INTRODUCTION

Human impacts on the natural world do not operate in isolation (Butchart et al., 2010). Climate change, land clearing and invasive species interact and feedback, resulting in the loss of species and ecosystem functions (Heller & Zavaleta, 2009; Pereira et al., 2010). Managing natural systems in the face of these threats will require us to understand and account for this complexity (Driscoll & Lindenmayer, 2012; Pereira et al., 2010). The first step in effective ecological management is for ecologists to recognise and synthesise recent research on all drivers of ecological change relevant to their study (Butchart et al., 2010; Cavanagh et al., 2017). This step...
is complicated by the exponential growth of scientific output in all fields of research, including applied fields of ecology (Larsen & von Ins, 2009). The increase in research volume, as well as the ease of electronic communication and search engines, may narrow the reading and citing habits of scientists (Evans, 2008) and potentially results in isolated and uncommunicative research ‘silos’ (Van Alstyne & Brynjolfsson, 1996, 2005).

Over the last 30 years, applied ecology has formed several branches, each of which has developed a specialised literature of its own. Some of these branches are recognised and referred to as discrete subfields, including climate change biology (Bellard, Bertelsmeier, Leadley, Thuiller, & Courchamp, 2012; Peterson, Menon, & Li, 2010), conservation biology (Griffiths & Santos, 2012; Soule, 1985), invasive species biology (Lockwood, Hoopes, & Marchetti, 2013; Vermeij, 1996) and restoration ecology (Hobbs & Harris, 2001; Young, Petersen, & Clary, 2005). While other research subfields exist, these four are not system- or taxa-specific and have clear links to ecological management. In addition, these subfields, and applied ecology as a whole, are linked by commonalities in underlying ecological theory (Slobodkin, 1988) and have enormous potential to collectively address major ecological problems (Driscoll et al., 2012). These subfields have been examined in several literature reviews, which have found that between-subfield connectivity is far from universal. There are strong links between conservation and climate change biology, but not invasion biology (Lawler et al., 2006). Climate change biology often fails to consider other threats to species and ecosystems (Fazey, Fischer, & Lindenmayer, 2005), and restoration ecology and conservation biology focus on different taxa and study scales (Young, 2000).

These past reviews have been limited in sample sizes (mostly fewer than one thousand papers) and the generality of questions they were able to address. Bibliometrics offer a complementary way to examine this problem, trading depth for breadth, allowing us to study publication data from the entire population of scientific publications in the mainstream peer-reviewed literature (Borgman & Furner, 2002; Hood & Wilson, 2001). Using these data, we can model the publication trajectories over time in these subfields, including subfield sizes and growth rates. In addition, by treating citations as units of connectivity and information sharing between publications, we can study patterns of connectivity within and between subfields at a range of scales, including the rates at which papers are cited, and the keywords used by the papers most-cited by different subfields.

We aggregated publication data on 284,494 ecology papers published between 1990 and 2017, connected by c. 3.15 million citations. Using a subset of 40,505 papers identified as climate change biology, conservation biology, invasion biology or restoration ecology, we: (1) quantified the overall publication and citation trends in these subfields, (2) used citation rates to estimate current and historical interconnectivity among these subfields and (3) identified publication, citation and word-use patterns that may represent barriers to future connectivity between these subfields. Detailed methods for all of our analyses can be found in the Supporting information.

2 PUBLICATION AND CITATION RATES

For each year in our study period, we calculated the proportion of all published ecology papers in each subfield and the proportion of all citations (from all ecology papers in a given year) of papers in a given subfield. We then modelled trends in these variables over time, for all subfields combined and for each subfield separately. Summed together, new publications in the four subfields increased from 1.8% of new ecology publications in 1990 to 22.9% in 2017 (Figure 1a), and new citations increased from 1.2% in 1990 to 22.9% in 2017 (Figure 1b). This rapid expansion of applied ecology research reflects the increased importance of real-world applications in ecology, and mirrors an increase in the public visibility of ecology and its importance for tackling environmental issues, particularly climate change and species conservation (Novacek, 2008). We note that some of this growth may also reflect an increase in the use of our key terms over time, rather than reflecting an actual increase in subfield research.

When subfields were modelled separately, trends over time diverged substantially (Figure 1c,d). Conservation biology showed the greatest increase in publication and citation proportions during the 1990s, and though growth slowed after 2000, it was still the largest and most cited subfield in 2017 (Figure 1c,d). In contrast, growth in climate change biology’s publication and citation proportions was consistent during the 1990s, and increased rapidly from 2000 (Figure 1c,d and Figure S1). Invasion biology showed rapid increases in publication and citation proportions in the mid-2000s, but plateaued and

![Figure 1](image-url) Trends in new publications and citations received for four subfields of applied ecology (a, b) summed and (c, d) individually (climate change ['CI', red], conservation ['Co', green], invasion ['I', yellow] and restoration ['R', blue]) between 1990 and 2017. Yearly publication and citation totals were proportionised by the total number of new papers or new citations in ecology each year. Splines were estimated using generalised additive models (Tables S1–S4). Shaded regions behind splines are 95% confidence intervals. Note that y-axis scale differs between (a, b) and (c, d)
began to decline by 2012 (Figure 1c,d). This decline coincides with the rise of alternate terminology (e.g. ‘novel ecosystems’), and debates on the direction and validity of the subfield (e.g. Blondel, Hoffmann, & Courchamp, 2014; Russell & Blackburn, 2017). Growth in the use of ‘novel ecosystem’ and ‘novel community’ did rise over this period (Figure S2), but is unlikely to explain the entirety of this decline. Restoration ecology showed growth in publication and citation proportions across the study period, but by 2017 this subfield published half as many papers and received a third as many citations as the other subfields (Figure 1c,d). It appears from our results that restoration ecology has not experienced the same publication and citation growth as other subfields, despite its recognised potential to reduce the impacts of environmental change (Perring et al., 2015).

3 | CITATION CONNECTIVITY BETWEEN SUBFIELDS

We examined citation patterns within and between subfields by modelling the probability that at least one paper in one subfield was cited by a paper in another subfield (including within-subfield citations) across the study period, examining all subfield pairs. All subfields showed similar trends in the probability of citation within the same subfield; within-subgroup citation probabilities in 1990 varied between 0.2 and 0.4, but rose to >0.8 by the late 2000s (Figure 2a–d). Such high levels of within-subgroup citation are perhaps unsurprising and also indicate that our chosen subfield categories captured genuinely discrete areas of research. The probability of citing a paper from another subfield also increased over time in all cases, with conservation biology papers most likely to be cited by papers in other subfields (Figure 2a,c,d). The probability of a different subfield citing a climate change biology paper increased rapidly after 2005, reflecting the observed trends in publication and overall citation rates in this subfield (Figures 1c,d and 2a–d). These results suggest that researchers are aware of the importance of other subfields, and are integrating papers from other subfields at ever-increasing rates.

That said, 33.8% of papers that cited papers from another subfield only cited a single paper in that subfield, likely as part of passing general statements (e.g. early in the introduction or in the final discussion paragraphs), rather than supporting central concepts, hypotheses or questions. For papers that cited another subfield, we also modelled the proportion of these papers’ citations that came from each subfield. Predictably, most of these papers cited a greater proportion of papers from within the same subfield (Figure 2g), likely due to the taxon-specific focus of many invasion research efforts. The average proportion of cited papers from other subfields rarely exceeded 7% (Figure 2e–h).

4 | IMPORTANT CONCEPTS WITHIN AND BETWEEN SUBFIELDS

To gain insights about differences in research focus between subfields, we identified core ‘concepts’ in each subfield, based on commonly used words in paper titles and keywords between 2007 and 2017.
Many of the same concepts were identified in multiple subfields. We summed the total number of times that the most common concepts from each subfield were cited by papers in that subfield (where a citation to a paper equaled a citation to each ‘concept’ in that paper’s title and keywords). These ‘internal concept citation counts’ reflect the perceived value of a concept within each subfield. We also calculated the number of times that each subfield’s concepts were cited by papers from each of the other subfields. These ‘external concept citation counts’ reflect the value of each subfield’s concepts to the other subfield. We then relativised all concept citation counts by usage (the total times the concept was used in the title and keywords of the subfield’s papers) to represent a citations-to-usage rate. We compared these internal and external ‘concept citation rates’ for all subfield pairs to identify whether the concepts most valued within each subfield were similar to those valued by each other subfield.

Internal concept citation rates were almost all greater than one, indicating that these concepts were cited more often than they were used in titles and keywords (diagonal panels in Figure 3). In

**FIGURE 3** Comparison of internal and external concept citation rates between four subfields of applied ecology. In each panel, points represent the most popular concepts (n = number of concepts) in a subfield’s papers (words used in titles and keywords of papers in the subfield shown in x-axis labels). The x-axis shows internal concept citation rates (citations from other papers within the same subfield), and the y-axis shows external concept citation rates (citations from papers from the subfield shown in y-axis labels). The 10 most well-cited concepts along each axis have been labelled with point colour corresponding to associated subfield. Note that axes are ln-transformed and have different scales.
both internal and external concept citation rates, climate change biology valued papers concerning large-scale patterns, especially species distributions, range shifts and migrations (Figure 3a–e,i,m). Conservation biology showed a strong preference towards papers on bird species and conservation planning, including reserve selection, conservation priorities and threat assessments (Figure 3b, e–h,j,n). Invasion biology valued large and small-scale impacts of invasive species, particularly those concerned with extinctions (presumably local extinctions), biological control, rapid evolution and propagule pressure (Figure 3c,g,i–l,o). Restoration ecology valued work that was strongly vegetation-focused, especially on grasslands and ex-agricultural land, and on vegetation community development and assembly (e.g. succession, seeds and dispersal limitation; Figure 3d,h,l,m–p).

Previous literature reviews have identified biases in study taxa and system in certain subfields (Lawler et al., 2006; Young, 2000). Our results accord with this, and suggest this may be the case across all four studied subfields. Climate change and conservation biology most often cited concepts related to large spatial scales, whereas invasion biology and restoration ecology most often cited concepts associated with local-scale processes (Figure 3). One potential explanation is that large-scale studies, such as those resulting from remote sensing or big data, may be cited more by smaller-scale research than the reverse. Quantifying this would require data on the content of these studies, rather than simple keyword analysis, and is beyond the scope of our study.

In addition to scale differences between subfields, the most cited concepts in each subfield related more to applications than underlying ecological theory. While there are some exceptions (e.g. ‘succession’ and ‘niche’), the fundamental ecological processes that link these subfields were not well-cited. A lexical scan of the titles and keywords of subfield papers for common terms associated with ecological theories found consistently low usage rates (Table S7). Many terms had usage rates close to zero, and even the most common terms were only used in 1%–3% of papers. While ecological theory can be difficult to incorporate into applied studies (Driscoll & Lindenmayer, 2012), our results suggest there is unrealised potential for many theoretical concepts to be explored in broader applied contexts.

5 | JOURNAL PREFERENCES

We visualised journal preferences between subfields using non-metric multidimensional scaling (nMDS). We treated journals as ‘sites’ and subfields as ‘species’, only including journals if they published at least one paper from one of the four subfields. To test whether some subfields were disproportionately represented in high-impact journals, we fitted an isotropic journal impact factor surface to the nMDS plot using the 2016 InCites Journal Citation Reports published by Clarivate Analytics. Subfield loadings were near-orthogonal, indicating that journals predominantly contained papers from a single subfield (Figure 4). Not surprisingly, journals that identified with particular subfields were strongly aligned with that subfield (Figure 4 and Table 1). High impact journals were located near to the centre of nMDS space, although the impact factor surface peaked towards climate change biology (Figure 4). These patterns suggest that most subfield research is aggregated into discrete ‘silos’, which is likely a combination of two interacting factors: increased subject specialisation of journals, and authors targeting papers to specific journals. This, combined with the decreasing breadth of papers that scientists read (Evans, 2008), almost certainly results in important and relevant knowledge from other subfields being systematically overlooked.

6 | CONCLUSIONS

Since 1990, peer-reviewed research in four major subfields of applied ecology has grown substantially and developed some interconnectivity. This is especially true of climate change biology, which appears to be experiencing a dramatic increase in both overall publication growth and citations in other subfields. Despite this, there are still asymmetries in growth and representation, particularly in restoration ecology. In addition, while the probabilities
that papers in different subfields will cite each other were high, most papers cited more papers from within their subfield than from other subfields.

We recognise that previous efforts have been made to bring these subfields together conceptually (e.g. Hampe & Petit, 2005; Harris, Hobbs, Higgs, & Aronson, 2006) and there are many examples of excellent applied research that account for multiple ecological threats (e.g. Ackerly et al., 2010). Our bibliometric analyses serve to provide an overarching perspective on the trajectory of interconnectivity within four major subfields of applied ecology. Specifically, we identified three barriers to greater subfield connectivity: (a) pervasive differences in study scale, taxa and systems, (b) within subgroup ‘publication silos’ and (c) connectivity focused on overlap in common applications rather than overlap in fundamental ecological concepts. By making these barriers more visible we hope they can be more easily overcome, as we endeavour to improve our understanding of natural systems and how to manage them.

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AUTHORS’ CONTRIBUTIONS
T.L.S. and C.E.W. originally devised the project and T.L.S., J.M.D. and M.M.M. developed the research questions. T.L.S. processed publication data, performed all analyses and created all figures. All authors contributed to the writing and editing of the manuscript and gave final approval for publication.

DATA ACCESSIBILITY
Publication data were obtained and used with permission of Clarivate Analytics through their Web of Science portal. Code and minimal data necessary to reproduce all results and figures are available at Zenodo - https://doi.org/10.5281/zenodo.2572033 (Staples, 2019) and Figshare - https://doi.org/10.6084/m9.figshare.7700057.v1 (Staples, Dwyer, Wainwright, & Mayfield, 2019). These repositories also contain a complete R script and necessary functions to clean, process and analyse the Web of Science publication data.

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REFERENCES

### TABLE 1
Journals where subfield papers comprised at least 40% of the total number of papers that were published between 1990 and 2017 and indexed by Web of Science (n) (see Table S8 for counts of all included journals). Abbreviations are used in Figure 4 to indicate journal position on the non-metric multidimensional scaling.

<table>
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<tr>
<th>Journal name</th>
<th>Abbreviation</th>
<th>n</th>
<th>Climate change</th>
<th>Conservation</th>
<th>Invasion</th>
<th>Restoration</th>
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<tr>
<td>Animal Conservation</td>
<td>AC</td>
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<td>0.313</td>
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<td>Applied Vegetation Science</td>
<td>AVS</td>
<td>837</td>
<td>0.030</td>
<td>0.121</td>
<td>0.093</td>
<td>0.276</td>
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<tr>
<td>Aquatic Invasions</td>
<td>AI</td>
<td>415</td>
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<td>0.019</td>
<td>0.677</td>
<td>0.005</td>
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<td>B&amp;C</td>
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<td>0.406</td>
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<tr>
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<td>0.051</td>
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<tr>
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<td>0.028</td>
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<td>Diversity and Distributions</td>
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<td>0.547</td>
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<td>0.049</td>
<td>0.085</td>
<td>0.752</td>
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</table>
Larsen, P. O., & von Ins, M. (2009). The rate of growth in scientific publication and the decline in coverage provided by Science Citation Index. Scientometrics, 84, 575–603.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.