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Mini Review

Potential of Herbarium-based Phenological Studies to Predict the Climate Change Impacts

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Abstract

Herbarium records provide a valuable historical database for assessing plant phenology shifts in the context of global climate change. The herbarium specimens, collected from diverse locations and periods, offer comprehensive data illustrating how many plants are altering their blooming times in response to global climate change. The appropriate use and analysis of long-term herbarium records offer an additional dimension for the study of plant phenology through the application of advanced experimental methodologies such as bioinformatics and satellite imagery, statistics, and Artificial Intelligence (AI) which, coupled with field observations, will improve ecosystems evaluation. These efforts can significantly contribute to conservation strategies and climate change mitigation and further support the synchronization of scientific inputs for evaluating the impacts of climate change and its ecological implications.

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Herbarium-based phenological studies are invaluable for understanding the effects of climate change on plant species [1-8]. These studies leverage the extensive historical records provided by herbarium specimens, which have shown congruence with field observations, effectively assessing patterns and mechanisms of plant phenological responses [6,9]. Specimens collected from various locations and times enable comprehensive investigations into the phenological shifts of plants over time in response to changing climates.

Meticulously documented by taxonomists or botanists, herbarium specimens contain detailed information such as collection date, location, elevation, habitat type, and conservation status. This information allows researchers to determine historical flowering, fruiting, and leafing times, providing temporal datasets to identify global shifts in phenological events. By comparing herbarium data with current observations, researchers can assess how different species respond to climate change.

Phenological shifts, such as earlier or later flowering, fruiting, or leafing, indicate the impacts of climate warming [10]. Numerous studies have documented these changes [1,11-16], highlighting their correlation with climatic changes. Herbarium-based studies are cost-effective compared to long-term or real-time field studies, and many herbaria have digitized their collections, making them accessible for global research. Unlike modern methods, herbarium-based research does not disturb current ecosystems or require additional land use.

However, herbarium collections have spatial and temporal coverage gaps, leading to potential biases. Certain regions or periods may be underrepresented, and the condition and completeness of specimens can vary. Older specimens might be damaged, requiring more precise collection and intricate analysis. Sometimes, the collected specimens are unclear regarding their collection dates, phenological stages, and occurrences in their populations [16]. Estimating phenological stages from herbarium specimens is less accurate than real-time observations, providing snapshots rather than continuous data. Nonetheless, herbarium records offer long-term datasets essential for studying climate change impacts. To fully realize the potential of herbarium records, it is crucial to amend and update them for climate change studies.

- Herbarium records can be complex to analyze due to the selection biases introduced by different botanists

or taxonomists collecting specimens under non-experimental conditions. The cumulative database indicates geographical mismatches and inconsistent frequencies, resulting in non-normality and non-linearity. Addressing these complexities requires appropriate statistical tools to enhance the scientific rigor of studies. Gaira, et al. [11] suggested the Generalized Additive Model (GAM), which is flexible enough to handle complex data series. Application of GAM was found suitable for the study conducted on eight high-value medicinal herbs, where 04 species represent alpine/sub-alpine regions and the other 04 represent the temperate zone of the Indian Himalayan Region (IHR) and projected phenological changes due to warming winter season [13], which further adopted by Khan, et al. [15].

- It is crucial to validate the predictions of phenological changes with field data under current conditions. This validation process should also analyze other parameters, such as habitat composition, plant productivity, biomass, and soil conditions which may support an understanding of the ecosystem's functioning. Validation not only ensures the accuracy of phenological trends but also enhances the reliability of the research. In addition, validation may offer to establish an ecological mismatch between plant blooming times and pollinator activity to evaluate ecosystem services [17]. Further, the herbarium-based sensitivity demonstrates their utility in a broad range of ecological contexts which may be helpful to underscore the ecosystem dynamics.

- Integrating herbarium data with other sources, such as satellite imagery, climate records, and contemporary field observations e.g. PhenoCam, and bioinformatics, can yield more robust insights. A recent development in a formal semantic framework for plant phenology data, the plant Phenology Ontology (PPO), compares the integration of field and herbarium-based phenology data on a global scale [18], which needs to be extended to the remaining parts of the world. However, Park [19] correlated the herbarium-based phenological records with satellite imagery at a regional scale, signifying the potential use of their integration in future research to supplement the deficiencies of other data sources. This integration plays a crucial role in addressing the pressing concerns of ecology and bioclimatology, underscoring the importance and relevance of current concerns. Herbarium digitization may be the basis of Artificial Intelligence (AI) to exemplify the phenological characteristics and plant dynamics according to seasonal climate variations, further strengthening the phenological models in response to current climate change. Advanced technologies like machine learning and image analysis can significantly enhance the accuracy of phenological assessments from herbarium specimens, thereby increasing the relevance and impact of the research.

- Citizen science initiatives must be considered when collecting specimens and real-time field observations. These initiatives enable filling data gaps by encouraging public participation in phenological observations [14] and improving the consistency of the herbarium specimen repository.

Conclusion

Herbarium-based phenological studies are invaluable for understanding climate change's historical and ongoing impacts on plant life. They offer unique insights for predicting future ecological shifts and formulating conservation strategies. Despite some limitations, integrating herbarium data with appropriate statistical tools, modern technologies, and methodologies promises to enhance our understanding and response to the complex effects of climate change. The field validation process of herbarium specimens also supports understanding the ecosystem's function by considering the ecological parameters and integration of modern technologies like satellite imagery, Artificial Intelligence (AI), etc. Further, citizen science will encourage to improvement of taxonomic repositories consistently. Such efforts may help to generate long-term herbarium databases, support the formulation of conservation strategies, and enhance knowledge of mitigating and adapting to climate change impacts on plant phenology.

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