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OPINION PIECE

Non-traditional data and innovative methods for autumn climate change ecology

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ABSTRACT: Changes in autumnal climate affecting ecosphere diversity and productivity are arguably as important as those during other seasons, which tend to be more closely studied. Motivated by recent calls for more research on the biological and ecological consequences of seasonal climate change, we present 3 examples of innovative biogeoscience, employing novel data sets and methodologies, which refine our ability to monitor the physiological functioning and ecosystem performance during autumn. Drawn from recent research in wildlife biology (big-game hunting), wood anatomy (tree-ring formation) and mycology (fruit-body picking), these studies provide original insights that contribute to an improved understanding of how varying environmental and climatic conditions in autumn impact the phenology, productivity and diversity of different organisms.

KEY WORDS: Animal migration · Citizen science · Cross-disciplinary assessment · Global change ecology · Hunting inventories · Mushroom fruiting · Tree-ring formation

1. MOTIVATION AND BACKGROUND

Many organisms are mainly active during the warm season. Our understanding of season-specific biological and ecological responses to intra- and inter-annual environmental changes, including climate, is therefore biased. Novel combinations of large data sets and innovative methodologies now provide ample opportunities for extending climate change biology and ecology throughout the year. Spatially explicit, long-term surveys and crowd-sourcing programs, for instance, are a new and valuable basis of seasonal information (Newman et al. 2012, Mills et al. 2015). By posing the right questions to the right people, applying the most accurate techniques and searching for elusive signals in hitherto unknown and putatively unsuitable archives (Isaac et al. 2014), citizen-science projects and similar data sources can, despite various uncertainties, reveal novel and unexpected findings (Henderson 2012).

Here, we present 3 case studies from disparate disciplines that refine our ability to monitor ecosystem responses to autumnal climate conditions. These examples from wildlife population ecology, wood anatomical-oriented dendroecology and mycology are intended to encourage further innovative research on the responses of biological and ecological systems to seasonal climate change. Our examples illustrate how the unconventional assessment of phenology, productivity and diversity of organisms, during periods other than when it is most convenient, or when empirical evidence is most abundant, can provide new insights into the intra-annual processes that are, directly or indirectly, affected by climate change. The recent maturity of massive datasets, often initially developed for non-scientific purposes, ranging from

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agency surveys to citizen science, offer unprecedented opportunities for innovative experiments, if replication is large enough to compensate for any lack in precision and coordination. With the right questions and appropriate methodologies, these data can be an invaluable resource to expand our understanding of responses in biological and ecological systems to seasonal climate and environmental changes.

2. ANIMAL MIGRATION

Warming-induced range shifts along altitudinal and latitudinal gradients have been reported for many plant and animal species around the world (Parmesan & Yohe 2003, Thomas et al. 2004, Lenoir et al. 2008, Harsch et al. 2009, Chen et al. 2011, Gottfried et al. 2012, Pauli et al. 2012). Although often complex at different spatiotemporal scales, the mobility and behavioural plasticity of large animals provides an opportunity to detect climate-induced population movements throughout various parts of the year. For example, long-term, massively replicated and geographically detailed hunting records can supplement traditional animal tracking studies (Kays et al. 2015). Since 1991, the Swiss canton of Grisons has amassed more than 230 000 harvest locations of 4 ungulate species (Büntgen et al. 2017b). This inventory reveals yearly and decadal niche tracking of free-ranging ibex, chamois, red deer and roe deer populations at higher elevations, late in the year. A species-specific upward trend in the ungulates' autumnal harvest locations between 1991 and 2003 coincides with a mean September–October temperature increase of 1.3°C during the same period, which translates into more favourable, snow-free and vegetation-rich autumnal conditions. Linear regression reveals statistically significant ($p < 0.05$) uphill shifts of 135, 95 and 79 m for ibex, chamois and red deer, respectively (Büntgen et al. 2017b), whereas only a small upward trend in roe deer remained statistically non-significant. Such findings underscore the advantage of considering climate and its influence on environmental conditions throughout the year. Since hunting inventories are not routinely considered in the assessment of biological and ecological systems' responses to climatic changes, such data open up possibilities for answering pending questions related to temporal variation in the physiological condition, community composition and spatial distribution of different species in different regions. Similar insights are likely to be included in spatially explicit, long-term data sets from rodent traps (Kausrud et al. 2008), the fishing industry (Stige et al. 2010) and various pest controls (Stenseth et al. 2006), for instance. By the same token, early-year census data — from which autumnal hunting quotas are derived — could be mined for resolving connections between population density, harvest intensity and climate variability. Thus, a more complete picture of the external drivers of wildlife performance, including inter-annual changes in species-specific returns to winter ranges (Rivrud et al. 2016), can be obtained.

3. TREE-RING FORMATION

Though tree-ring formation in many extra-tropical species is restricted to the warm season, several auxin-driven plant development processes (Vanneste & Friml 2009), such as the thickening and lignification of xylem-cell walls, occur mainly at the end of the growing season. Following recent advances in quantitative wood anatomy (Steppe et al. 2015), and improvements in process-based plant physiological modelling (Yang et al. 2017), our understanding of the circumstances that control the precise timing of lignification has greatly improved. A state-of-the-art study that combines high-resolution dendrometer readings with cell-level measurements has found xylem lignification of conifer species in northeastern France to persist into late autumn/early winter (Cuny et al. 2015). The timing and duration of such processes strongly depend on the species, microenvironment and climate. Favourable autumnal conditions can stimulate and prolong woody biomass production, leaving a fingerprint on the intra-annual course of the global carbon cycle (Piao et al. 2008). The application of wood anatomical studies, particularly in environments with strong and regular summer droughts such as the Mediterranean, could help identify moisture-controlled metabolic processes and ecophysiological reactions during the formation of tree rings, thereby enabling the separation of different development stages from anatomical traits. Although our ability to connect short-term seasonal climate variations and weather extremes with intra-annual fluctuations in wood quality and quantity has increased (Battipaglia et al. 2016, De Micco et al. 2016), further progress in the intra-annual tracking of wood formation will offer a more detailed view on seasonal-specific growth-climate responses. The introduction of 'Blue Intensity' for generating high-resolution wood density profiles is an important methodological advancement towards fine-scale measurements of intra-annual growth behaviour that can help to improve the cross-dating success of relict samples and the signal-to-noise ratio in summer temperature reconstructions (Wilson et al. 2017, Kaczka et al. 2018).

4. MUSHROOM FRUITING

Rapid emergence, short lifespans and limited photoperiodic constraints (Körner & Basler 2010) make mushroom fruiting bodies ideal indicators of changes in late growing season conditions. Inter-annual and multi-decadal variations in the abundance of autumnal sporocarps (productivity), as well as the intra-annual timing of their occurrence (phenology) and species abundance (diversity), are closely related to the multifaceted interplay of biotic (mycelium and host interaction) and abiotic (environment and climate) factors (Boddy et al. 2014). Experimental findings, local observations, national inventories and their continental-scale compilations allow seasonal- and species-specific mushroom 'fruit body' dynamics to be reconstructed. Despite the generally smaller economic, social and ecological importance of mushrooms (Büntgen et al. 2017c), in comparison to most plant and animal species, over 7 million *in situ* observations of wildlife mushroom fruiting bodies, representing more than 10 000 fungal species from 9 countries spanning most of the 20th century (Andrew et al. 2017), have been drawn from various scientific and citizen-science projects. In addition to providing evidence of warming-induced spatiotemporal shifts in spring and autumn mushroom phenology — fruiting has shifted by weeks (Kauserud et al. 2012) — a pan-European mycological inventory offers unique macro-ecological opportunities to assess how fungal communities interact with the environment (Büntgen & Egli 2014), including symbiotic associations with their host vegetation (Büntgen et al. 2013). Exploring how fungal fruit body productivity and species diversity are linked to biotic and abiotic factors, such as spore maturation and dispersion (Kauserud et al. 2011, Büntgen et al. 2017a), and climate variation and nitrogen deposition, respectively (Boddy et al. 2014, Andrew et al. 2016, Van Strien et al. 2018), will provide new biological and ecological insights throughout the year. Since the compilation and evaluation of historical mushroom inventories is so far restricted to Europe and parts of the USA (Diez et al. 2013), there is great potential for expanding similar approaches over space (and time).

Other non-traditional, broadly ignored sources of important mushroom-related data for seasonal climate change research, are governmental emergency services. Poison centers such as the Swiss National Poisons Information Centre deliver 24-hour/7-days-a-week nationwide free medical advice (http://toxinfo.ch). Since its establishment in 1966, the centre has registered over one million poison-related inquiries with around 1% of all cases attributed to mushrooms (Schenk-Jäger et al. 2016). Comparison between these >12 000 mushroom-related calls with survey information from the Swiss National Data Centre for Biodiversity (Senn-Irlet 2010) demonstrates the ability of poison centre data to capture spatiotemporal patterns of fungal phenology, productivity and diversity (Schenk-Jäger et al. 2016).

5. WHAT'S NEXT?

By providing these examples of research initiatives that further a better understanding of biological and ecological responses to autumnal conditions (Gallinat et al. 2015), we hope to have successfully demonstrated how non-traditional data sets, creatively mined, can be used to reveal valuable insights into climate-change impacts. However, non-traditional data sets are not without their own challenges and pitfalls. In fact, such data often lack the degree of experimental precision and coordination most directed research is accustomed to. Such data may also include systematic changes in procedures and instrumentation that can impose artificial extremes and long-term trends in their observation. For instance, details in the hunting inventory data described above only represent the hunted animals, and poison centre databases only include information on those cases reported. Nevertheless, such collections still provide valuable evidence if the right question is addressed by the right analysis (Büntgen et al. 2018), the number of observations is large, and over-interpretation is avoided.

Though here we have emphasized the value of studying autumnal conditions, further research should also consider the biological and ecological importance of other seasons (Diez et al. 2014, Williams et al. 2015). Knowledge of the intensity and duration of climate variability during winter is particularly critical for ecosystems at higher latitudes and altitudes (Williams et al. 2015), where the impacts of cold-season temperature and precipitation persist through most of the year. Although varying between organisms and habitats, trends and extremes in winter climate may alter species-specific chilling requirements, as well as the risk of frost injury, demands on energy and water balance, and responses to phenological mismatch and shifting community composition and interaction. At the same time, winter warming generally exceeds that during other months, with implications not only for the amplitude of the annual temperature cycle (Duan et al. 2017) and the Earth's carbon balance (Piao et al. 2008, Friend et al. 2014), but also for the spatiotemporal alignment between the biological requirements of different ecosystem components and climate (Williams et al. 2015, Marra et al. 2015).

In a similar vein, we cannot ignore the wide range of phenological indicators, such as the timing of bird migration (Jenni & Kéry 2003) and wine harvest (Cook & Wolkovich 2016), which have been used to obtain high-spatiotemporal-resolution data on biological and ecological responses to climatic and environmental variation during different seasons of the year. Moreover, aquatic organisms retain life histories in distinct seasonal increments (Cole & Fairbanks 1990, Morrongiello et al. 2012, Black et al. 2014, Reynolds et al. 2016, Butler & Schöne 2017). For instance, the assessment of long-lived fish, bivalve and coral species can reveal autumnal and even winter signals at high temporal resolution (Black et al. 2016). Such data might be particularly valuable for supplementing insights from terrestrial archives to draw a more complete picture of biological and ecological responses throughout the year (Piermattei et al. 2017).

6. CONCLUSIONS

Curiosity-driven, proactive research on ecology should consider the effects of climate change in all seasons. Emphasis should be given to investigations of the temporal synchronization of climate variability and species-specific biological demands. Future efforts should also consider mining the whole range of non-traditional environmental inventories and metrics that exist today, or that are planned in the future. However, caution is advised as the interpretation of cause-and-effect relationships in large, unconventional data sets, often based on citizen science, can be biased, both systematically and unsystematically, due to an overall limited quality of the source material. Quantifying the influences of seasonal climate on the biological controls that regulate yearly growth patterns can only improve the efficacy of (process-based) mechanistic models by providing valuable details of intra-annual and species-specific behaviour throughout an organisms' life cycle.

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