Supplemental Information

Addressing context dependence in ecology

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Appendix S1: Publishing trends regarding context dependence in ecology

Methods

To gauge general research interest in context dependence in ecology over time, we searched Scopus for journal articles that explicitly mentioned context dependence (or some derivative of it) in their title, keywords or abstract (search terms listed below). We undertook three types of searches based on research field: i) general ecology and biodiversity conservation (2297 papers found); ii) invasion science (779 papers found); iii) invasion ecology, which was a combined search of i and ii (315 papers found). The three searches enabled us to gauge whether notably differed between the research field of ecology and conservation, the parallel but overlapping field of invasion science, and the subfield of invasion ecology. Removing the "context dependence" search terms enabled us to extract total numbers of papers in each of these categories (173,337 ecology papers; 107,089 invasion science papers; 19,242 invasion ecology papers). We included all years in the search, restricting the fields to agricultural and biological sciences, environmental sciences, decision sciences, and multidisciplinary. The search was conducted on 21 April 2020 and, because of logistics, limited to English-language peer-reviewed journal articles. Working with the subset of papers that included "context dependence", we undertook text mining with revtools R package [S1] (R version 3.6.1 [S2]) of paper titles, keywords and abstracts to look for thematic patterns in these papers. Within revtools, we set the number of topic clusters to five, used LDA processing and ran 10,000 iterations of the model [S1]. We note that our literature search is indicative only and detected thematic and temporal trends are therefore approximate.

Context dependence search terms: ("context depend*" OR "context specific" OR depend* AND context* OR "varies with context")

Ecology & conservation search terms: (ecology OR bio* AND conservation OR ecological OR biodiversity)

Invasion science search terms: (alien OR non-native OR introduced OR non-indigenous OR invasive OR invader OR exotic OR invasion)

Invasion ecology search terms: (ecology OR bio* AND conservation OR ecological OR biodiversity) AND (alien OR non-native OR introduced OR non-indigenous OR invasive OR invader OR exotic OR invasion)

Findings

Prevalence of "context dependence" in the literature

Based on our literature search, context dependence first appeared in ecology & conservation papers in 1967, in invasion science papers in 1976 and in invasion ecology papers in 1987. Since the first appearances of the phrase, papers referring to context dependence made up 1.3%, 0.7% and 1.6% of papers in ecology & conservation, invasion science and invasion ecology respectively. There was a slight but unremarkable increase in relative use of "context dependence" over time (Fig. S1), but a marked increase in its use in absolute terms (Table S1). Before 2000, only 73 ecology & conservation papers featured the term context dependence (or derivatives of it) in paper titles, keywords or abstract, whereas 2,133 papers published since 2000 included the term, and 1067 papers in the period 2015-2019. Trends were similar for invasion science and invasion ecology (Table S1, Fig. S1). Of all of the pre-2020 papers that feature the term "context dependence", almost 50% have been published since 2015, pointing to a marked rise in the use of this term and concept (Table S1). Context dependence appears to be a research theme of this millennium and is growing in prominence over time. By searching only the title, abstract and keywords for a limited set of keywords, our estimates of prevalence are likely very conservative; in many cases, context dependence (and contingency) may only discussed in the main text of journal papers, not in the title, abstract or keywords.

Themes in "context dependence" papers

Within the ecology & conservation papers, the five topic clusters appear to cover the breadth of the discipline, with plants and animals represented, data and modelling, management and biodiversity conservation, and different scales of assessment including populations, habitats and landscapes (Fig. S2a & Table S2). Biological invasions featured in one of the five topics (plant-soil-invasive), illustrating that invasion ecology is one key area of ecology where context dependence is being actively discussed. The topics for invasion science and invasion ecology were similarly varied, with no one theme dominating (Fig. S2b-c, Table S2).

Supplemental References

S1 Westgate, M.J. (2019) revtools: An R package to support article screening for evidence synthesis. *Research Synthesis Methods* 10, 606-614.

S2 R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing.

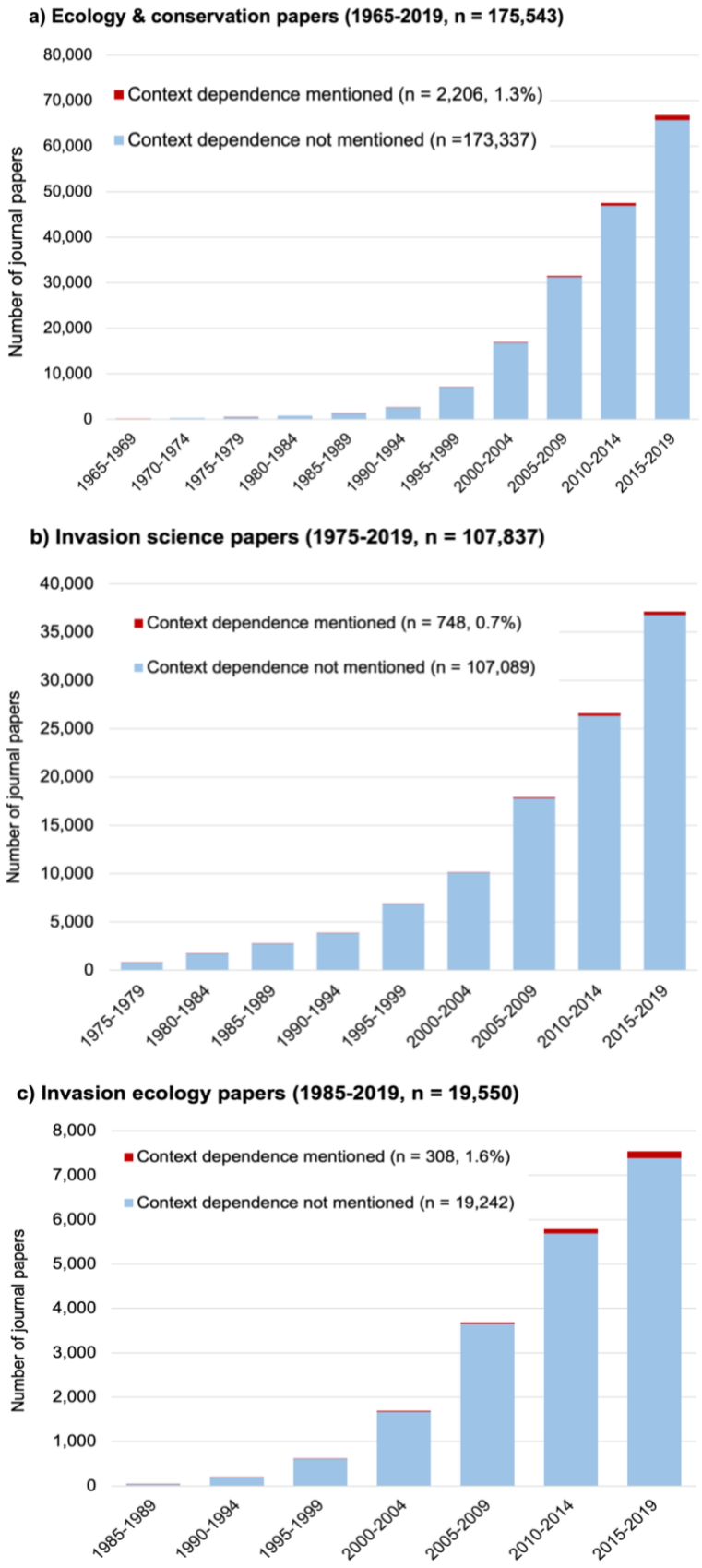

Figure S1: Journal articles that do versus do not mention "context dependence" in the papers title, abstract or keywords over time, broken into 5-year time periods: a) ecology & conservation; b) invasion science; c) invasion ecology.

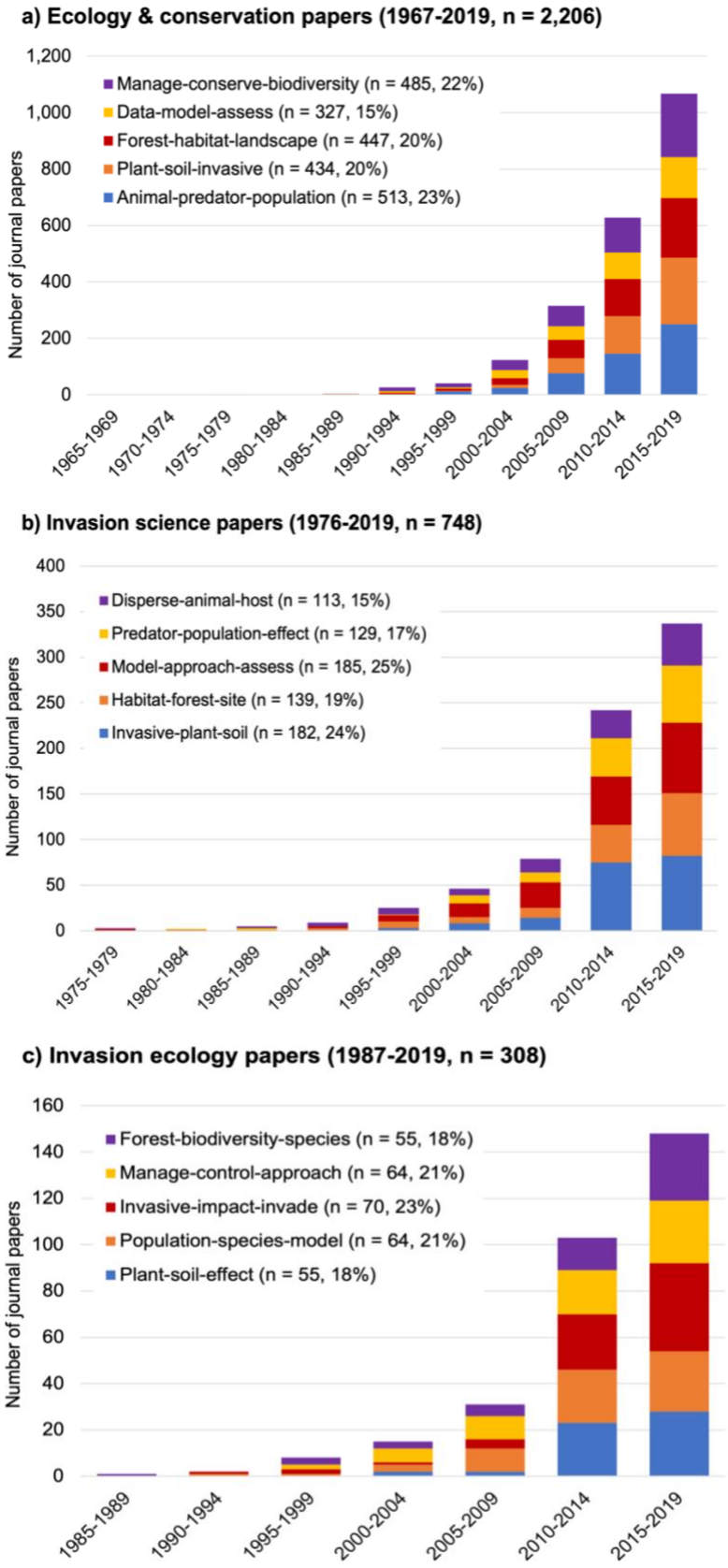

Figure S2: Topics within journal articles that explicitly mention “context dependence” in the paper titles, abstracts or keywords over time: a) ecology & conservation; b) invasion science; c) invasion ecology. Three key terms that typify each of the five topics in each panel are shown, but other terms also help distinguish the paper topics (Table S2).

Table S1: Number of journal papers that featured the term context dependence (or derivatives of it) in paper title, keywords or abstract relative to publication year.

Search topic	Number of papers that mention context dependence		
	All years	Before 2000	2015-2019
Ecology & conservation	2206	73 (3%)	1067 (48%)
Invasion science	748	44 (6%)	337 (45%)
Invasion ecology	308	11 (4%)	148 (48%)

Table S2: Topic keywords in literature. Revtools setup: 5 topics specified for each set of papers; LDA processing methods; 10,000 iterations of model.

Topic abbreviation	High likelihood	High weight	High likelihood & weight	N
Ecology papers (n = 2,206)				
1) Animal-predator-population	population, animal, size, fish	dispersal, host, life, prey	predator	530
2) Plant-soil-invasive	effect, interact, increase	biomass, invasive, ecosystem function	plant, soil	462
3) Forest-habitat-landscape	species	site	habitat, forest, landscape, tree	464
4) Data-model-assess	used, assess, study	flow, parameter, indices	data, model	342
5) Manage-conserve-biodiversity	conserve, develop, biodiversity, system	ecosystem service, sustain, human, social	manage	499
Invasion papers (n = 748)				
1) Invasive-plant-soil	invasive, soil, effect, native	seed, trait, biomass, grass	plant	139
2) Habitat-forest-site	species, habitat, change	land, urban, cover	site, forest	185
3) Model-approach-assess	model, used, assess, manage	pest, inform, value, review	approach	129
4) Predator-population-effect	population, differ, effect, size	fish, prey, river, food	predator	113
5) Disperse-animal-host	context	gene	disperse, animal, host, cell	182
Invasion ecology papers (n = 308)				
1) Plant-soil-effect	plant, effect, interact, invasive	experiment, growth, grass, herbivore	soil	57
2) Population-species-model	species, model, disperse, seed	predator, host, population dynamics, dynamic	population	65
3) Invasive-impact-invade	invasive, impact, invasive species, invade, study	fish, temperature, freshwater, lake, functional response	NA	71
4) Manage-control-approach	control, uses, conserve	risk, measure, pest	manage, approach	66
5) Forest-biodiversity-species	species, biodiversity, change	landscape, land, vegetation	forest, diverse	56

Table S3: Sources of variation, or context dependence, in the relationship between independent variable X and dependent variable Y. Sources of variation are not mutually exclusive and can co-occur.

Context	I) Interaction effects	II) Confounding factors	III) Statistical inference	IV) Methodological differences
Description	Observed variation in X-Y relationship stems from presence of covariate Z, which interacts with X to affect Y (effect of X on Y is contingent on Z) If Z is not considered within a given study or model, X-Y relationship will likely appear highly uncertain	Observed variation in X-Y relationship stems from relationships with potentially multiple, often unidentified, confounding factors C, which can obscure the true X-Y relationship Mostly an issue between studies where presence and influence of confounders can vary, resulting in variation in the detection of the true X-Y relationship	Low statistical power (from measurement error, low sample size and weak relationships), systemic bias in data collection, or inappropriate application or interpretation of statistics in some or all studies reduces ability to detect and report true X-Y relationship, meaning that results about the X-Y relationship can incorrectly appear variable across studies, in turn leading to incorrect inferences (conclusions)	Apparent variation in X-Y relationship between studies results from methodological differences and inappropriate inter-study comparisons (different study scales, gradients of X, or metrics of X and/or Y)
Type of error	Mechanistic; affects X-Y relationship because of interactions between X and interactor (Z); process error when Z is unknown	Methodological; affects detectability of X-Y relationship; process error when confounder (C) is unknown	Methodological; inaccurate or imprecise estimates of X or Y affects detectability of true X-Y relationship; relationships across studies can also appear to vary if statistical results are reported or interpreted inaccurately (e.g. incorrectly treating statistical non-significance as evidence of no relationship)	Methodological; affects interpretation of consistency of X-Y relationships across studies
Aspect of X-Y relationship most affected	Magnitude, sign &, when Z is unknown, uncertainty of X-Y relationships	Uncertainty, magnitude and, in strong cases, sign of X-Y relationships	Largely uncertainty of relationships, but inaccuracy (systematic bias) can affect magnitude and potentially even sign	Magnitude & sign of X-Y relationships

Appearance of relationship if source not dealt with	Uncertain and/or neutral (within studies); stochastic (between studies)	Uncertain and/or neutral (within studies); stochastic (between studies)	Stochastic (between studies)	Stochastic (between studies)
Issue	Problematic if interaction not acknowledged or not accounted for	Problematic if influential confounders not included in study design or analytical models; relationships can incorrectly appear variable and context dependent; confounders are especially hard to eliminate in non-randomised observational studies or when confounders are unknown	Insufficient power to detect relationships that are weak or obscured by measurement error (often combined with stochasticity associated with process error from unknown confounders); estimated relationships can be inaccurate if there is systematic bias in data; incorrect use and interpretation of statistical measures (e.g. assuming a statistically significant vs non-significant dichotomy) can led to spurious relationships and apparent contradictions	Relationships can incorrectly appear variable and context dependent
Can variation be completely accounted for?	Mostly	No, some will always remain	No, some measurement error and statistical uncertainty inevitable	Yes