The Spatial and Temporal Domains of Modern Ecology

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Observational scales play a critical role in shaping understanding of ecological pattern and process. To gain insight into the spatial and temporal domains being addressed by modern ecological science, we conducted a meta-analysis of papers published in 30 ecological journals between 2004 and 2014. We estimated two spatial dimensions (resolution and extent) and two temporal dimensions (interval and duration) of 371 ecological observations reported within 140 papers (out of 364 randomly selected titles). Our analysis revealed that ecology largely remains a field-based discipline that primarily collects observations within narrow spatial and temporal domains. Ecologists still make limited use of methods for observing larger-scale patterns and processes (e.g. remote sensing, used for 6% of observations), but make greater use of those which permit high frequency or temporally continuous *in situ* measurements (12% of observations). Observational scales were not clearly reported in the majority of three dimensions, which, together

with the narrow spatio-temporal ranges of observed scales, suggests a limited ability to generalize the findings of many studies.

The scales at which ecosystems are observed plays a critical role in shaping our understanding of their structure and function (*1–3*). Ecological patterns emerge from temporal and spatial domains that may be coarser or finer than the processes that shape them, which means that investigation across multiple scales is the *sine qua non* for understanding ecological phenomena (*1*). Awareness of the importance of scale has grown rapidly since the 1980s, accelerated by the need to understand how changes in the global climate, ocean, and land systems are affecting everything from individual populations (*4*) to entire biomes (*5*), while technological advances in areas such as remote sensing and genetics are making it ever-easier to quantify ecological features across a broad range of scales (*2, 6*).

Given the centrality of scale to understanding ecology, and the growing ability to study ecological phenomena across a broad range of spatial and temporal scales, it is important to assess the scales at which ecological research is presently being conducted. To gain insight into this question, we quantified the spatial and temporal domains of empirical observations that were reported in a representative sample of studies published between 2004-2014 in the top 30 ecological journals (by 2014 impact factor). Empirical observations provide the necessary means for developing and testing the models that explain why ecological patterns vary in time and space (*1, 7*), thus it stands to reason that the temporal and spatial distributions of ecological observations may be indicative of modern ecology's progress towards achieving a holistic, predictive understanding of ecosystems (*1, 2*).

We characterized observational domains along two key spatial dimensions, resolution (grain) and extent, and their temporal corollaries, sampling interval and total temporal duration. We calculated the actual (as opposed to representative; SI) scales of observation for these four dimensions from 371 discrete observations (defined here as data collected from non-experimentally manipulated, or "natural" (*7*), systems) reported within a 140 paper subset of 364 randomly selected articles (0.85% of total). To account for uncertainty in the estimation of observational dimensions due to 1) unclear methodological description in the reviewed papers, and 2) observer interpretation, we conducted a resampling analysis (n=1000) in which scale values were randomly perturbed within the bounds of estimated inter-observer variation (SI). We constructed histograms for each dimension from the mean of the perturbed ensembles, and estimated 95% confidence intervals for each histogram bin (Fig. 1). We constructed kernel density estimates from the full resampled ensemble in order to assess observational distributions within different juxtapositions of the four space-time dimensions (Fig. 2).

In terms of spatial resolution (the two-dimensional space in which all measurable features of a natural object(s) were recorded, as opposed to sub-sampled), the majority (67%) of observations were collected in plots of <1 m^2 resolution, 24% were collected within plots of 1 m^2 up to 1 ha, and the remaining 9% in plots of ≥ 1 ha (Fig. 1A). The total spatial extent (the number of sampled sites multiplied by the spatial resolution) of 86% of observations was <10 ha, while 36% covered less than 1 m^2 (Fig. 1B). Only 14% covered an extent ≥ 10 ha, with just 4% spanning areas ≥ 1 million ha.

In the temporal dimensions, 36% of observations were not repeated (Fig. 1C), 15% were repeated at short intervals (sub-second to daily), 21% at daily to monthly intervals, 19% at monthly to yearly intervals, and 8% at yearly to decadal intervals. The temporal duration of studies (the total amount of time the ecological feature was directly observed, calculated as the number of repeat observations multiplied by the effective sampling duration; SI) was less than one day for 71% of sampled observations, between one day and one month for 17% of observations, between one month and one year for 7% of observations, and greater than one year for 5% of observations (including several paleoecological studies covering centuries to millennia; Fig. 1D).

Juxtaposing the observational dimensions provides further insight into the spatio-temporal dis-

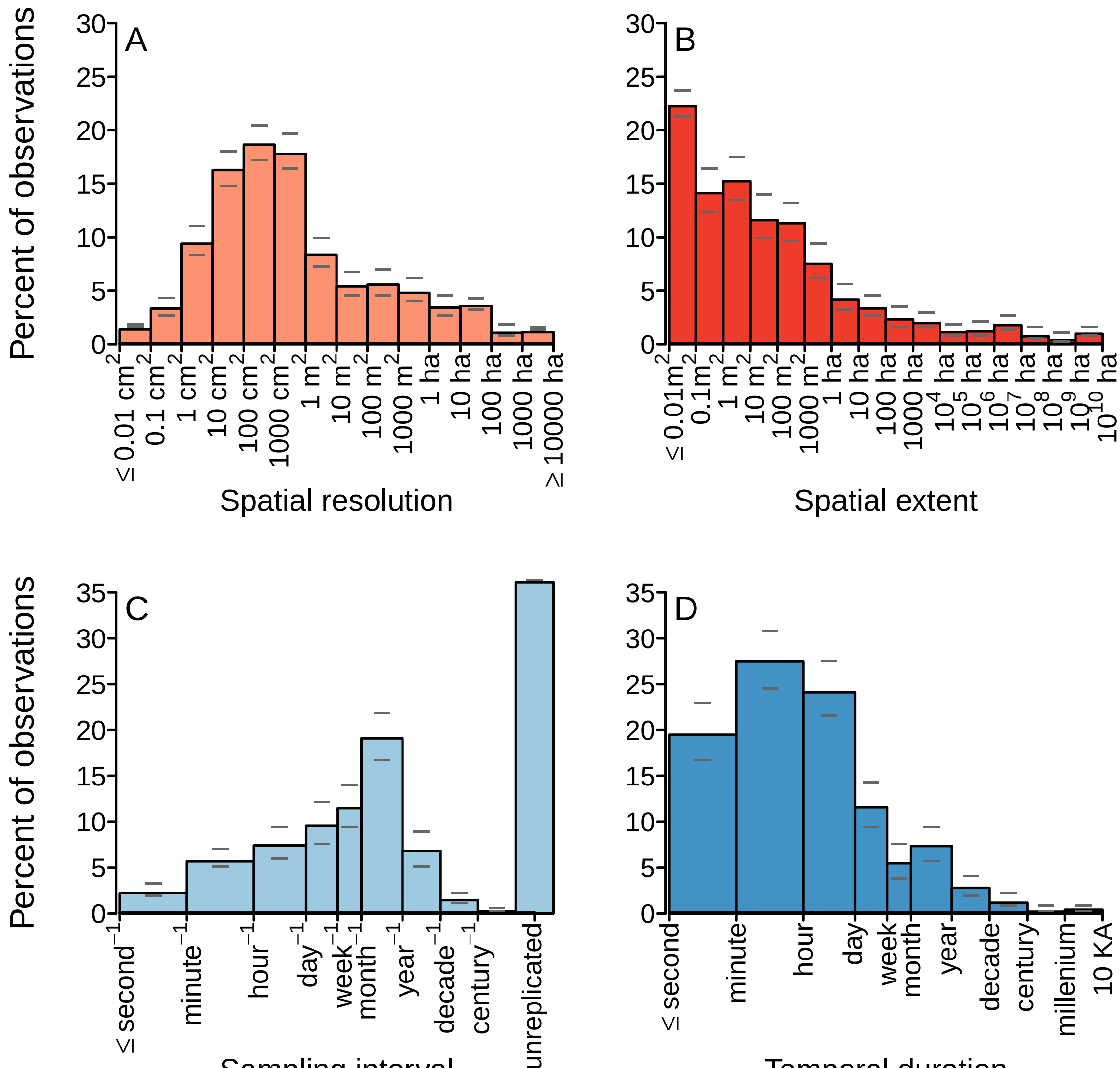

Figure 1: Histograms of the spatial resolution (A) and extent (B), sampling interval (C) and temporal duration (D) of ecological observations collected from the surveyed ecological studies. Bars represent the average percentages for each bin realized after 1000 perturbed resamples, while grey bars indicate the 95% confidence interval.

tribution of ecological observations and the domains in which they are concentrated (Fig. 2). Contrasting spatial resolution with sampling interval reveals that the majority of temporally replicated observations (the 36% that were unreplicated were excluded because they have no interval value) had resolutions of 10 cm^2-1 m^2 and were revisited at daily to yearly intervals (Fig. 2A). A less dense, oblong concentration of observations bounded on the lower right by monthly to yearly observations at 100 m^2 and on the upper left by near-daily to monthly observations with 1-10 ha resolution is also evident. This lower right to upper left orientation reflects the tradeoff between resolution and return interval that is typical of satellite imaging (*8*), and stands in contrast to the upper right to lower left line that stretches between this concentration and the high frequency (minute-hour intervals), high spatial resolution (0.1-100 cm^2) observations. This line demonstrates the opposite tradeoff that occurs with field-based observations, where larger plot sizes demand greater effort that in turn reduces sampling frequency (*9*).

Contrasting temporal duration and spatial extent (for all observations) reveals that the bulk of ecological observations covered total time periods of one minute to <1 month and areas of ≤ 1 m^2 (Fig. 2B). The next greatest concentration were instantaneous (≤ 1 second) observations of <1 m^2 extent, followed by a fainter concentration centered on 1 hour duration and between 1 m^2 and 1 ha in extent. Very few observations had spatial extents $>$1,000,000 ha, and because these were collected by satellites that make near-instantaneous measurements, they tended to have aggregate durations of ≤ 1 hour. In contrast, the longest periods of observation were provided by paleo-ecological or long-term weather stations, both of which produce continuous, point-scale measurements (e.g. sediment cores and weather instrumentation).

Comparing the two spatial dimensions against one another (for all observations) reveals a log-linear relationship wherein resolution strongly constrains extent, such that the ratio between extent and resolution falls as the latter increases (Fig. 2C). As with interval, this pattern indicates that spatial replication diminishes with plot size (*9*) in field-based studies, which accounted for 80%

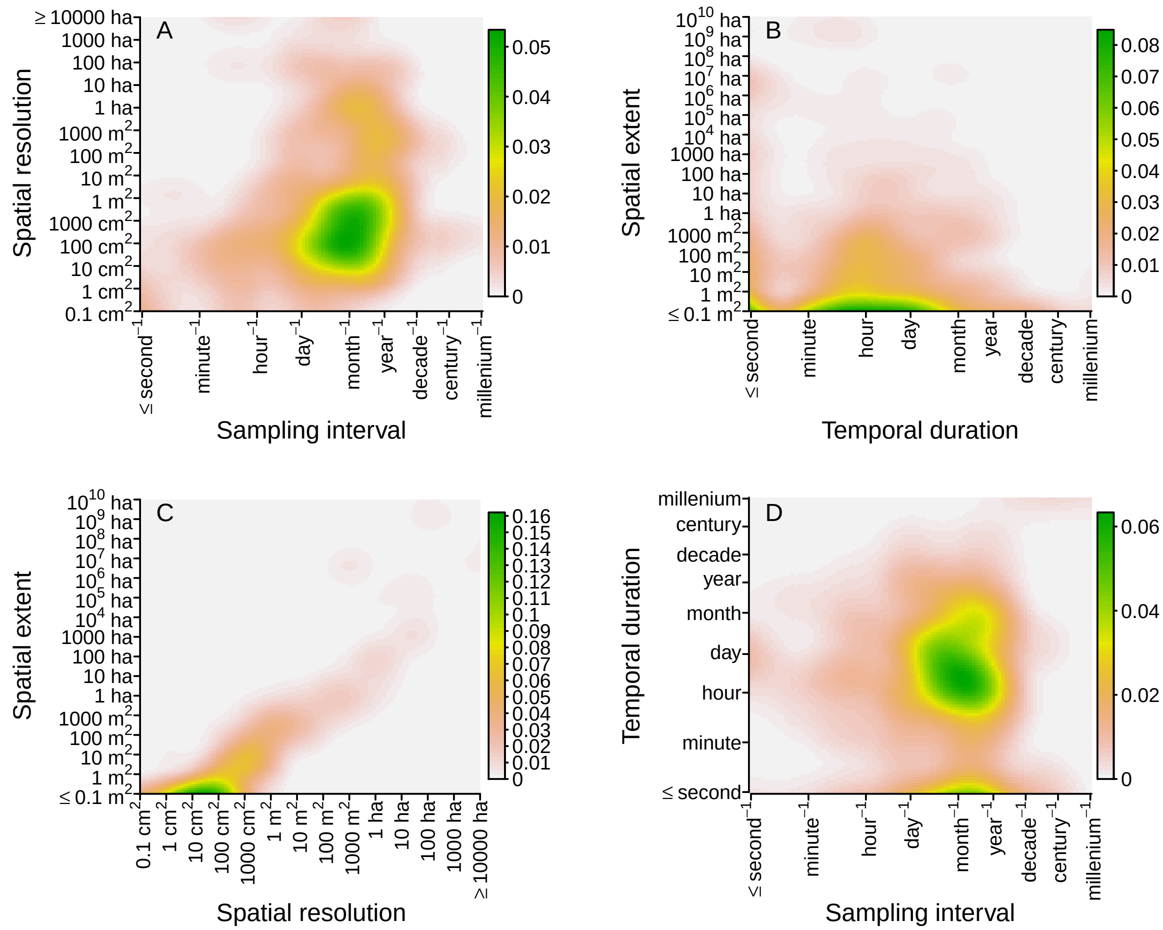

Figure 2: Two-dimensional kernel density estimates of observational densities within the domains defined by A) sampling interval and spatial resolution, B) temporal duration and spatial extent, C) spatial resolution and spatial extent, and D) sampling interval and temporal duration. Density estimates were applied to the log-transformed values of each observational dimension, and density estimates are rescaled to represent percentages.

of observations. This stands in contrast to the 6.5% of observations that were made with remote sensing, which have fine spatial resolutions relative to their large extents. These comprise the majority of observations in the four low density patches (e.g. 0.1-10 ha resolution and 1-10 million ha extent) falling above the denser line that terminates at 100 ha resolution and 1000 ha extent.

A similar linear relationship between sampling interval and temporal duration was not evident (unreplicated observations were excluded because they lacked interval values). For repeated observations, the greatest concentration was among those made at daily to yearly intervals with overall durations of hours to months (Fig. 2D). A second concentration of sub-monthly to yearly observations lasting one second or less is also evident. Very few repeat observations exceeded a year in duration, and these were collected at daily to yearly intervals.

This analysis did not necessarily quantify the scales *represented* by ecological observations (SI). Observations that were non-continuous in time or space (e.g. point-based field measurements) may effectively represent larger scales than our estimates suggest, due to phenomenon-dependent factors such as autocorrelation and representativeness of the sampling scheme (*10–14*). From a spatial perspective, this concern does not apply to contiguous sampling schemes, which were primarily based on remote sensing and cover the largest area, thus the net effect is that this analysis may underestimate the effective areas of smaller observational extents. From a temporal perspective, our analysis likely underestimates the effective duration of many observations, particularly those where instantaneous, repeated measures of slow-changing ecological features were made. Snapshots in time may be sufficient to capture the temporal dynamics of such phenomena (e.g. changes in vegetation cover (*15*)), and for these the total time elapsed between the first and last measurements (the span of observation) may more closely approximate effective duration. However, many studies focused on more dynamic phenomena, and for these long periods of continuous observation may be more important for understanding dynamics than frequent repeats. For example, wildfire extent and duration can be mapped by daily return satellites (*16, 17*), but the instantaneous nature of the imaging means that it cannot be used to directly measure fire behavior (*18*), except patterns resolving themselves at scales greater than 12-24 hours. For this reason, and to provide a consistent standard for estimating duration, we recorded actual duration.

Adding to our motivation to record actual observational scales was the fact that most studies provided insufficient methodological detail to judge whether sampling schemes were suitable matched to and representative of the phenomena they were measuring. The observational scales were not clearly reported in many studies, such that we had to estimate spatial resolution and extent in 62% and 68% of cases, respectively, and temporal interval and duration in 40% and 86% of cases. Although the confidence intervals around our scale estimates (Fig. 1) suggests that our findings are robust to this level of uncertainty (SI), it would have likely confounded efforts to estimate effective scales.

Despite these caveats, our results provide valuable insight into the spatial and temporal domains being addressed by modern ecological research. Our findings suggest that most observations are collected at small spatial scales, are either unrepeated or relatively infrequent ($\geq$1 month interval), and in aggregate cover relatively narrow periods of time ($\leq$1 month). Very little research is conducted at high spatial and temporal resolutions over large areas or for long time periods, suggesting that, despite the well-established understanding of the importance of multi-scale assessments for understanding ecological patterns and processes (*1, 3*), efforts focused on larger scales are still relatively sparse within the discipline (*1, 3*). Furthermore, the unclear documenting of observational scales suggests that scale is not a primary concern in much ecological research (*2, 19*). Taken together, this narrowness and poor documentation (a tendency that is also evident in the geographical sciences (*20*)) suggests that the findings associated with many of these observations may have limited generalizability (*3, 19, 20*).

The generally small spatial scales of observation is a consequence of the continued dominance of field-based research, and the limited use of methods that allow larger areas to be comprehensively observed, such as remote sensing. Despite early and repeated calls for ecologists to use remote sensing because it provides a synoptic view that field measurements cannot (*21–23*), and subsequent demonstration of its importance for multi-scale studies (*24, 25*), our results indicate this observational method is has not yet been widely adopted in for ecological research. There may two reasons for the low penetration of remote sensing into ecology. First, remote sensing can be a challenging method for ecologists to learn, many of whom may not have access to appropriate training (*23*). Second, satellite observations typically have lower information content than field measurements for a given location, and in many cases only provide proxy measures for the ecological features of interest, such as forest understorey structure (*26*), thereby making ecologists less inclined to use the technology (*21*).

In contrast to remote sensing, ecologists have made broader use of technologies that increase the temporal resolution of observations. Automated sensors were used to record 12% of all observations, and accounted for most very high frequency measurements (intervals $\leq$1 hour). As with spatial data, finely resolved temporal data can be aggregated to facilitate multi-scale analyses (and many of the reviewed studies that used automated sensing aggregated the resulting observations before analyzing them), whereas longer-interval data (e.g. annual biomass accumulation) cannot be disaggregated into shorter interval measurements (e.g. weekly biomass accumulation) without interpolation, which turns data into modeled, rather than direct, observations.

In the coming years, rapid technological advances should increase the concentration of ecological observations in currently under-represented domains. The growing numbers of high-resolution satellite sensors, together with new analytical platforms that provide free access to large volumes of pre-processed data and computational power (*27*), will lower technical barriers that have so far prevented ecologists from adopting this observational technology (*23*). Similarly, the advent of unmanned systems offers the ability to measure ecological features at high spatial and temporal frequencies over large areas (*28*), which were scales that were previously impractical to access. The ever-falling cost of sensor technology and the ubiquity of cell phone connections also means that ecologists have a growing ability to make spatially dense, high frequency observations (*29–31*). A greater attentiveness to scale in general, including more meticulous documentation of observed dimensions, may help to facilitate the spread of ecological research to sparsely studied scales, while improving transferability of knowledge within the discipline.

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