Interdiscplinary Ecolog

Simon Goring and Sarah Supp

13 January, 2016

# Training and Hiring Patterns for Interdisciplinary Ecologists

Simon J. Goring1

Sarah Supp2

David Inouye3

Andria Dawson4

1 Department of Geography, University of Wisconsin - Madison

2 School of Biology and Ecology, University of Maine

3 Department of Biology, University of Maryland, College Park

4 University of Arizona

Corresponding author: Simon Goring - [goring@wisc.edu](mailto:goring@wisc.edu)

## Abstract

*Increasing emphasis has been placed on training interdisciplinary scientists in the ecological sciences. While ecology has historically been viewed as an interdisciplinary science, there is an increasing push to borrow deeply from related disciplines in an effort to tackle the "wicked problems" that require interdisciplinary solutions.*

*Using postings from ECOLOG-L, a mailing list strongly associated with the Ecological Society of America, we examine patterns of hiring for graduate and tenure track positions. We use text mining and a machine learning algorithm (random forest), trained on manually classified data to estimate rates of posting for interdisciplinary positions at the tenure track and graduate/postdoctoral level.*

*Clear patterns of hiring seasonality are apparent in the data that may be of use to other researchers. Our results indicate that since 2000 the number of pre-tenure and tenure track positions advertising for interdisciplinary scholars has increased. Rates of advertising for interdisciplinary tenure track positions are lower than rates of advertising for interdisciplinary graduate and postdoctoral positions. While the rate of advertising tells us little about the actual hiring practice, it is a vetted process that often results from a committee of individuals making explicit decisions about how the position is to be filled. Our results point to an evolving system of interdisciplinarity within the ecological sciences, interdisciplinarity by proxy, whereby disciplinary researchers hire graduate or postdoctoral students to conduct research into interdisciplinary hypotheses, but, possibly, seek out disciplinary researchers as colleagues at the tenured level.*

## Formatting Instructions:

Research Communication:

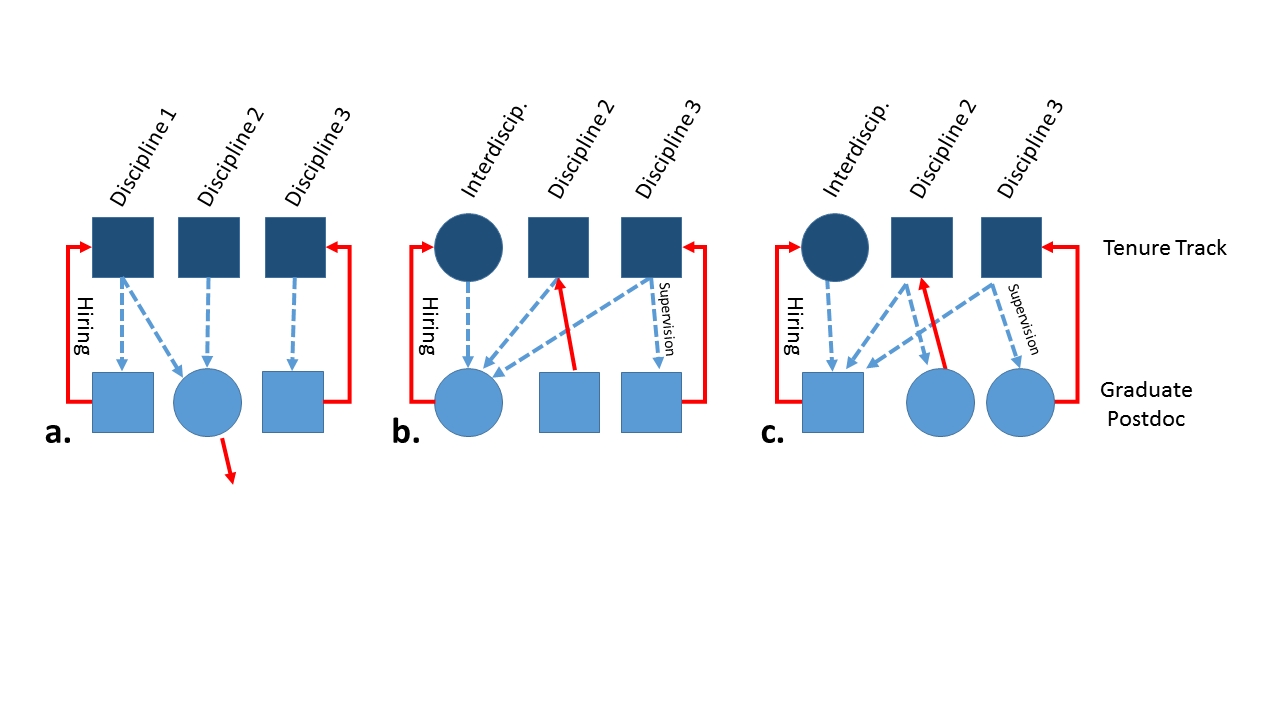
* relatively short, high-impact primary research papers, with implications for policy making and resource management
* Topics should have broad, interdisciplinary appeal
* Research Communications should always be divided into the standard IMRAD sections: Introduction, Methods and Materials, Results, Conclusions
* Text should be understandable not only to ecologists and environmental scientists but also to those in related disciplines
* Length: about 150 words for the abstract, **2500 words** (currently at 3400 words), not including a short abstract, not more than **20 references** (currently at 28 references), and a total of 3 figures, tables, and/or panels
* A limited number of additional figures, tables, and/or panels may be included as Web-only material for the journals website; however, if this material exceeds four journal pages, an additional page charge will be added to the cost of publication. Alternatively, very large datasets or other long or complex material can be included as pdfs; these will not be converted to the journals design style
* Writing style must be crisp, concise, and accessible, and should avoid or explain all terminology and concepts that might be unfamiliar to a multidisciplinary readership
* Content should involve one or more of the following:
  + Research with important policy or resource management implications (this should be an underlying theme in all Frontiers papers and should be reflected in a strong Conclusions section, involving a discussion of these implications)
  + Research with practical applications
  + Global environmental or resource issues
  + Fundamental, novel advances in ecological science or related areas
  + Use of new approaches, techniques, or technologies to address current and/or long-standing ecological/environmental issues

## Introduction

Interdisciplinarity has been receiving increased attention in the sciences, both as a method of studying key processes, but also as a subject of interest in and of itself. Part of this increased attention is the result of improved access to data and tools that allow researcheres to address the complex set of problems facing modern ecologists, where biological responses intersect with land use change, climate change, changes in biogeophysical processes, and human interactions (Basche et al. 2014, dawson2011beyond; Goring et al. 2014, Heffernan et al. 2014, White et al. 2015). To help support the increased need for interdisciplinary approaches in research, a number of training programs and funding sources have been structured to address needs at the graduate and post-doctoral levels (Schmidt et al. 2012, Wagner et al. 2012, Hibbert et al. 2014, Stamp et al. 2015), and new models for promoting and improving interdisciplinarity within academia have been proposed (Cheruvelil et al. 2014, Ciannelli et al. 2014, Goring et al. 2014), but challenges and questions remain.

Perceptions of risk for researchers engaged in interdisciplinary research are real, particularly for early career researchers (Fischer et al. 2012), and must be addressed within academia. These risks are often balanced by the promise of doing exciting work, greater likelihood of future collaboration (Hampton and Parker 2011), higher rates of publication (Porter et al. 2012, but see Van Noorden 2015), and, higher rates of funding (Bellotti 2012). Hibbert *et al*. (2014) use narrative analysis to decribe the optimism of Doctoral students who feel that their interdisciplinary experience has created a unique niche for them, but also indicate that interdisciplinary students may feel lost on their "quest" without adequate supervision. Ultimately, it is unclear the extent to which the trend toward increasing interdisciplinarity within graduate training programs is playing itself out at the faculty level, especially given that some data on interdisciplinary collaboration points to explicit costs to the interdisciplinary researcher (Van Rijnsoever and Hessels 2011, Goring et al. 2014, Van Noorden 2015). There is a role for increased integration between traditional academic & non-academic outcomes within interdisciplinary programs (Ciannelli et al. 2014), but interdisciplinary research itself is often supported by tenured or tenure track researchers who may or may not themselves be a product of interdisciplinary research programs.

While ecology is often perceived as being highly interdisciplinary, publications patterns do not neccessarily reflect this belief (Romolini et al. 2013, Van Noorden 2015). Regardless, it is important to clarify what is meant by interdisciplinarity in the context of this paper, and in the broader discussion. There are multiple terms used in discussions about disciplinarity, primarily "multidisciplinary", "interdisciplinary" and "transdisciplinary". Choi and Pak (2006) provide a unique framing for the three models: **Multidisciplinary** research is additive (*"2 + 2 = 4"*) where individuals maintain their disciplinary roles, and the outcome is the sum of the parts. **Interdisciplinary** research is interactive (*"2 + 2 = 5"*) and involves the integration of disciplines, resulting in something that is more than the sum of its parts. **Transdisciplinary** research is holistic (*"2 + 2 = yellow"*) with results that transcend the traditional disciplinary boundary (Choi and Pak 2006). Currently, ecology is broadly disciplinary, and rarely transdisciplinary. For the purposes of this paper we use the term interdisciplinary as a catch-all, and identify the "interdisciplinary" worker, an individual who is able to integrate multiple disciplines within their own research practice, rather than interdisciplinary teams.



**Figure 1**. *Three models for interdisciplinary research & hiring within research departments. Blue lines represent supervision by tenured researchers (upper row), red lines represent hiring of untenured researchers (postdoctoral & graduate; lower row). We use circles to represent interdisciplinary researchers and squares to represent disciplinary researchers. Model (a) represents a siloed system where non-tenured researchers (lower row) carry out interdisciplinary research, but disciplinary researchers are strongly favored for tenure track positions. Model (b) indicates some role for interdisciplinary researchers at the tenure track level, but this role is stable through time. Model (c) indicates that current interest in interdisciplinary training carries through to increased interdisciplinary hiring at the tenure track level.*

It is possible to conceptualize multiple "preferred" models for interdisciplinary research at the institutional level. The siloed model (Fig. 1a) involves deeply disciplinary researchers collaborating on an interdisciplinary project and hiring graduate or postdoctoral researchers who will act as the disciplinary bridges. In this model we might believe that tenure-track or tenured researchers would prefer colleagues who may appear more deeply disciplinary than interdisciplinary. Hiring in the siloed model is largely drawn from disciplinary (squares) researchers, and interdisciplinary collaboration is undertaken by interdisciplinary graduate students (circles). Here, we might predict that hiring for tenure-track interdisciplinary researchers would remain low, and be relatively unchanged through time.

The balanced model (Fig. 1b) conceptualizes a system where embedded interdisciplinary researchers are replaced by interdisciplinary researchers at the tenure-track level, and elsewhere disciplinary researchers are hired. In this model, we might believe that tenure-track or tenured researchers prefer a mixture of interdisciplinary and disciplinary colleagues, but that hiring trends remain stable through time. This model then predicts that hiring of tenure-track interdisciplinary researchers should be roughly equivalent to hiring patterns at the tenure-track level overall.

The growth model (Fig. 1c) suggests that recent funding initiatives via largely interdisciplinary programs (*e.g.*, NSF's Macrosystems Biology, EarthCube, Coupled Human Systems & others) would lead to the increased hiring of tenure-track interdisciplinary researchers, via new positions and via the replacement of some disciplinary researchers, through time.

ECOLOG-L (refered hereafter as Ecolog) is a LISTSERV® that essentially acts as a massive, unmoderated group blog (currently 20,500 members). It was started in 1992 by David Inouye, who still moderates it, and hosted by the University of Maryland. It is unofficially affiliated with the Ecological Society of America, and is recognized as one of the largest aggregators for ecology grants, jobs, news, announcements, and discussion threads. Anyone can view posts, or register and contribute to posts for free. Jobs posted to Ecolog are almost certainly biased to jobs in the United States, but frequently include international listings as well. We used posts from Ecolog from January 2000 - January 2015 as representative of trends in graduate and postdoctoral vs. tenure-track job markets.

Here, we aim to test whether increased training at the graduate and postdoctoral levels are translating into increased hiring rates for tenure-track faculty with interdisciplinary backgrounds. Using job postings from Ecolog https://listserv.umd.edu/archives/ecolog-l.html we classify and assess the rates of change in job postings for graduate, postdoctoral and tenure track positions, both with and without interdisciplinary focus. Using relative rates of posting between job-type classes (tenure track, postdoctoral and graduate level) we aim to test whether differential rates of hiring have changed over time, and ultimately, use these rates of change to identify patterns in the academic job market and strategies for carrying out interdisciplinary work within the academy.

## Methods

We used a web scraper written in R (Team 2014) to read messages from Ecolog from the years 2000 - 2015. This program pulled the Ecolog message, message date and message subject for each posting. Messages from Ecolog were used as the basis for the document corpus, which was then transformed into a term matrix using text analysis tools in the tm package for R (Meyer et al. 2008, Feinerer and Hornik 2012). Data pre-processing included the removal of excess whitespace, punctuation, and HTML tags and entities (all processing is preserved in the file load\_terms.R) using tm\_map function from the tm package (Meyer et al. 2008, Feinerer and Hornik 2012). To eliminate pseudo-duplicates ("student" and "students") we used word stemming implemented as part of the snowballC package. Because of the volume of messages, we removed all sparse terms, retaining only the top 1% by count.

We classified a number of records by hand using a Shiny (Chang et al. 2015) application (available publically [here](http://ec2-52-0-223-101.compute-1.amazonaws.com:3838/ESA_Shiny/)). Messages were identified as academic job ads, non-academic job ads (generally), and non-job postings. Academic job adds were classified into graduate, postdoctoral, and tenure track positions, and then also classified as interdisciplinary or not. In addition, we provided the opportunity to classify salary type, but do not present this data here.

Using the surveyed messages (*n* = 4731), we built a model using a random forest to classify messages as tenure track jobs, postdoctoral positions and graduate positions, and to test whether messages indicate interdisciplinarity (package *randomForest*; Liaw and Wiener 2002). Based on the model constructed we then predict the class of the remaining messages to build a time series of job ads. Since hand coding messages was an iterative process, we used the confusion matrix from the predictive models to weight Ecolog messages selected for display and classification in the Shiny app. Messages that were predicted to be interdisciplinary from the partial models were weighted most highly, as were messages with high rates of confusion for tenure track, postdoctoral or graduate positions.

Once all Ecolog messages were classified using the RF model, a Generalized Additive Model was applied (gamm in the package mgcv: Wood 2004). A binomial model is constructed, using the employment class as a random effect, with the week of the year (1 - 52) modeled using a cyclic penalized cubic spline that varies by employment class. This model then allows us to examine the trends in each employment class, over the 15 years of data. Since there is a gradual trend in uptake in the use of Ecolog as a message board, and since individual weeks and years are unlikely to be independent, we tested several correlational structures and found an ARMA(1) (using the year of the message) to provide the best modeling support.

## Results

Ecolog returns 50154 messages for the period from January 2000 to January 2015. Cleaning & stemming the individual words in the messages leaves with a set of 1474 unique terms.

The frequency of terms in the Ecolog corpus follows a log distribution. The most frequent terms ('will', n=8.450810^{4}; 'research', n=6.674710^{4}; university, n=NA; 'field', n=3.690110^{4}; and 'ecology', n=NA) have much higher frequencies than the mean ( = 3474.7795115). Because the term matrix was constrained to the top 1% of all terms, the least common words in the term matrix ('enjoy', 'helpful' and 'speaking') still occur several hundreds of times (all n=592).

**Table 1**. *Cross-over between terms in the top 95%ile of importance for the random forest model between classification models for Tenure-Track, Postdoctoral, and Graduate positions, as well as for Interdisciplinary positions.*

|  |  |  |  |
| --- | --- | --- | --- |
|  | Tenure | PostDoc | Graduate |
| **PostDoc** | 32.2 | NA | NA |
| **Graduate** | 31 | 49.4 | NA |
| **Interdisciplinary** | 39.1 | 54 | 46 |

Four independent random forest models were also constructed to enable us to assess term importance for each individual employment class and for interdisciplinary postings. While the overall model (7 classes) has an out of bag error estimate of 18.4%, the higest error rates within any one class occur between classes and their "interdisciplinary" alternative. This indicates higher rates of uncertainty within classes, and particularly, potential differences in the terms used for interdisciplinarity between job classes.

**Table 2.** *Confusion matrix for the complete random forest model. The confusion matrix shows the hand classified coding in rows and the model classifications in the columns. For example, of the 64 postings classified as "interdisciplinary tenure track" (TT\_Int), the random forest model classified one message as a graduate student position, one as an interdisciplinary postdoctoral position (PD\_Int) and 13 as non-interdisciplinary Tenure track positions. The Class Error is the proportion of incorrectly classified samples for any one class.*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | GR | GR\_Int | Other | PD | PD\_Int | TT | TT\_Int | class.error |
| **GR** | 221 | 34 | 27 | 7 | 4 | 2 | 0 | 0.25 |
| **GR\_Int** | 19 | 61 | 3 | 2 | 1 | 0 | 0 | 0.29 |
| **Other** | 416 | 47 | 2726 | 86 | 83 | 84 | 48 | 0.22 |
| **PD** | 7 | 0 | 20 | 170 | 23 | 1 | 1 | 0.23 |
| **PD\_Int** | 0 | 2 | 6 | 29 | 44 | 2 | 0 | 0.47 |
| **TT** | 3 | 0 | 17 | 1 | 0 | 127 | 12 | 0.21 |
| **TT\_Int** | 1 | 0 | 1 | 0 | 1 | 13 | 48 | 0.25 |

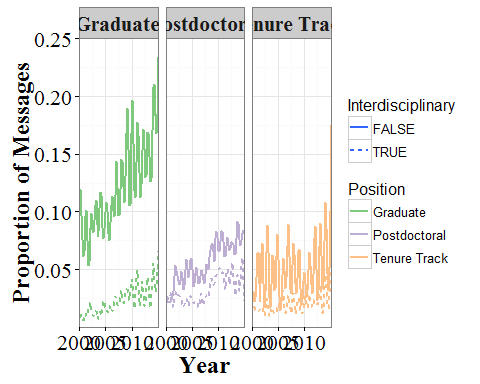
The random forest model provides an importance table, indicating the utility of a term in classifying individual messages into the various classes. The importance value represents the mean decrease in the Gini index across trees when the particular variable is used as a classifier. The tables themselves are very long, but rank of individual terms can provide some insight into the processes underlying the hiring trends in ecology. Tenure-track and postdoctoral positions show higher cross-over of high-importance terms than do tenure-track and graduate positions (or postdoctoral and graduate positions). Both graduate and postdoctoral positions show much higher cross-over with interdisciplinary terms than do terms of importance for tenure-track postings.

**Table 2**. *Importance terms for the classification of Tenure Track, Postdoctoral, and Graduate student positions. Bolded terms represent terms that are unique within the top 99%ile of terms. Many of the top key terms for positions relate specifically to those positions (tenure track, graduate).*

|  |  |  |  |
| --- | --- | --- | --- |
| Tenure | PostDoc | Graduate | Interdisciplinary |
| **professor** | postdoctor | **student** | **interdisciplinari** |
| **tenuretrack** | posit | assistantship | applic |
| **teach** | univers | graduat | posit |
| depart | applic | phd | research |
| applic | research | univers | **develop** |
| **assist** | model | avail | model |
| **faculti** | avail | research | **ecosystem** |
| **undergradu** | **postdoc** | project | **seek** |
| posit | **dynam** | applic | project |
| candid | **interact** | ecolog | univers |
| univers | **refer** | depart | **climat** |
| **commit** | **fellow** | **motiv** | **opportun** |
| **chair** | project | **studi** | postdoctor |
| **vita** | **doctor** | posit | strong |
| **program** | three | **interest** | assistantship |
| **success** | candid | **tuition** | **system** |
| research | **base** | scienc | scienc |
| **curriculum** | ecolog | **fall** | phd |
| **biolog** | **experi** | candid | avail |
| graduat | strong | **lab** | three |

The random forest model to explicitly identify tenure-track positions indicates that terms of high importance include "tenuretrack" (indicating the removal of a hyphen), "assistant", "professor" and "undergraduate" (Table 2). For postdoctoral positions, the model identifies "postdoctoral", "position", and "research" as most important. The key term in this case is "interdisciplinary". We're really looking at interdisciplinary jobs here, so it's no surprise that terms like "position", "project", "applications" show up, but the importance rank of "postdoctoral" (rank = 5) is much higher than the importance of "tenuretrack" (rank = 215) or "professor" (rank = 215), indicating a much higher incidence of interdisciplinary advertisments for graduate and postdoctoral positions than for professors.

Job postings on Ecolog have increased along with the increase in posting volume since 2000, however the increase in total postings as a proportion of job postings for graduate positions is much stronger than for any other job position (**Figure X**).



**Figure X.** *Job postings as a proportion of all postings on ECOLOG. Postings for graduate student positions increase strongly from 2000 - 2015 as do postdoctoral position postings. Tenure track postings appear to remain relatively stable through time. Interdisciplinary postings remain low through time and appear to increase at a rate equal to, or lower than the disciplinary postings.*

Seasonal trends suggest differences in timing and intensity for the different job classes (Figure). In all cases the amplitude of the disciplinary curve is much higher than the amplitude of the interdisciplinary curve, although this may be, in part, a function of the total number of postings. The timing of peak posting and the lowest rates of posting also varies by class. The lowest proportion of postings for graduate positions occurs at the end of July (as with Postdoctoral positions), while the lowest volume for Tenure Track positions occurs a month earlier in June. The peak time of tenure track posting occurs in mid-November (similar to Postdoctoral postings), while the graduate posting peak appears to be broader, with a peak in late February.



**Figure X**. *The seasonal trend in position posting shows differences between job classes, and between interdisciplinary and disciplinary postings. Panels represent job types and line coloring indicates whether a position in interdisciplinary (purple) or disciplinary (green). Positive values suggest higher than average posting proportions. The model is derived using a generalized additive mixed model, with job class as a random effect and a one year ARMA lag.*

All three types of postings appear somewhat bimodal, wheras the major peak for Tenure Track and Postdoctoral jobs occurs in November, the secondary peak is in the early spring, coincident with the Graduate position peak.

For interdisciplinary positions the amplitude of the seasonal trend is much lower and there appears to be a shift from bimodal to unimodal posting seasonality.



**Figure X** *Annual trend for Ecolog job postings. Overall there is a trend of increasing total postings for each job class, with interdisciplinary postings increasing at a lower rate for graduate and postdoctoral students than for tenure track positions, which have been subject to much greater fluctuations.*

Year over year changes show considerable fluctuations. In particular, a significant drop for disciplinary Graduate and Tenure Track postion posting volume (and for interdisciplinary Postdoc postings) occurs in 2004, while the same trend appears absent from the disciplinary postdoc postings and from the interdisciplinary Tenure Track and Graduate postings.

**Some of this may be due to a limitation of the modeling we apply currently.** Andrea Dawson is taking a look at the model & will likely contribute a better model that should decompose the trends and take into account the temporal autocorrelation I can't presently get rid of.

## Discussion

### Main points to discuss:

**First two to three paragraphs.**

* refs on ac hiring trends generally (e.g. proportion of ecology grads/postdocs that get t-t jobs) & increasing importance of interdiscip.
* Our RESULTS: declining number of opportunities at each academic career stage (more grad positions than postdoc than t-t). (as a proportion)
* Differences in trends for interdiscip vs traditional
* how does this match our models?

**Two paragraphs (caveats and considerations)**

Judging the intent of job advertisments and understanding the distinction between familiarity with a tool, and deeper engagement with a discipline is a critical challenge in classifying the opportunities for interdisciplinary researchers. Many tools commonly used within ecology are drawn from advances within other disciplines, where the "tool" is studied as a discipline in and of itself. The conflict between tool and discipline has been elucidated for geochronology, used extensively as a tool within paleoecology and paleobiology, but a discipline in its own right (Harrison et al. 2015). Within ecology it is often possible to make a clear distinction: A job that requires a landscape ecologist with GIS experience is likely not seeking a cross-disciplinary GIScientist, since GIS is largely used as a tool within ecology. Job ads requiring familiarity with R are also generally not asking for cross-disciplinary researchers, however the extent of statistical knowledge (for example), or intent of the position may make this distinction less clear.

This is further complicated by within-discipline splitting. Is a paleoecologist with landscape ecology experience cross-disciplinary, what about paleoecology and microbial ecology or microbiology? Analysis of citation patterns that make use of defined conventional disciplines show that ecology (as a specialty within biology) cites outside its discipline (biology) only 37% of the time, somewhat less than botany (42%) and zoology (48%), and has historically been one of the most disciplinary of the biological sciences by this measure since the 1950s (Van Noorden 2015).

The breadth of ecological sub-disciplines is overwhelming (community ecology, chemical ecology, microbial ecology, invasion ecology, animal communication, biogeography, landscape ecology, macroecology, spatial ecology, terrestrial ecology, behavioral ecology, paleoecology), and new sub-disciplines are being proposed continually (*e.g.*, Heffernan et al. 2014). A similar challenge to identifying interdisciplinarity is understanding whether individuals see the philosophical differences between subdisciplines as large enough to require realignment of views to tackle complex problems. The perception of a divide between sub-disciplines likely varies between indviduals and between sub-disciplines, but the problem is clear enough within ecology that disagreements over semantics have arisen a number of times, and a standardized nomenclature within ecology has been suggested (Herrando-Pérez et al. 2014). All this means that many people perceive of the possibility of an interdisciplinarity *within* ecology, but we argue here that whether or not semantic differences exist within ecological subdisciplines, they are dwarfed by the differences that result from reaching outside the discipline, to human geographers, psychologists and geologists, few of whom will have had the foundational training and background that many of us as ecologists share.

* do department t-t hiring trends follow their ads - e.g. just because they don't use the word interdisciplinary, are they biased for/against candidates with interdisciplinary backgrounds?
* Most job ads at the tt level have been "written by committee" and so there is evidence of direction & intention in the ads.
* interdisciplinarity in the grad & postdoc ads may be overstated.

**Two paragraphs**

* **David, could you take the lead on this possibly?**
* broader discussion about Ecolog
* increasing # of postings per year, esp. for graduate/postdoc jobs (perhaps what we really want to plot is proportion of interdisciplinary jobs?)
* increase in postdoc interdisc. jobs, esp 2005-2010, then level off? (similar pattern for graduate work?)
* relatively flat trend for faculty t-t jobs (ony very slight increase?)
* also the impact of economic issues (jobs during recession)

**One paragraph**

* refs that give suggestions or "rules of thumb" for interdisp. job candidates?
* important for interdiscp t-t candidates to still be able to have "story" they can tell - important not to appear unfocused or too broad, like to be categorized.
* does interdisp. work have particular benefits for non ac vs. ac careers? (can't really measure in our survey because we didn't finely divide up non-ac jobs, can only speculate)

**One paragraph** This dataset provides opportunities beyon understanding the state of the interdisciplinary job market. Recent questions have been raised about the extent of seasonal & unpaid internships (Fournier and Bond 2015) and further textual analysis of this dataset would provide opportunities to study this. Ecolog is more than just a job board though. Conversations about evolutionary theory, field work, sexism in the academy and more have been carried out throughout its existence. We provide this dataset and our analytical code as a

**Final Paragraph**

* Summary of findings

## Acknowledgements

SJG developed the idea behind this paper, contributed to the hand classification of postings, the bulk of the code and to writing and editing of this paper. SS helped with the framing, hand classification and writing of the paper. AD assisted with the framing, writing and statistical analysis (to do). DI contributed to the framing of the paper, assisted in writing and editing the draft paper.

This material is based upon work carried out by the PalEON Project (paleonproject.org) with support from the National Science Foundation MacroSystems Biology program under grant no. DEB-1241868. SJG would like to acknowledge NG, CG & AG in providing support for this analysis. **Add anything here**

## References

Basche, A. D., G. E. Roesch-McNally, L. A. Pease, C. D. Eidson, G. B. Lahdou, M. W. Dunbar, T. J. Frank, L. Frescoln, L. Gu, R. Nagelkirk, and others. 2014. Challenges and opportunities in transdisciplinary science: The experience of next generation scientists in an agriculture and climate research collaboration. Journal of Soil and Water Conservation 69:176A–179A.

Bellotti, E. 2012. Getting funded. multi-level network of physicists in italy. Social Networks 34:215–229.

Chang, W., J. Cheng, J. Allaire, Y. Xie, and J. McPherson. 2015. Shiny: Web application framework for r.

Cheruvelil, K. S., P. A. Soranno, K. C. Weathers, P. C. Hanson, S. J. Goring, C. T. Filstrup, and E. K. Read. 2014. Creating and maintaining high-performing collaborative research teams: The importance of diversity and interpersonal skills. Frontiers in Ecology and the Environment 12:31–38.

Choi, B. C., and A. W. Pak. 2006. Multidisciplinarity, interdisciplinarity and transdisciplinarity in health research, services, education and policy: 1. definitions, objectives, and evidence of effectiveness. Clinical and investigative medicine 29:351.

Ciannelli, L., M. Hunsicker, A. Beaudreau, K. Bailey, L. B. Crowder, C. Finley, C. Webb, J. Reynolds, K. Sagmiller, J. M. Anderies, and others. 2014. Transdisciplinary graduate education in marine resource science and management. ICES Journal of Marine Science: Journal du Conseil:fsu067.

Feinerer, I., and K. Hornik. 2012. Tm: Text mining package. R package version 0.5-7.1.

Fischer, E., K. Mackey, D. Cusack, L. DeSantis, L. Hartzell-Nichols, J. Lutz, J. Melbourne-Thomas, R. Meyer, D. Riveros-Iregui, C. Sorte, and others. 2012. Is pretenure interdisciplinary research a career risk? Eos, Transactions American Geophysical Union 93:311–312.

Fournier, A., and A. L. Bond. 2015. Volunteer field technicians are bad for wildlife ecology. Wildlife Society Bulletin.

Goring, S. J., K. C. Weathers, W. K. Dodds, P. A. Soranno, L. C. Sweet, K. S. Cheruvelil, J. S. Kominoski, J. Rüegg, A. M. Thorn, and R. M. Utz. 2014. Improving the culture of interdisciplinary collaboration in ecology by expanding measures of success. Frontiers in Ecology and the Environment 12:39–47.

Hampton, S., and J. Parker. 2011. Collaboration and productivity in scientific synthesis. BioScience 61:900–10.

Harrison, Mark, S. Baldwin, M. Caffee, G. Gehrels, B. Schoene, D. Shuster, and B. Singer. 2015. Geochronology: It’s about time. Eos 96.

Heffernan, J. B., P. A. Soranno, M. J. Angilletta Jr, L. B. Buckley, D. S. Gruner, T. H. Keitt, J. R. Kellner, J. S. Kominoski, A. V. Rocha, J. Xiao, and others. 2014. Macrosystems ecology: Understanding ecological patterns and processes at continental scales. Frontiers in Ecology and the Environment 12:5–14.

Herrando-Pérez, S., B. W. Brook, and C. J. Bradshaw. 2014. Ecology needs a convention of nomenclature. BioScience:biu013.

Hibbert, K. M., L. Lingard, M. Vanstone, E. A. Kinsella, P. McKenzie, T. D. Wilson, and A. Pitman. 2014. The quest for effective interdisciplinary graduate supervision: A critical narrative analysis. Canadian Journal of Higher Education 44:85–104.

Liaw, A., and M. Wiener. 2002. Classification and regression by randomForest. R News 2:18–22.

Meyer, D., K. Hornik, and I. Feinerer. 2008. Text mining infrastructure in r. Journal of Statistical Software 25:1–54.

Porter, A. L., J. Garner, and T. Crowl. 2012. Research coordination networks: Evidence of the relationship between funded interdisciplinary networking and scholarly impact. Bioscience 62:282–288.

Romolini, M., S. Record, R. Garvoille, Y. Marusenko, and R. S. Geiger. 2013. The next generation of scientists: Examining the experiences of graduate students in network-level social-ecological science. Ecology and Society 18:42.

Schmidt, A. H., A. S. Robbins, J. K. Combs, A. Freeburg, R. G. Jesperson, H. S. Rogers, K. S. Sheldon, and E. Wheat. 2012. A new model for training graduate students to conduct interdisciplinary, interorganizational, and international research. BioScience 62:296–304.

Stamp, N., A. Tan-Wilson, and A. Silva. 2015. Preparing graduate students and undergraduates for interdisciplinary research. BioScience 65:431–439.

Team, R. C. 2014. R: A language and environment for statistical computing (version 3.1. 0). vienna, Austria: R foundation for statistical computing.

Van Noorden, R. 2015. Interdisciplinary research by the numbers. Nature 525:306–307.

Van Rijnsoever, F. J., and L. K. Hessels. 2011. Factors associated with disciplinary and interdisciplinary research collaboration. Research Policy 40:463–472.

Wagner, H. H., M. A. Murphy, R. Holderegger, and L. Waits. 2012. Developing an interdisciplinary, distributed graduate course for twenty-first century scientists. BioScience 62:182–188.

White, R. L., A. E. Sutton, R. Salguero-Gomez, T. C. Bray, H. Campbell, E. Cieraad, N. Geekiyanage, L. Gherardi, A. C. Hughes, P. S. Jørgensen, and others. 2015. The next generation of action ecology: Novel approaches towards global ecological research. Ecosphere 6:art134.

Wood, S. N. 2004. Stable and efficient multiple smoothing parameter estimation for generalized additive models. Journal of the American Statistical Association 99:673–686.