



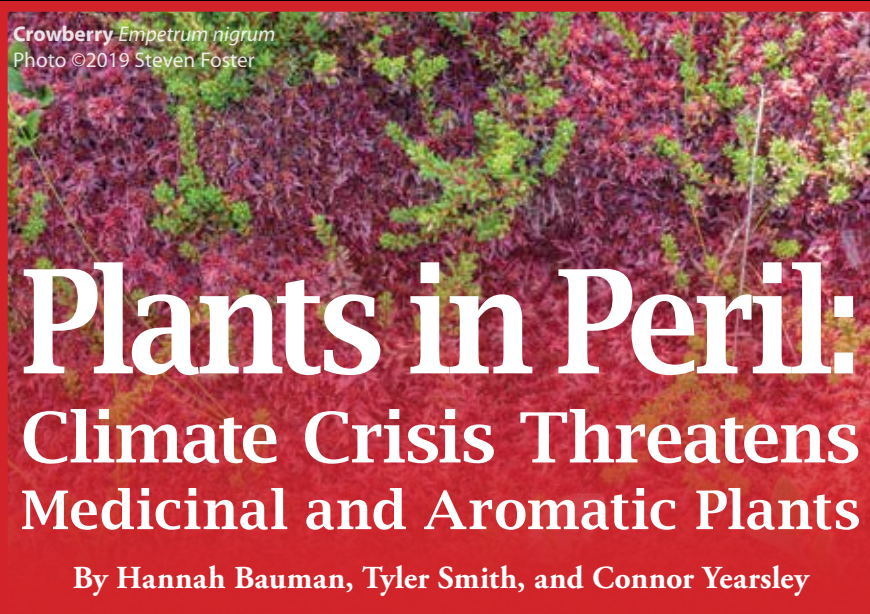
Labrador tea *Rhododendron groenlandicum*
Photo ©2019 Steven Foster



Motherwort *Leonurus cardiaca*
Photo ©2019 Steven Foster



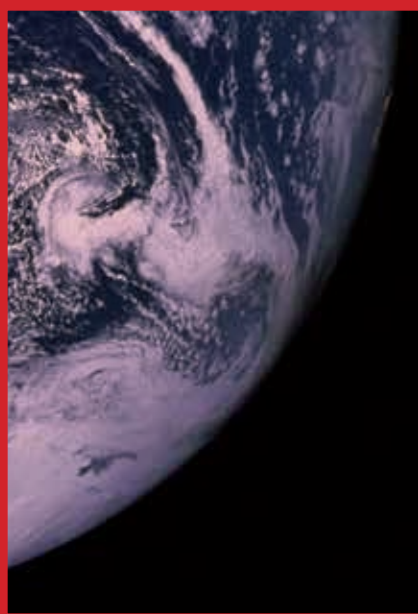
Rhodiola *Rhodiola rosea*
Photo ©2019 Petra Illig



Crowberry *Empetrum nigrum*
Photo ©2019 Steven Foster

Plants in Peril: Climate Crisis Threatens Medicinal and Aromatic Plants

By Hannah Bauman, Tyler Smith, and Connor Yearsley



Introduction

HerbalGram issue 81, published in 2009, featured an extensive article by then-Managing Editor Courtney Cavaliere about the effects of climate change on medicinal and aromatic plants (MAPs).¹ In the decade since then, the situation has intensified, and new insights have emerged.

In the face of climate change, plants, including MAPs, may move, adapt, or go extinct. Indeed, large-scale changes in plant distributions, flowering times, and community assemblages are occurring across the globe due to climate change. For now, there is little evidence of plant extinctions caused by climate change, but extinctions are expected to occur



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if plants cannot move or adapt quickly enough and current trends continue.² A recent report found that 1 million plant and animal species are threatened with extinction, with climate change listed as the third biggest driver of “change in nature.”³

Levels of carbon dioxide, a prevalent, heat-trapping greenhouse gas, are higher now than at any time in the past 400,000 years, as shown by ancient air bubbles trapped in ice. In 2013, carbon dioxide levels surpassed 400 ppm for the first time on record.⁴ Forestation can remove, or sequester, atmospheric carbon dioxide. A 2019 study found that, under the current climate regime, the Earth can support an additional 0.9 billion hectares of continuous forest (excluding existing trees and agricultural and urban areas). This has the potential to reduce current atmospheric carbon dioxide by up to 25%, to levels last seen almost a century ago. However, as temperatures rise, suitable land area for forests decreases. Preserving existing forests and phasing out fossil fuels remain vital, since new forests take decades to mature.^{5,6}

According to a 2018 study, Earth’s climate could resemble that of the mid-Pliocene (3-3.3 million years ago) by 2030, and, without emission reductions, it could resemble Early Eocene climates (ca. 50 million years ago) by 2150. This suggests that humans are rewinding the climate clock by about 50 million years and reversing a multimillion-year cooling trend in less than two centuries.⁷

All species on Earth today have an ancestor that survived these epochs, but “large climate changes expected for the coming decades will occur at a significantly accelerated pace compared with Cenozoic climate change and across

a considerably more fragmented landscape, rife with additional stresses,” the authors wrote. Plus, over the past 50 million years, species have adapted “away from hothouse climates to a world that was cooling, drying, and characterized by decreasing atmospheric CO₂.” The potential rapid reversion to Eocene-like climates causes serious concerns about the adaptive capacity of species, including MAPs.⁷

Some news outlets have started changing their style guides to emphasize the situation’s seriousness. For example, in May 2019, *The Guardian* stated that the publication’s preferred terms are “climate emergency, crisis or breakdown.... The phrase ‘climate change,’ for example, sounds rather passive and gentle when what scientists are talking about is a catastrophe for humanity.”⁸

Medicinal and Aromatic Plants in the Arctic

The Arctic is the region above the Arctic Circle and the northernmost region on Earth.⁹ While Earth’s average surface temperature has increased about 1°C (1.8°F) since the 1880s, the Arctic has warmed more than twice as fast. Although the tundra, which is home to hardy flora and fauna, is one of the coldest and harshest biomes on Earth, it is also one of the fastest warming. Shrubs are growing taller, and some plants are migrating north, an indication of the greening of the Arctic.¹⁰

According to one model, by 2036, Arctic summers may be so hot that most of the sea ice that forms in winter will melt. That means that the Arctic Ocean will be navigable except for the last remaining ice along the northern Canadian islands and Greenland, and much of the surrounding land is expected to be green. By mid-century, the Bering

According to one model, by 2036, Arctic summers may be so hot that most of the sea ice that forms in winter will melt.

A depiction of Arctic sea ice on September 12, 2013, the day before the National Snow and Ice Data Center estimated sea ice extent at its annual minimum. The yellow line shows the 30-year average minimum extent.

Credit: NASA Scientific Visualization Studio/Cindy Starr



Sea, which lies between Alaska and Russia, will likely be open most of the year, and algae that grow on ice and are part of a food web that extends to fish and whales will likely disappear.¹⁰

Melting sea ice is not believed to increase sea levels since sea ice is already part of the ocean's mass, but land ice melting into the ocean, in the Arctic and elsewhere, is causing rising sea levels. Also, water expands as it warms (i.e., thermal expansion), which also contributes to sea level rise.^{9,10} In addition, permafrost (ground that remains frozen year-round) is thawing, causing the ground to collapse and visibly changing the Arctic.¹¹ As snow and ice melt, large amounts of carbon dioxide, previously trapped for millennia in the ocean and permafrost, are being released. Climate change will continue to speed up because of this and what is called ice-albedo feedback. That is, snow and ice reflect most incoming sunlight back into space. Open water, however, is much less reflective and absorbs more heat. Melting means more open water, a "feedback loop" that causes more warming.⁹⁻¹¹

Warming in the Arctic is also extending the ranges of animals, which can have significant impacts on the landscape. For example, beavers, which are attracted by larger and more abundant shrubs, are colonizing northern Alaska, moving at about five miles per year.¹¹ They reportedly mostly prefer to chew down trees in the willow (*Salicaceae*) family, like *Populus* and *Salix* species.¹² When beavers dam

up creeks, this process creates new ponds and lakes, causing permafrost to collapse and changing the land. Large foragers like moose also are moving into new areas, affecting Arctic vegetation.¹¹ While a warmer Arctic may enable access to new fishing grounds; vast deposits of gas, oil, and minerals; and open shipping lanes (which will cause more carbon emissions), it has significant and far-reaching implications for plants, people, and animals.^{10,11}

Since he was quoted in *HerbalGram's* 2009 article, Alain Cuerrier, PhD, an adjunct professor at the University of Montreal and botanist at the Montreal Botanical Garden, has conducted more research and made new observations about Arctic plants.

Cuerrier and his colleagues have analyzed phenol and/or terpene concentrations of various plants and observed that concentrations typically increase with latitude until the plants seem to reach their northern limits. "We have done studies on Labrador tea [*Rhododendron groenlandicum*, Ericaceae], mountain ash [*Sorbus decora* and *S. americana*, Rosaceae], and a carnivorous pitcher plant [*Sarracenia purpurea*, Sarraceniaceae]," Cuerrier wrote (email, October 1, 2019). "Climate change may affect (lower) the concentrations, because the plants do not need to combat photoinhibition."*

Cuerrier also has studied berries growing in small open-top chambers that mimic warming (1-2°C), but, according to him, antioxidant levels were not significantly differ-

* According to Cuerrier, photoinhibition can cause cell death that disturbs photosynthesis. The problem occurs when light intensity is high and either or both water deficit/temperature are low, creating free radicals through lack of carbon dioxide production. This phenomenon is more relevant in places like the Arctic or at high altitudes.

Cloudberry *Rubus chamaemorus*
Photo ©2019 Alain Cuerrier



ent between those berries and berries growing in control plots, “although we could see that antioxidant activity was dropping, but not significantly on the basis of a few years.”

One of the new concerns voiced by Inuit (a group of indigenous peoples, most of whom inhabit northern Canada) is seashore erosion, according to Cuerrier. “This is where rhodiola [*Rhodiola rosea*, Crassulaceae] thrives,” he wrote. “So, some Inuit have seen rhodiola plants being washed away.” Root preparations of rhodiola have been used for many purposes, including the treatment of altitude sickness and boosting energy, and are considered adaptogenic (i.e., they can increase the state of non-specific resistance to stress).¹³

Cuerrier added that all plants growing on the shore are vulnerable to inundations from melting snow and ice. “In Canada, this includes rhodiola, honckenya [*Honckenya peploides*, Caryophyllaceae], willows [*Salix* spp., Salicaceae], and some Northern Labrador tea [*Rhododendron tomentosum*],” he wrote.

Besides the rhodiola example, Cuerrier is not aware of any notable die-offs of Arctic medicinal plants. “I am more concerned with lower concentration of metabolites [i.e., the plants’ chemistry], thus the quality of medicinal plants,” he wrote.

According to Cuerrier, it is too soon to say whether any native medicinal plant species are being harmed noticeably because of new competition from other species. “With more tamarack/larch [*Larix laricina*, Pinaceae] and spruces [*Picea mariana*, Pinaceae], the [Canadian] landscape, from a local perspective, will definitely change,” Cuerrier wrote. “We obviously need to understand the ecology of the northern mosses and lichens.”

A 2019 study, co-authored by Cuerrier, summarized data from 191 interviews that assessed the relationships of Inuit peoples to different berry species in the Canadian territories of Nunavut, Nunavik, and Nunatsiavut. For the Inuit, berry picking is an important cultural practice and contributes to physical and mental health. In fact, berries are reportedly the most widely harvested plants by the Inuit today and are used for food, medicine, fuel, and bedding. In addition, berries have been important famine food for the Inuit. However, in some places, climate change and other factors are impacting berry availability, accessibility, and possibly quality. Over the last century, many areas where berry picking is important have seen milder winters and warmer and drier summers.¹⁴

All Inuit interviewees were considered knowledge holders, and most were elderly. The most commonly harvested berries were blueberries (*Vaccinium uliginosum*, *V. caespitosum*, Ericaceae), lingonberries (*V. vitis-idaea*), cloudberry (*Rubus chamaemorus*, Rosaceae), and crowberries, also called blackberries (*Empetrum nigrum*, Ericaceae). Bearberries (*Arctous rubra*, *A. alpina*, Ericaceae)



Mountain ash *Sorbus americana*
Photo ©2019 Steven Foster



Lingonberry *Vaccinium vitis-idaea*
Photo ©2019 Steven Foster



Cloudberry *Rubus chamaemorus*
Photo ©2019 Steven Foster

also are found at most of the interview sites but are harvested at only one site. Most of the Inuit who were interviewed pick berries at the end of summer before the first frost. Previously, berries also were harvested throughout the year as they ripen, under the snow or right after snowmelt. Some Inuit also described past practices of preserving the berries by storing them in the ground in hide pouches, fish swim bladders, caribou stomachs, and other containers. It is unclear from the study if climate change has affected these practices, however. Throughout the Arctic, berries often are mixed with fat, blubber, fish, and other fruits and vegetables. They also are used to make jams.¹⁴

Some Inuit thought drier conditions have changed the berries' taste. Because climate change is associated with increasing height and cover of erect shrubs, this has reduced the accessibility of some berry patches. "In some instances, shrubs are perceived to diminish berry productivity while in others, like during a warm and dry summer, they may provide shade and thus have a positive influence on the quality of the berries," the study authors wrote. Other studies have shown "that the cover and productivity of berry species usually diminished under erect shrubs." The authors noted that the Inuit historically have had to adapt to fluctuations in climate, animal populations, and plant productivity, but suggested that berry picking should be considered in land-use planning, especially since food insecurity and consumption of low-quality foods are important issues in the Canadian Arctic.¹⁴

According to a 2010 study, Alaskan tribal communities noted that berries can be compromised or enhanced by climate fluctuations. Wild berries are an important dietary component for native peoples in Alaska and are rich in polyphenolic compounds that can help treat disorders such as obesity and diabetes. This study analyzed five Alaskan berry species — Alaska blueberry (*Vaccinium ovalifolium*), *V. uliginosum*, cloudberry, salmonberry (*Rubus spectabilis*), and crowberry — from different tribal communities and found significant site-specific variations in some berry constituents.¹⁵

Joshua Kellogg, PhD, lead author of the study and assistant professor in the department of veterinary and biomedical sciences at Pennsylvania State University, explained: "We could not definitively say that climate was the driving force of the chemical differences between the collection sites.... But...the colder, 'harsher' environment further north seemed to correlate with more potent berry chemistry. Definitely, there is a need for a follow-up study on a more longitudinal scale that also can determine the contributions that the climate, environment, and genome have on the berries' chemistry and bioactivity" (email, October 1, 2019).

Petra Illig, MD, a physician and resident of Anchorage, Alaska, who in 2008 started a rhodiola cultivation effort in Alaska, said she is "extremely concerned" about the potential effects of climate change on the plant (email, September 28, 2019).

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Crowberry *Empetrum nigrum*
Photo ©2019 Steven Foster

"I don't know if climate change is going to translate to better or worse conditions for rhodiola," Illig wrote. "Rhodiola cultivation in Denmark and northern Germany is going well, and they seem to get their plants to maturity a year or so sooner than we do in Alaska. But there are so many variables that it is difficult to assign one cause. One wonders if rhodiola will do better in a somewhat milder climate, as long as it gets the long summer daylight and enough moisture. But if climate change brings drier conditions, then that may not be a good thing for this succulent plant."

She noted that many unknowns come with climate change, so it is difficult to predict. "But, for sure, things will be quite different from before. We may even get more rhodiola farms further north in Alaska, which would be nice." The first Alaskan rhodiola harvest occurred in 2013, because the plant takes four or five years to reach maturity, so there has not yet been enough time to notice if and how climate change may impact the plant in Alaska, according to Illig. "Except, some growers further north in the interior have had a couple of very hot and dry summers," she wrote. "If this continues, growers in the interior of Alaska, far from the wetter coastal areas, may need to consider irrigation."

According to Illig, potential changes in the therapeutic properties of rhodiola as a result of climate change "would only be noticeable over a long period of time and with a large, well-defined patient population. Quality of rhodiola products has more to do with the country of origin, method of harvest, processing of roots, and manufacturing of the end product."

Illig suspects climate change may have a significant negative effect on the natural habitat of wild rhodiola. This species has "a niche in hostile environmental conditions where other plants cannot grow," she wrote. "However, it does not compete well with many other plants, so if climate change invites other larger species, such as tall grasses and brush, they may crowd out natural rhodiola habitat much higher up in elevation where it now grows well. I worry about its native habitat. Combined with overharvesting, especially in China, rhodiola may struggle to survive as a species."

NordGen (the Nordic Genetic Resource Center), an organization based in Alnarp, Sweden,¹⁶ sees "large possibilities using genetic resources to try to solve future challenges regarding food security, agricultural productivity, climate change, and sustainable environmentally friendly agriculture," wrote Ulrika Carlson-Nilsson, PhD, a senior scientist at NordGen (email, October 3, 2019). "NordGen is a Nordic gene bank that conserves accessions originating from, or having been of great importance and relevance to, one or more of the countries in the Nordic region [part of which lies above the Arctic Circle]." NordGen's gene bank includes accessions of MAPs and crop wild relatives.

All accessions are preserved as seeds, which are kept dried in freezers (at -20°C) at NordGen's storage facility in Sweden, with a backup collection in Denmark and at the Svalbard seed vault situated near Longyearbyen at Svalbard, the remote Norwegian archipelago in the Arctic Ocean.

Svalbard Global Seed Vault located near Longyearbyen, Norway.
Photo ©2019 Einar Jørgen Haraldseid



The main part of the collection is free to order for scientists, breeders, museums, and schools. Hobbyists can also order via NordGen's web shop.

One NordGen project involved collecting cultural relict plants mainly in Denmark and Sweden. Relict plants are plants that were once, but are no longer, cultivated in a specific area, where part of the population still exists but is no longer maintained. According to Carlson-Nilsson, these relict plants are most often MAP species that have survived at places where people used them centuries ago. Some of them originated from Europe and were brought to the Nordic area by monks to their monasteries. Relict species collected by NordGen include angelica (*Angelica archangelica*, Apiaceae), black horehound (*Ballota nigra*, Lamiaceae), chicory (*Cichorium intybus*, Asteraceae), houndstongue (*Cynoglossum officinale*, Boraginaceae), and motherwort (*Leonurus cardiaca*, Lamiaceae).

Medicinal and Aromatic Plants in Alpine Areas

Alpine regions generally are defined as high-altitude environments situated above the treeline, the point at which trees are unable to grow. These areas can be found in mountain ranges in many different climate zones around the world, including tropical, continental, and polar.¹⁷ Alpine ecosystems are typically rugged, remote, and sparsely populated, accounting for roughly 3% of the global land area¹⁸ and housing an estimated 4% of all known vascular plants.¹⁹

As plant cell growth is reduced significantly at near-freezing temperatures, alpine plants are usually small, slow-growing, long-lived herbaceous perennials and small shrubs.²⁰ Although they have adapted to the harsh conditions of high-altitude regions, these plants “live at the edge of adequate warmth” and remain vulnerable to fluctuations in temperature and precipitation. To retain heat, alpine plants grow close to the ground, and many are reliant on snow cover for shelter from extreme cold and wind. They also benefit from limited competition for resources above the treeline.¹⁷

Because of the specific tolerances of alpine plants and limited human interference in alpine regions, both alpine plants and the alpine zone are of particular interest

Angelica *Angelica archangelica*
Photo ©2019 Steven Foster



to scientists studying the effects of climate change.²¹ “As an ecosystem at a climate extreme — one that is very temperature dependent — the alpine zone is a sensitive indicator of climate changes,” explained Jim Bishop, PhD, a botanist with the United States Forest Service, in a presentation on alpine plants and climate change. “And it is an ideal habitat to observe globally for biological change. Understanding the environmental stresses on alpine plants, and their adaptations, is the foundation for viewing their climate responses.”¹⁷

The effects of climate change on alpine regions are well documented. Mountain surface air temperatures in alpine zones in North America, Europe, and Asia are increasing faster than the global average, at a rate of approximately 0.3°C per decade, according to the Intergovernmental

Panel on Climate Change (IPCC) *Special Report on the Ocean and Cryosphere in a Changing Climate* (SROCCC), published in September 2019. The SROCCC cites greenhouse gas emissions as the primary driver of recent rising temperatures, noting that “anthropogenic influence is the main contributor to surface temperature increases.” The report also describes precipitation changes, including increased summer drought and likelihood of extreme rainfall, both of which the IPCC attributes with a high degree of certainty to climate change.²²

These changes in temperature and precipitation patterns have a direct impact on alpine flora. Rising temperatures in a highly temperature-dependent ecosystem produce a domino effect. As alpine regions warm, treelines begin to advance upward, which can have both positive and negative effects. For lowland species, such as trees and larger shrubs, advancing treelines result in population increases and new, larger growing areas. Endemic alpine plants, however, are forced to compete with the encroaching tree and shrub species or migrate further upslope. In some regions, this leads to a so-called “nowhere to go” scenario, which results in decreased populations or even local extinctions.^{23,24}

In general, slow-growing, long-lived alpine plants are not well-suited to adapt to climate change.²⁵ “As a whole, the simulations performed have demonstrated that the adaptability of the plants cannot keep up with the fast climate changes,” explained Anne Marie Panetta in a 2018 research article on alpine plants. “The circumstance that older indi-

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GLORIA field work on Ghacktkogel, Hochschwab, Austria, in the northeastern Alps. Photo ©2019 Schronkovie

viduals persist in a worsening environment hides the fact that an extinction debt is slowly developing.”²⁴

Much of the research on the effects of climate change on alpine plants has used modeling studies and simulations, but field work and analyses of data from permanent research sites on mountain summits around the world have provided valuable insights, particularly in the well-studied regions of Himalaya and the Alps.²⁶

Effects in Himalaya

The Himalayas are the highest mountain chain on Earth and separate the Indian subcontinent from the Tibetan Plateau. Himalaya is one of the 36 global Biodiversity Hotspots determined by Conservation International,²⁷ and the Great Himalayan National Park Conservation Area, which is home to approximately 805 vascular plant species, is designated as a UNESCO World Heritage Site for its environmental significance.²⁸

According to the SROCCC, “the Himalaya are predicted to experience a rise in temperature of 5-6°C and precipitation increases of 20-30% by the end of the twenty-first century making them among the most threatened non-polar regions of the world. The rapid changes in temperature and precipitation have earned them the monikers, ‘thermometer of the world’ and ‘early detection tool for global warming.’”²²

Climate change research in Himalayan alpine regions has confirmed that temperature and precipitation changes already are impacting local flora, including medicinal plants. Although much research has focused on the physical changes to the environment — including upslope migration of species, glacial retreat, and precipitation changes — and their impacts on flora,

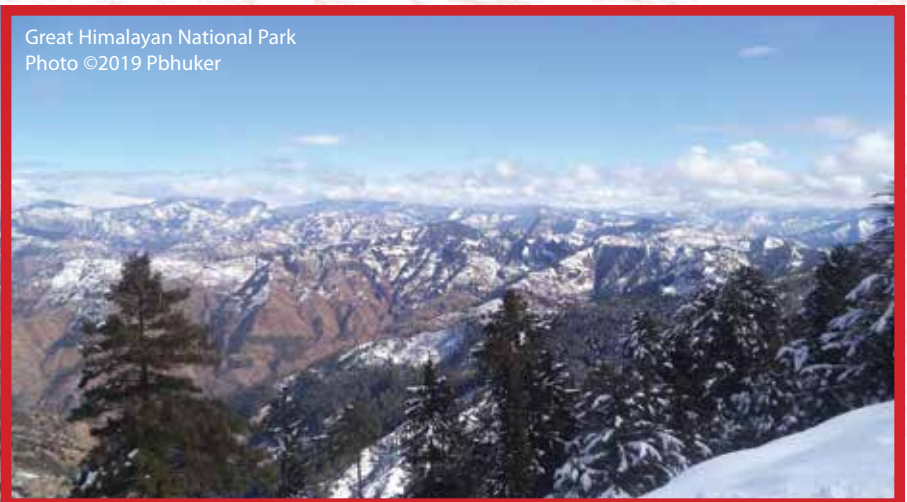
these changes also are affecting local human populations.²⁹⁻³¹ “Human dimensions of climate change are of great consequence in the Himalaya, where alpine habitats are especially important to indigenous populations as collection grounds for medicinal plants,” wrote Jan Salick, PhD, the emeritus senior curator of ethnobotany at the Missouri Botanical Garden, who has conducted extensive climate change research in the Himalayas.³¹

In recent years, the popularity and price of Himalayan caterpillar fungus, or cordyceps (*Ophiocordyceps sinensis*, Ophiocordycipitaceae), have

skyrocketed, driven largely by increased demand from Chinese consumers, who value the fungus for its many claimed medicinal benefits. In 2017, the price per kilogram of high-quality cordyceps was twice that of gold, and, in Tibet, sales of wild-harvested cordyceps make up a “substantial proportion” of the region’s gross domestic product. In a 2018 paper, researchers used multiple methods, including interviews with harvesters and ecological and statistical models, to assess the impact of climate change on this so-called “high-altitude organic gold.” They concluded that “climate change may be amplifying the negative effects of harvesting and playing a role in the ecosystem degradation observed by some collectors, thus interacting with collection pressure to affect the status of this resource.”³²

In 2014, Salick’s research team analyzed data from sites in the Himalayas that are part of the Global Observation Research Initiative in Alpine Environments (GLORIA) network to assess the effects of climate change on alpine vegetation.³¹ As discussed in Cavaliere’s 2009 *HerbalGram* article, GLORIA is a program that “operates a world-wide long-term observation network with permanent plot sites

Great Himalayan National Park
Photo ©2019 Pbhuiker



in alpine environments ... to discern trends in species diversity, composition, abundance, and temperature, and to assess and predict losses in biodiversity in these fragile alpine ecosystems which are under accelerating climate change pressures.”²⁶

Salick found that elevation and precipitation had a significant effect on alpine vegetation. “Our results ... corroborate predictions that climate change — increasing temperature and precipitation — will greatly affect Himalayan diversity,” she wrote in the 2014 article. “The outlook for useful, rare, and endemic Himalayan alpine species, left with nowhere to go, is of great concern for conservation.”³¹

In 2019, Salick and colleagues re-surveyed plots on 11 summits in the eastern Himalayas to assess vegetation changes over the past seven years. They found that the number, frequency, and diversity of alpine plants increased significantly during this time period. Surprisingly, they found that the number and frequency of *endemic* species also are increasing. “Plants newly colonizing the mountain summits came from other Himalayan alpine areas, perhaps contradicting a summit trap hypothesis; rather than species moving up the mountains and getting stranded on mountain tops, they appear to be dispersing among distant summits,” Salick explained in the paper. “Nonetheless, to the extent that plant ranges ‘track’ the upward movement of temperature, Himalayan ‘sky islands’ will be reduced in area as vegetation colonizes higher elevations.”³³

Effects in European Alpine Regions

Although alpine zones compose only 3% of Europe’s total land area, they are home to roughly 20% of its native vascular flora — an estimated 2,500 species.³⁴ In her article, Cavaliere discussed a 2009 study by Grabherr et al. that used GLORIA’s alpine summit monitoring stations to assess the effects of climate change in European alpine zones.¹ The study found “that vegetation extends to higher elevations than previously, that species numbers have increased (except where precipitation is decreasing), and that rare and endemic species make up a smaller proportion of the flora.”³⁵

Since then, GLORIA’s global network has grown, and studies have continued to monitor and investigate alpine ecosystems. In 2012, in a study described then as “the largest and most comprehensive of its kind in the world,” Grabherr and colleagues analyzed 867 plant samples collected in 2001 and 2008 from 60 European mountain summits.³⁴ GLORIA’s Michael Gottfried, PhD, the lead author of the study, was quoted as saying: “We expected to find a greater number of warm-loving plants at higher altitudes, but we did not expect to find such a significant change in such a short space of time. Many cold-loving species are literally running out of mountain. In some of the lower mountains in Europe, we could see alpine meadows disappearing and dwarf shrubs taking over within the next few decades.”³⁶ According to one modeling study of European mountain flora, researchers projected that 36%-55% of alpine plant species would lose at least 80% of their habitat by 2070-2100.³⁷

In a separate study, using data from GLORIA’s permanent site on Schrankogel, a mountain in the Central Alps in Austria, Lamprecht et al. analyzed plant data from 1994, 2004, and 2014. They found increased species richness for

the entire period and noted that “changes in species cover and plant community composition indicate an accelerating transformation towards a more warmth-demanding and more drought-adapted vegetation, ... which would favour a period of accelerated species declines.”³⁸

IPCC’s 2019 report notes that these human-induced changes in climate will continue to have significant impacts on ecosystems in the future. “Current trends in cryosphere-related changes in high-mountain ecosystems are expected to continue and impacts to intensify (very high confidence),” the report explains. “While high mountains will provide new and greater habitat area, including refugia for lowland species, both range expansion and shrinkage are projected, and at high elevations this will lead to population declines (high confidence). The latter increases the risk of local extinctions.”²²

Medicinal and Aromatic Plants in Other Regions

The Royal Botanic Gardens, Kew’s 2017 *State of the World’s Plants* report discusses how some biomes have higher percentages of plant species with traits that make them more resilient to climate change. Identifying these traits can inform efforts to ensure the future survival of rare, endangered, and important plants, including MAPs.²

Traits allowing plant species to better tolerate drought are higher wood density (enabling movement of water and solutes through the plant; as seen in forests); thicker leaves (preventing water loss; in grasslands, savannas, and shrublands); higher water-use efficiency (or more frugal water use; in forests and desert); and deeper roots (enabling plants to reach water lower in the soil; in grasslands). Traits enabling tolerance of higher temperatures are plant height (taller plants seem more tolerant in grasslands, while shorter plants seem more tolerant in forests), thicker leaves (in grasslands), and greater below-ground biomass (enabling access to resources; in grasslands).²

Traits enabling tolerance of more frequent fires are thicker bark (protecting the cambium; in forests), ability to resprout (in forests), and serotinous cones (which require burning to melt the resin covering the seeds, releasing them for wind distribution). Some studies suggest that increasing carbon dioxide levels may cause some plants to improve water-use efficiency that may help them tolerate other climate changes. Plants with a combination of these traits will likely cope better with climate change, while plants without these traits will likely be less tolerant and should be the focus of conservation efforts.²

Since he was quoted in *HerbalGram*’s 2009 article, Will McClatchey, PhD, a former professor of botany at the University of Hawaii at Manoa, has studied ecosystem management in the Solomon Islands off northeastern Australia.

According to him, foreign logging and fishing in that country are having dramatic impacts on local health because of destruction of resources that people have used for millennia (email, September 30, 2019). “Local fishing is decreasing in quality and quantity,” McClatchey wrote. “Local medicinal plants from native forests are harder to find. However, the vast majority of plants that people use as medicines are weedy and grow around gardens or in disturbed areas of secondary forest, so in some sense there is an increase in the availability

of medicinal plants. However, I am quite certain that this is more than offset by decreased food quality and subsequent health problems from diseases that are more impactful on people eating lower quality diets.”

In the 2009 article, McClatchey said that Pacific plants generally are more resilient to climate change partly because they are well adapted to storms and often resistant to salt-water. “I think that the general observation that medicinal plants [in the Pacific] are relatively resistant to climate change still holds true, with the important exception of unusual endemic species that are not used regularly...and because of environmental degradation are now less likely to be used and therefore passed on to future generations,” he wrote.

Sea levels have not yet risen enough to seriously affect specific Pacific plants, but the ecology of mangrove swamps and coastal strand zones is changing, according to McClatchey. “These systems are where most people in the tropical Pacific islands live and are the main places where medicinal plants grow,” he wrote. “I don’t think we have yet reached the tipping point, but in places with low atolls, such as the Marshall Islands, this is just a matter of time.”

McClatchey thinks that the Pacific islands and their diverse peoples could be viewed as canaries in a coalmine. “These peoples, and peoples in the Arctic, are living in and managing the most sensitive kinds of environments, and as they go, so do the rest of us,” he wrote, adding that it is important to monitor levels of foreign versus local medicines and foods used in Pacific communities. He noted that greater use of local rather than foreign resources is more sustainable and more reinforcing of local conservation and traditions, which often leads to better health for people.

“Climate change is causing people to make choices, and many of our international aid systems respond by trying to change local practices, adopting international (foreign) practices for

landscape management, health, food, etc.,” McClatchey wrote. “These generalized strategies, which may be [well-intentioned], leave people with less knowledge of their own environments, less ability to deal with climate change, and fewer future choices.”

In 2015, McClatchey moved home to Oregon, where he and his wife, Valerie, operate a five-acre farm south of Eugene with about 3,000 fruit trees. “We wanted to work together on a focused project examining the ecology of orchard management systems and how some are more resilient to climate change,” McClatchey wrote. “We will need at least another four or five years before we have something of substance to report, but we already believe that the integrated orchard-garden systems of Spain and Italy, sometimes called *huerta*, are far more productive and resilient to [climate] change than the other systems we are developing.”

All of McClatchey’s experiments involve apple (*Malus* spp., Rosaceae) trees and are based on techniques he learned in several parts of Europe while studying how orchardists were growing apples to produce cider. In one system he is testing, which is a simplified version based on methods he learned in Spain and Italy, each apple tree is surrounded by a species from the mint (Lamiaceae) family (e.g., species in the genera *Lavandula*, *Melissa*, *Mentha*, *Nepeta*, *Ocimum*, and *Origanum*). These are then surrounded by different species in the celery (Apiaceae) family and legume (Fabaceae) family. Strawberries (*Fragaria* × *ananassa*, Rosaceae) also are mixed in. This mix is intended to help with nutrient cycling and insect control. The other experimental models McClatchey is testing, which are based on other European methods, have much less diversity and do not seem to be as effective so far.

Brian Boom, PhD, vice president for conservation strategy and the Bassett Maguire Curator of Botany at the New York Botanical Garden, noted that, since *HerbalGram*’s 2009 article, the “potential impacts of a changing climate on MAPs, and all

Sea levels have not yet risen enough to seriously affect specific Pacific plants, but the ecology of mangrove swamps and coastal strand zones is changing.

Will McClatchey on his farm.
Photo courtesy of Will McClatchey



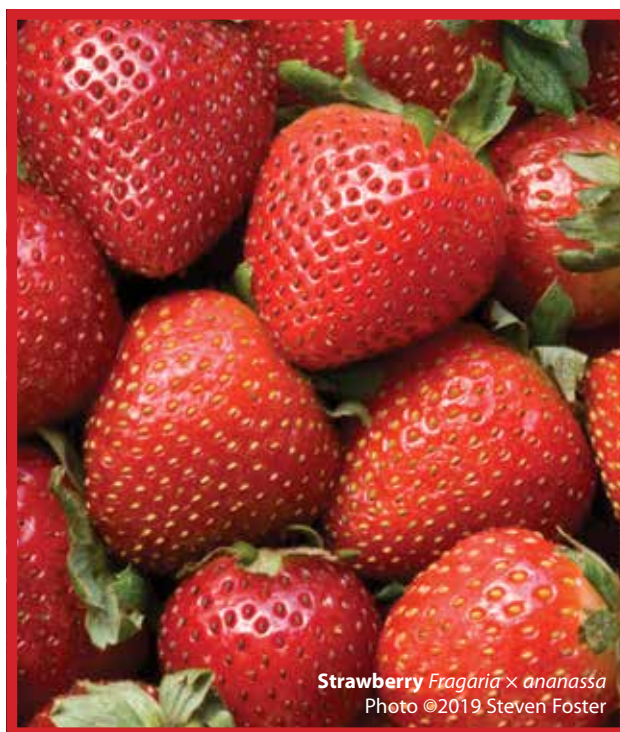
plants for that matter, have come into sharper focus, and the urgency of finding ways to mitigate and/or adapt to [climate change] is all the more keen" (email, October 4, 2019).

Boom pointed to a recent study in the Andes that found that, due to warming, tree species are migrating up in the mountains to cooler elevations, but that the rate of migration is probably not fast enough to avoid species' loss.³⁹ A separate study in Amazonia analyzed the effects of 30 years of climate change on trees in more than 100 plots in the Amazon Forest Inventory Network (RAINFOR). They found that the composition of the forest is changing in response to greater warming and drought, but the changes are not keeping up with the rate of climate change. As the climate got hotter and drier, species that are adapted to those conditions moved in, but not as fast as the less drought-tolerant trees died out.⁴⁰

"The take-home message from these two unrelated studies is that in the face of climate change, human interventions are going to be needed more than ever to keep desired MAPs growing and producing products for people," Boom wrote. "Species can move up to cooler environments in the Andes or to moister sites in Amazonia, but probably not fast enough for many of them."

Another study determined that the implications of climate change for the wine industry would be "substantial." The climate change models that were used in the study predicted that, by 2050, viticulture suitability will decrease in many traditional wine-producing regions (e.g., the Bordeaux and Rhône valley regions in France and Tuscany in Italy) and increase in more northern regions of North America and Europe, for example.⁴¹

"Wine grape [*Vitis vinifera*, Vitaceae] growers are already planning for their future livelihoods and actively searching for higher, cooler locations for their vineyards," Boom wrote. "Places as far-flung as Tasmania, central China, and in the region of Yellowstone National Park in the United States are all being considered. The



Strawberry *Fragaria × ananassa*
Photo ©2019 Steven Foster

future health of much of the MAP industry could depend on strategic, proactive transitioning to new plant sourcing locales over the next several decades and not assuming that the plants will be able to migrate on their own fast enough to where growing conditions are suitable."

Dan Metcalfe, PhD, a senior lecturer in the Department of Physical Geography and Ecosystem Science at Lund University in Lund, Sweden, is investigating what happens to cloud forests without clouds. Near Wayqecha Biological Station in the Andes of southern Peru, Metcalfe's experiment involves a large wall of loosely woven fabric that stretches through the forest. Fog rolling up the hill blows into the fabric, and the fog's

moisture is trapped, so that the area behind the curtain is clearer and drier than normal.^{42,43}

Tropical montane cloud forests (TMCF) and *páramo*, a set of alpine ecosystems above some TMCF, are home to thousands of unique species. In fact, TMCF are among the most biodiverse ecosystems on Earth. Trees in TMCF often are covered in epiphytes (plants that grow on other plants but are not parasitic), which are adapted to obtain water specifically from the air, not through the ground. Monarch butterflies overwinter, by the millions, in TMCF of Central Mexico. A recent study found that in less than 25–45 years, "70–86% of páramo will dry or be subject to tree invasion, and cloud immersion declines will shrink or dry 57–80% of Neotropical TMCF, including 100% of TMCF across Mexico, Central America, the Caribbean, much of Northern South America, and parts of Southeast Brazil." Warmer air temperatures may force air to travel further up mountains before it cools enough to

form clouds, reducing TMCF humidity or area. This may have significant implications for TMCF plants that are uniquely adapted to mist and fog.⁴⁴

Metcalfe's research is ongoing, and he claims it is the only large-scale experimental manipulation of cloud abundance in the world (email, October 5, 2019). "We now have around two years of a wide range of ecological and climatological measurements showing a variety of poten-

"Many cold-loving species are literally running out of mountain. In some of the lower mountains in Europe, we could see alpine meadows disappearing and dwarf shrubs taking over within the next few decades."



Apple *Malus* spp.
Photo ©2019 Steven Foster

tially significant impacts of cloud reduction on various ecosystem processes,” Metcalfe wrote. “Broadly, cloud reduction appears to affect the growth and survival of both mature trees and a range of epiphytic plant groups.”

According to Metcalfe, four species that are used by the local Andean communities for various purposes, including medicinal, have been planted in the experiment: *Alnus acuminata* (Betulaceae), *Clethra cuneata* (Clethraceae), *Clusia sphaerocarpa* (Clusiaceae), and *Prunus integrifolia* (Rosaceae).

Metcalfe hopes to keep the experiment going for at least another 10 years to observe the longer term ecological effects of cloud changes. “I expect and hope the experiment will contribute some of the clearest direct evidence yet for the likely ecological impacts of future shifts in cloud abundance on tropical cloud forests,” he wrote.

The Impact of Phenology and Shifting Ranges

Changes in Phenology

Phenology, or the study of the seasonal activities of organisms, involves the intricate relationships between the climate and plant life cycles. This can include interactions between plants and animals that depend on seasonal cues. Long-term monitoring of these activities, such as the emergence of leaves and flower buds and the movements of pollinators and fruit dispersers, can provide insights about climate change. If one factor in this web shifts, the repercussions may be felt in

various ways, up to and including the ultimate survival of a plant’s population in a certain area.

Research in this area requires more, longer-term observations, but patterns have emerged regarding the relationship between plant phenology and climate. In general, phenology has changed for many plants, particularly in more temperate areas, according to Kathy Gerst, PhD, associate research scientist and data product coordinator of the USA National Phenology Network (USA-NPN) (oral communication, September 27, 2019). “In places that are more water-limited, such as the Mediterranean regions of California or the [US] desert southwest, we know a little bit less about how the timing of the seasons have been changing, because a lot of species [there] are really driven by precipitation,” said Gerst. “But most broadly, a trend toward warming springs has been documented. The timing of spring is getting earlier and earlier.”

Plants that rely on temperature to begin their seasonal activities, rather than moisture and precipitation, are more likely to be susceptible to the phenomenon of false spring, in which the temperature warms to the point of cueing the production of buds and leaves, but the last frost has yet to occur. For frost-sensitive plants, including many commercially grown crop species, a false spring can devastate the plant and its production. Fruit trees, such as apple and pecan (*Carya illinoensis*, Juglandaceae), are particularly vulnerable to false springs. Further testing and observation of the rela-



tionship between plant performance and climate change will require data on a greater variety of species across communities and environmental conditions.⁴⁵

For plant species that are active later in the season, these shifts in timing can cause what is known as a “phenological mismatch”: flowers that bloom before pollinators become active or fruits that appear after birds and other fruit dispersers have migrated to other areas.⁴⁶ These plants may also be at a disadvantage when competing for resources with species that are active earlier in the season. These conditions tend to favor invasive species.

According to Gerst: “A lot of invasive species have been found to be more phenologically labile, or variable, in their ability to take advantage of different climatic situations, [which] can lead to competitive advantages for invasive species over a native species because [the invasive species] can sort of ‘turn on’ and start growing earlier.”

Plant species that can better “track” changes in temperature increase their performance, and those that do not “track” temperature often decline with climate warming.⁴⁶ This suggests that phenological monitoring may be one strategy to set future conservation priorities for both wild and cultivated medicinal species. However, species performance is not limited to phenological sensitivity, but also other responses including physiology and interspecies interactions. The species most vulnerable to climate warming are those that not only fall victim to false springs and phenological mismatch, but those that are also less mobile and cannot shift to where conditions are more favorable.⁴⁷

“In the future, we’ll see more people use more sophisticated methods to forecast phenology,” said Gerst, “and I think it helps us better dial in on ... the implications of those shifts, because we can do it for multiple species and communities and also look, at the same time, at how our species distributions are changing.”

Changes in Native Ranges

In the face of a changing world, plants have choices: die out, move, or adapt. As temperatures increase and spring comes earlier, wild species with the ability to migrate are being found outside their native ranges, either creeping to higher latitudes and altitudes to find lower temperatures or settling into new territory where conditions are now more favorable to their life cycles. The ecological implications can be immense.

Loss of species in an area may result in a decline of the ecosystem, since diverse plant, animal, and insect life is considered a sign of a strong, adaptive environment.⁴⁸ As noted during a controlled, 10-year observation of an area of grassland in Germany, loss of species was correlated with “future impairment of ecosystem functioning, potentially decades beyond the moment of species extinction.” A simple example of this phenomenon is the practice of monoculture, or the cultivation of only one species on a plot of land, as is often used in commercial agriculture. This practice was found to decrease soil health over time, which led to the introduction of crop rotation and allowing fields to lie fallow for a period of time.

A review of surveys of European mountain summits dating back to 1871 found a significant increase in species over 145 years, with a significant acceleration in species gain over the past 20 to 30 years that is “strikingly synchronized with accelerated global warming,” the authors wrote.⁴⁹ The observed summits gained an average of 5.4 species from 2007 to 2016, as compared to an average of 1.1 species from 1957 to 1966. With these changes happening on an accelerating time scale, it is difficult to make long-term predictions about which species will thrive and which will be negatively impacted by different competitors.

Gerst said: “The process [of movement and adaptation] happens on longer time scales than what plants need to do right now to adapt to climate change.... We are kind of creating novel communities where different species are interacting with each other that didn’t before.”

For plants that adapt to their new climate, these changes may impact their medicinal value. Many active plant secondary metabolites are the result of environmental stressors. Without these stressors, or with different stressors than before, the production of metabolites may decrease or disappear altogether. Though the plant “wins,” people who depend on the plant for pharmacopeial-grade material may lose a

Many active plant secondary metabolites are the result of environmental stressors. Without these stressors, or with different stressors than before, the production of metabolites may decrease or disappear altogether.

source of income and medicine. For example, when foxtail millet (*Setaria italica*, Poaceae) plants were exposed to varying levels of salt, to mimic poor soil conditions, researchers observed that 29 proteins produced by the plant were significantly up- or down-regulated in response to this stress.⁵⁰ Similarly, several species of eucalyptus (*Eucalyptus* spp., Myrtaceae) showed changes in leaf metabolites in response to drought simulation, though many species in this genus are drought-tolerant or drought-resistant.

Seeding the Future

In the realm of commercial cultivation, farmers and producers have been adapting to shifts in phenology and range for years. In viticulture, as previously mentioned, growers are adjusting where certain grape varieties are planted depending on temperature and soil quality. Data gathered through organizations such as the USA-NPN, which supplies data to government bodies such as the US Environmental Protection Agency (EPA), can help growers predict the onset of spring.⁵¹ With this information, crops can be protected against false springs and invasive competitors and planted in optimal areas to ensure the ideal number of growing days.

Long-term observations and data still need to be gathered to recognize broad patterns in the relationship among climate change, phenology, and ecosystem survival. The ability to forecast is a large and relatively new development in this area of study, said Gerst. The overall positive and negative outcomes of rapidly shifting plant lifecycles and ranges also remain to be seen. Existing studies provide strong evidence that sensitivity to shifting conditions is a good indicator of species performance but “are limited to localized regions and need to be interpreted with the awareness that many factors, including temperature, have changed over time,” wrote the authors of a 2012 review.⁴⁶ In the future, the ability to track and forecast phenology and range will play a large part in the conservation of both wild and cultivated plants.

Conclusion

Over millions of years, plants have adapted to tolerate a wide range of environmental conditions. Plants can be found on remote, moisture-rich tropical islands as well as some of the most extreme ecosystems on Earth, from the cold, harsh Arctic tundra to barren mountaintops. Since the industrial era, plants have been exposed to an entirely new environmental variable: anthropogenic global heating and climate change. For the 10-year period from 2006 through 2015, the global average surface temperature was estimated to be 0.87°C warmer than the pre-industrial (1850-1900) average. By the end of this century, that number is projected to reach 1.5-2.0°C. According to the IPCC, more frequent and intense weather extremes have been observed during periods with warming of only 0.5°C.²²

Although a change in temperature of one or two degrees may seem inconsequential, global heating is changing ecosystems on a large scale, and researchers are continuing to investigate how these changes are impacting plants. In just the past decade, researchers have provided striking evidence that climate change is affecting medicinal plants and the humans who rely on them. Communities in the Arctic, for example, are seeing medicinal plants being washed away with coastal



Motherwort *Leonurus cardiaca*
Photo ©2019 Steven Foster



Grape *Vitis vinifera*
Photo ©2019 Steven Foster

erosion, and collectors in Himalaya who depend on wild-harvested medicinal plants for income are seeing populations decline. These changes are compounded by existing threats to medicinal plants, including overharvesting, exploitation, and habitat destruction to name just a few.

Without significant efforts to reduce carbon emissions, medicinal plants — and all life on Earth — will become increasingly threatened. In November 2019, writing in the journal *BioScience*, the independent Alliance of World Scientists expressed their concerns for the future: “[W]e declare, with more than 11,000 scientist signatories from around the world, clearly and unequivocally that planet Earth is facing a climate emergency.... The climate crisis has arrived and is accelerating faster than most scientists expected. It is more severe than anticipated, threatening natural ecosystems and the fate of humanity,” the authors wrote.⁵² “To secure a sustainable future, we must change how we live. ... The good news is that such transformative change, with social and economic justice for all, promises far greater human well-being than does business as usual.”⁵² HG

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Chicory *Cichorium intybus*
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