- 509 Kattge J, Díaz S, Lavorel S et al. 2011 TRY – a global database of plant traits. *Global Change*
510 *Biology*, 17:2905–2935.
- 511 Kent M 2012 *Vegetation Description and Data Analysis: A Practical Approach*. Wiley-Blackwell.
- 512 Kuss FR 1986 A review of major factors influencing plant responses to recreation impacts.
513 *Environmental Management*, 10:637–650.
- 514 Kuss FR, Graefe AR 1985 Effects of recreation trampling on natural area vegetation. *Journal of*
515 *Leisure Research*, 17:165–183.
- 516 Kuss FR, Hall CN 1991 Ground flora trampling studies: five years after closure. *Environmental*
517 *Management*, 15:715–727.

- 518 Leung Y, Marion J 2000 Recreation impacts and management in wilderness: A state-of-
519 knowledge review. In: *Wilderness ecosystems, threats, and management* (eds Cole D,
520 McCool S, Borrie W, Oloughlin J), pp. 23–48. U.S. Department of Agriculture, Forest
521 Service, Rocky Mountain Research Station, Ogden, UT.
- 522 Liddle MJ 1975a A selective review of the ecological effects of human trampling on natural
523 ecosystems. *Biological Conservation*, 7:17–36.
- 524 Liddle MJ 1975b A theoretical relationship between the primary productivity of vegetation and its
525 ability to tolerate trampling. *Biological Conservation*, 8:251–255.
- 526 Marren P 2013 Comment: Nature versus People: room for both on NNRs? *British Wildlife*,
527 25:138–139.
- 528 Newton AC, Stewart GB, Diaz A, Golicher D, Pullin AS 2007 Bayesian Belief Networks as a tool
529 for evidence-based conservation management. *Journal for Nature Conservation*, 15:144–
530 160.
- 531 Newton AC, Stewart GB, Myers G et al. 2009 Impacts of grazing on lowland heathland in north-
532 west Europe. *Biological Conservation*, 142:935–947.
- 533 Pullin AS, Knight TM 2003 Support for decision making in conservation practice: an evidence-
534 based approach. *Journal for Nature Conservation*, 11:83–90.
- 535 Pullin AS, Stewart GB 2006 Guidelines for systematic review in conservation and environmental
536 management. *Conservation Biology*, 20:1647–1656.
- 537 R Core Team 2005 R: A language and environment for statistical computing. *R foundation for*
538 *Statistical Computing*.
- 539 Roovers P, Verheyen K, Hermy M, Gulinck H 2004 Experimental trampling and vegetation
540 recovery in some forest and heathland communities. *Applied Vegetation Science*, 7:111–
541 118.

- 542 Ros M, Garcia C, Hernandez T, Andres M, Barja A 2004 Short-term effects of human trampling
543 on vegetation and soil microbial activity. *Communications in Soil Science and Plant*
544 *Analysis*, 35:1591–1603.
- 545 Rosenthal R 1991 *Meta-analytic procedures for social research*. Sage Publications, London.
- 546 Sharp S 1998 Meta-analysis regression: statistics, biostatistics, and epidemiology. *Stata Technical*
547 *Bulletin*, 42:16–22.
- 548 Stata Corporation 2003 *Stata statistical software*. Stata Corporation, College Station, TX.
- 549 Stewart G 2010 Meta-analysis in applied ecology. *Biology Letters*, 6:78–81.
- 550 Stewart GB, Altman DG, Askie LM et al. 2012 Statistical Analysis of Individual Participant Data
551 Meta-Analyses: A Comparison of Methods and Recommendations for Practice. *PLoS*
552 *ONE*, 7:e46042.
- 553 Sun D, Walsh D 1998 Review of studies on environmental impacts of recreation and tourism in
554 Australia. *Journal of Environmental Management*, 53:323–338.
- 555 Sutherland WJ, Pullin AS, Dolman PM, Knight TM 2004 The need for evidence-based
556 conservation. *Trends in Ecology & Evolution*, 19:305–308.
- 557 Sutherland WJ, Armstrong-Brown S, Armsworth PR et al. 2006 The identification of 100
558 ecological questions of high policy relevance in the UK. *Journal of Applied Ecology*,
559 43:617–627.
- 560 Talbot LM, Turton SM, Graham AW 2003 Trampling resistance of tropical rainforest soils and
561 vegetation in the wet tropics of north east Australia. *Journal of Environmental*
562 *Management*, 69:63–69.
- 563 Taylor KC, Reader RJ, Larson DW 1993 Scale-dependent inconsistencies in the effects of
564 trampling on a forest understory community. *Environmental Management*, 17:239–248.
- 565 Thompson SG, Higgins J 2002 How should meta-regression analyses be undertaken and
566 interpreted? *Statistics in Medicine*, 21:1559–1573.

567 Thompson SG, Sharp SJ 1999 Explaining heterogeneity in meta-analysis: a comparison of
 568 methods. *Statistics in Medicine*, 18:2693–2708.

569 Viechtbauer W 2010 Conducting meta-analyses in R with the metafor package. *Journal of*
 570 *Statistical Software*, 36:1–48.

571 Violle C, Navas M-L, Vile D et al. 2007 Let the concept of trait be functional! *Oikos*, 116:882–
 572 892.

573 Yorks T, West N, Mueller R, Warren S 1997 Toleration of Traffic by Vegetation: Life Form
 574 Conclusions and Summary Extracts from a Comprehensive Data Base. *Environmental*
 575 *Management*, 21:121–131.

576 Zuur AF, Ieno EN, Elphick CS 2010 A protocol for data exploration to avoid common statistical
 577 problems. *Methods in Ecology and Evolution*, 1:3–14.

Figure 1

Post-trampling recovery of vegetation.

A forest plot of the 188 effect size estimates pooled using random effects meta-analysis.

Solid horizontal lines represent trial 95 % confidence intervals. Trial confidence intervals not crossing the zero line of no effect indicate a positive or negative significant effect at the 5 % level. Individual central point estimates are omitted for clarity.

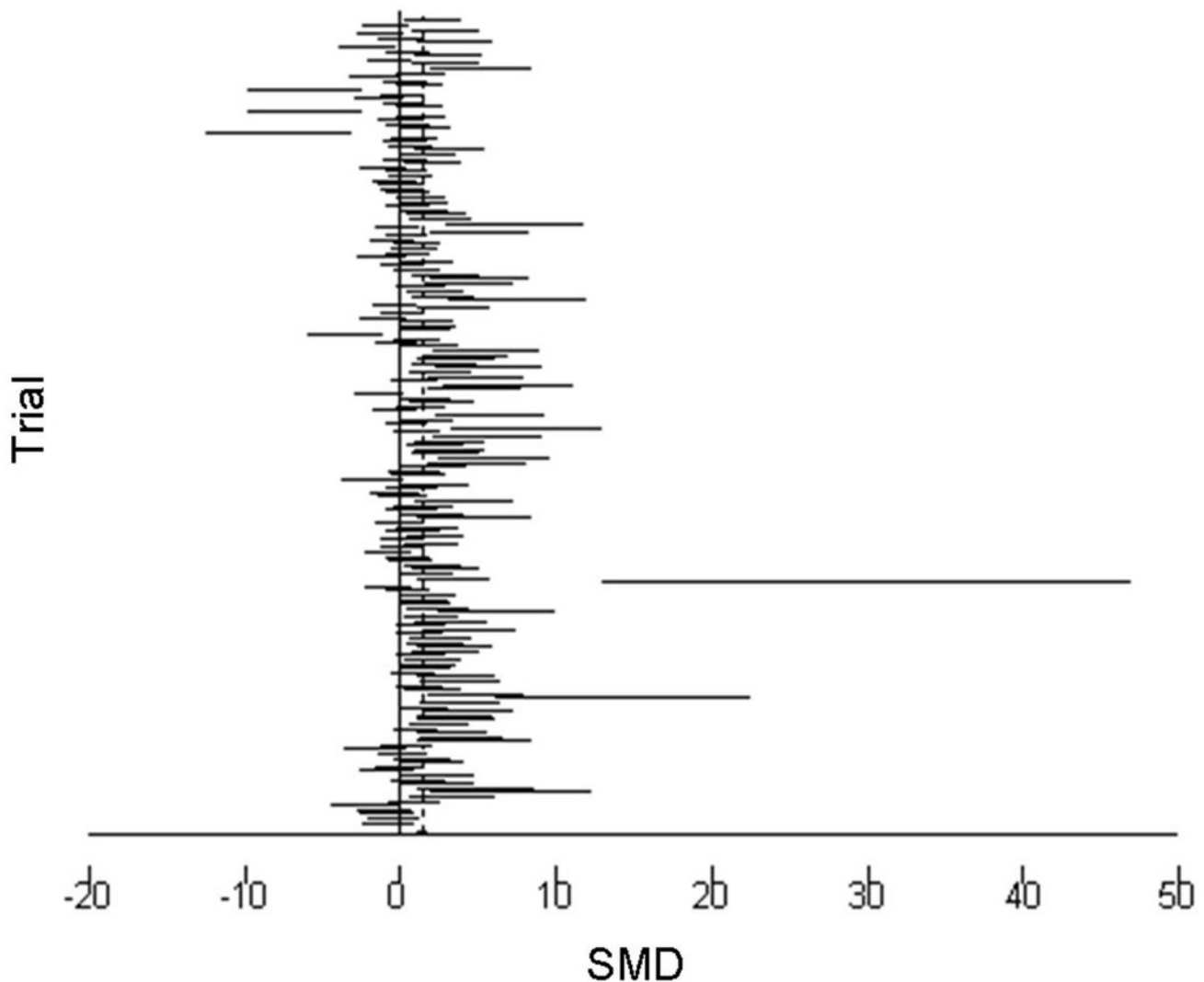


Figure 2

Post-trampling recovery of vegetation for Raunkiaer subgroups.

Point estimates of effects sizes with 95 % confidence intervals for Raunkiaer life-form subgroup analyses.

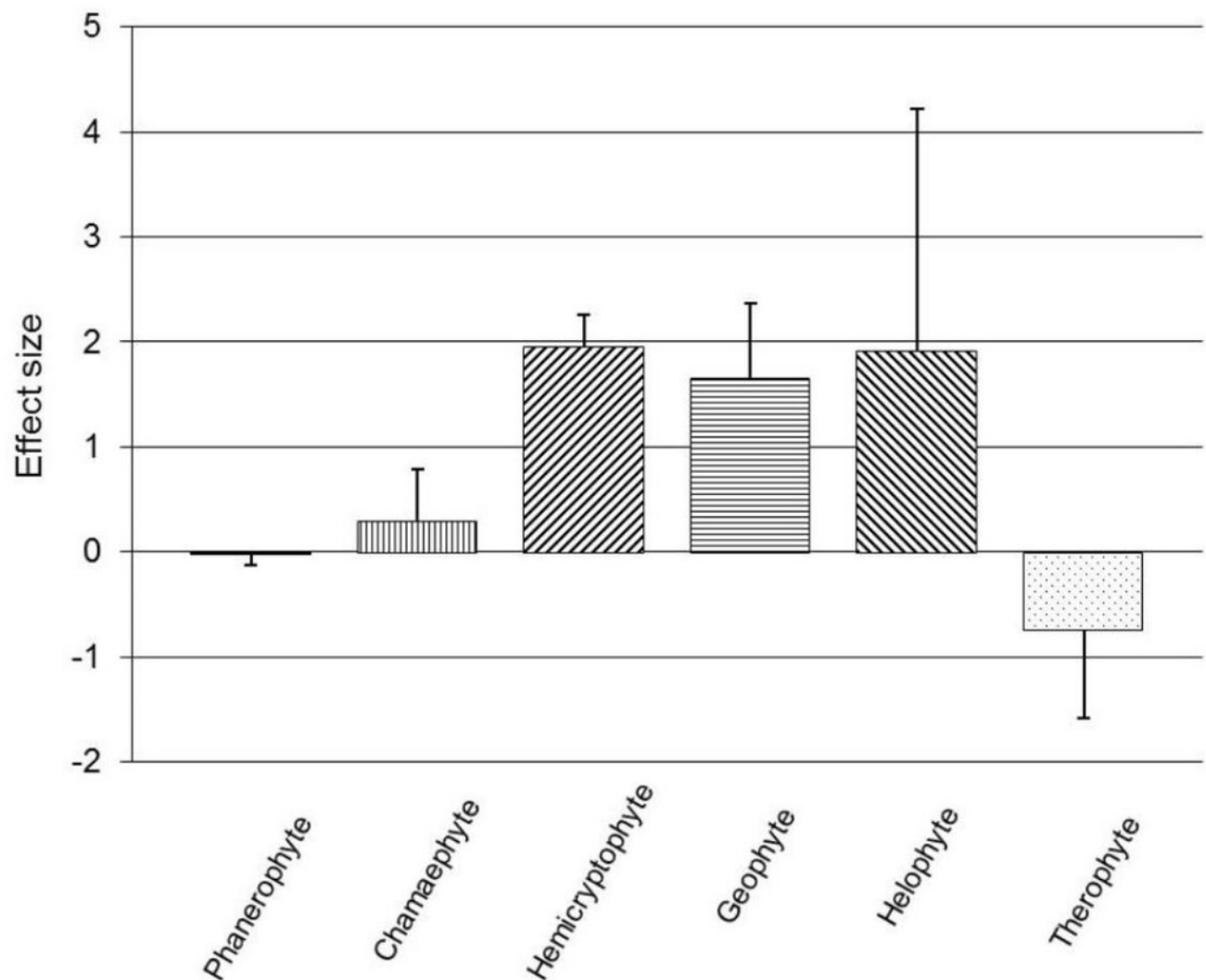


Table 1 (on next page)

Outcomes of multiple meta-regressions for Raunkiaer life-form subgroup analyses

Table 2. Outcomes of multiple meta-regressions for Raunkiaer life-form subgroup analyses

	Resistance			Recovery Time			Trampling intensity		
	Coeff.	z	p	Coeff.	z	p	Coeff.	z	p
Chamaephytes	-0.300	-3.69	<0.001	0.495	1.93	0.054	-0.001	-1.16	0.247
Hemicryptophytes	-0.233	-4.74	<0.001	-0.374	-1.95	0.051	0.001	0.97	0.330
Geophytes	-0.411	-3.41	0.001	N/A			0.002	1.26	0.206

Figure 3

Post-trampling recovery of vegetation within broad habitat types.

Point estimates of effects sizes with 95 % confidence intervals for habitat subgroup analyses.

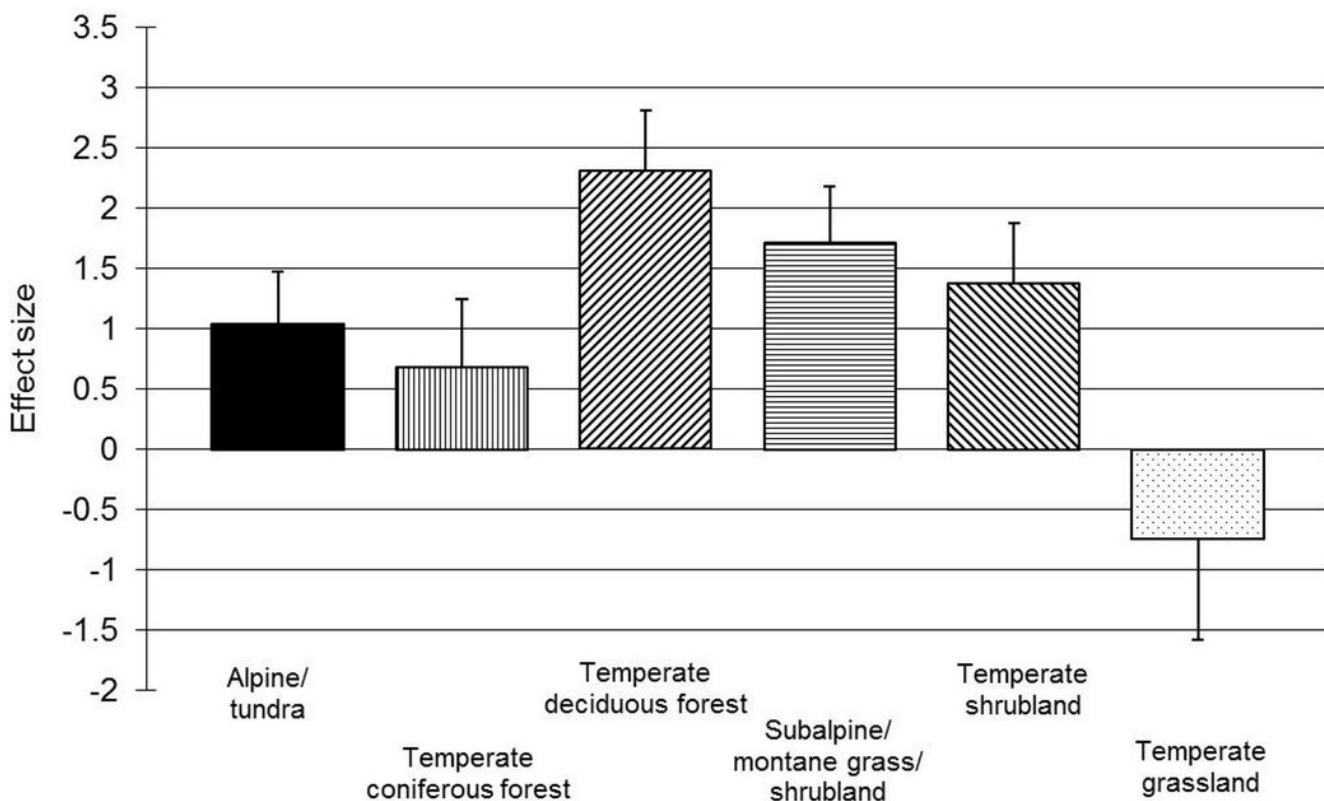


Figure 4

Funnel plot of main effect size estimates.

A funnel plot of 188 main effect size estimates in relation to inverse variance. Funnel plot asymmetry illustrates that there are fewer small negative effect sizes than small positive effect sizes indicating a possible publication bias.

