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Harrison Tasoff

Vast botanical data help solve Darwin’s puzzle of why some exotic plants become pests

There’s a conundrum that has perplexed biologists since Charles Darwin himself. Why do some exotic species take off as invasive pests while others don’t?

Scientists have documented dozens of factors influencing the spread of exotic plants and animals across scores of ecosystems. But they’ve struggled to identify overarching patterns and the primary mechanisms that generate them. Now, however, scientists have access to electronic records that report the locations and day of year when specimens of thousands of species were collected across vast geographic regions over more than two centuries. These data, along with new analytical tools, have enabled researchers to mine information from millions of plant specimens to find answers to this persistent, unresolved question.

The results, published in the Proceedings of the National Academy of Sciences, reveal how an interloper’s winning strategy varies based on climate. Harsh conditions favor invasive plants that are more similar to their native counterparts, while dissimilar species thrive in milder regions.

“These results imply that Darwin’s Naturalization Conundrum might not be a conundrum at all, but a predictable range of outcomes,” said lead author Tadeo

Ramirez-Parada, who conducted the research as a doctoral student and postdoc in Susan Mazer’s lab at UC Santa Barbara.

The results not only provide clarity on a century-old question, but offer practical guidance for how resource managers can identify the exotic species that have the greatest potential to disrupt intact plant communities.

Too many ideas

In his magnum opus, “On the Origin of Species,” Darwin proposed two explanations for why certain introduced species might become invasive. On the one hand, invaders that are similar to natives may be pre-adapted to local environmental conditions. On the other hand, those that are distinct from the native species may be able to take advantage of a unique lifestyle where competition is low.

“For decades, ecologists have been trying to figure out what determines a successful invader, and there are lots of studies of individual species that support many of the ideas proposed to explain their success,” said co-author Mazer, an evolutionary biologist and Ramirez-Parada’s former advisor. Some invasive species explode onto the scene because they’ve left their predators behind. Others have no major diseases in their new range. Some exploit new or more effective pollinators or seed dispersers in their new territory, facilitating their colonization of new regions.

It’s not that the case studies of individual species are uninformative; it’s just that they’re too specific to clearly identify the underlying principles. “It's only by detecting broad-scale patterns, and the factors that influence them, that we can begin to identify the general mechanisms that explain them,” Mazer said.

The story in the flowers

Now scientists possess the information, datasets, statistical methods and processing power needed to tackle this question. The team turned toward herbaria, where curated collections of pressed and dried plant specimens sampled from wild species are preserved. Each specimen includes standardized information such as the species name, harvest location, collection date, and whether it was flowering when collected.

Ramirez-Parada and his co-authors looked at phenology, the timing of any particular lifecycle event that recurs from year to year. They chose to examine flowering because it is such an important aspect of reproductive success. The timing and duration of flowering determines when sensitive tissues are exposed to the stressors of the external environment. “So, plants that get the timing wrong risk being unable to produce offspring,” Mazer said.

Dried specimens provide only a snapshot of a plant’s lifecycle. But collect enough snapshots, and you can make a movie. The team entered in the location and collection date of each specimen, along with whether it was in flower. They then combined the data from all the specimens of a single species with historical climate data. This weather hindcasting enabled them to correct for seasonal differences from year to year. By running the combined data through some sophisticated statistics, the authors were able to estimate each plant species’ flowering window.

The team examined the flowering times of species across a continuum of environmental conditions in the continental U.S., ranging from harsh to mild. They compared native to invasive species to determine whether their flowering phenology or evolutionary relatedness differed in response to these conditions. The authors used evolutionary relatedness as a proxy for similarity. “More closely related species are, on average, functionally and physiologically more similar to each other than distantly related species,” Mazer explained.

Finally, the authors placed their comparisons between native and invasive plant species in the context of the weather and climate of different regions in North America.

The winning strategy depends on the game

The team found that the attributes that make plant invaders successful — and their degree of similarity with the local flora — are strongly and predictably structured by climate. In harsh conditions, successful invaders are more similar to their native counterparts, while it’s precisely the opposite in mild climates.

Cold, hot or dry conditions place tight constraints on when a plant can flower, meaning successful invaders can’t deviate too much from the flowering time of the native community. Mild climates allow for a breadth of lifestyles, but there’s also more intense competition between species due to higher biodiversity and population density. As a result, invaders can get a leg up by being different enough to avoid direct competition with species already established in an area.

“I was surprised and excited to see such a strong pattern and clean agreement with theoretical expectations,” Ramirez-Parada said. “Ecology is typically messy — it deals with incredibly complex systems, after all — so signals are rarely this strong and clear.”

The authors were also surprised to find that invasive plants consistently flowered much earlier than natives in mild regions. Under harsh conditions, non-native plants need to respond to the same environmental cues to elicit flowering that the natives do, or risk freezing or desiccation. But mild climates with sufficient humidity have a broad flowering season. By putting out flowers earlier, invasive plants can monopolize pollinators, develop fruit and disperse seeds earlier and for longer.

“I've seen many places in California where native wildflower species have been replaced by exotic grass species, which germinate and grow rapidly early in spring,” Mazer said. “Especially for annual grasses, the common pattern for invasives seems to be to get a head start, occupy space, and displace the native competitors that are a little bit later to the game.”

A hands-on guide

These findings suggest a simple rubric for land managers trying to triage which exotic species to target as threats: In mild climates, target the early flowering, evolutionarily distinct plants. In harsh climates, focus on introduced species that are most similar to native plants.

Mazer’s group now plans to hone in on a regular antagonist to resource managers: invasive annual grasses. Her group will investigate how these species have become entrenched in Mediterranean ecosystems around the world.

Annual grasses can quickly colonize new areas and out-compete natives with their short lifecycles. California’s grasslands used to host a balance between native, long-lived grasses and wildflowers. Not only have invasive, annual grasses displaced most of the hardier, perennial grasses, but they’ve virtually eliminated the state’s wildflower diversity in many places. The results are species-poor grasslands that provide poor fodder for wildlife and livestock alike. What’s more, the dry thatch that develops prevents native plants from reestablishing and allows wildfires to race

Photo Credit
Jeremiah Bender
Invasive grass covered UC Santa Barbara’s Lagoon Island before restoration (behind) brought back the functional diversity of the region’s coastal sage scrub.

Since grasses are wind-pollinated, these fields often no longer support the insect diversity necessary for a healthy ecosystem. “In addition, wind-pollinated species have evolved to produce much more pollen than insect-pollinated plants because so much of their wind-borne pollen is lost,” Mazer explained.

One consequence of the proliferation of invasive grasses is that respiratory allergies linked to pollen result in more than $3 billion per year in medical expenses in the U.S., Mazer said. Importantly, insect-pollinated plants in natural habitats also provide a year-round resource and refuge for the pollinators that also pollinate our crops. Without diverse native habitats, these animals risk extinction, which threatens not only the pollinators themselves, but also the wild and crop plants that depend on them.

Leveraging big data to solve old questions

Ramirez-Parada and Mazer recognize that their findings come with some limitations. They looked only at flowering and relatedness, so it's possible that the effect they saw may be due to confounding variables not examined in this study. It's also possible that temperature and humidity aren't the only factors that determine whether conditions are mild or harsh for a plant. Other factors could include fire history, soil composition or the local pollinator community. Indeed, the variation in their results suggests that other climatic or biological factors do exert some influence on the success of invasive plants.

"The attributes that make an invader successful vary widely across places," Ramirez-Parada said, "but our results show that this variation is systematic and strongly aligned with climate."

And their success shows that long-standing questions can be addressed by applying careful statistical analyses to digitized specimens and biodiversity data to follow up on case studies. "This dialog between large- and small-scale studies seems more fluid than ever, and has the potential to generate huge breakthroughs in the field," Ramirez-Parada said.

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Media Contact
Harrison Tasoff
Science Writer
(805) 893-7220
harrisontasoff@ucsb.edu

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