

# Climate Change and Conservation

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**Abstract** – Conserving forest genetic resources and, indeed, preventing species extinctions will be complicated by the expected changes in climate projected for the next century and beyond. This paper uses case examples from rare spruces (*Picea* sp.) from North America to discuss the interplay of conservation, genetics, and climate change. New models show how climate change will affect these spruces, making it necessary to relocate them if they are to survive, a tool known as assisted migration or, preferably, assisted colonization. The paper concludes with some speculation on the broader implications of climate change, and the relevance of conservation to preserving the necessary ecological services provided by forests.

**conservation genetics / assisted colonization / extinction / *Picea mexicana* / *Picea martinezii* / *Picea chihuahuana* / *Picea breweriana***

**Kivonat – Klímaváltozás és génmegőrzés.** Az erdészeti genetikai erőforrások megőrzése, és különösen a fajkihalások megakadályozása az évszázad végére (és azutánra) előrevetített klímaváltozás fényében nehéz feladatnak tűnik. A tanulmány ritka észak-amerikai lucfenyő fajok példáján tárgyalja a klímaváltozásból adódó genetikai és megőrzési problémák együttesét. Modellek mutatják be klímaváltozás hatását a luc fajok elterjedésére. Ezek szerint szükség lesz a fajok megmentése érdekében a mesterséges áttelepítés, ill. kolonizáció megoldására. A tanulmány kitér a klímaváltozás tágabb következményeire és a konzervációnak az erdőtakaró ökológiai szolgáltatásaiban játszott szerepére.

**konzerváció-genetika / mesterséges kolonizáció / kihalás / *Picea mexicana* / *Picea martinezii* / *Picea chihuahuana* / *Picea breweriana***

## 1 INTRODUCTION: EX SITU AND IN SITU CONSERVATION

Conservation efforts can be placed into two categories: ex situ, meaning out of place, such as in clone and seed banks, and in situ, meaning in place, as in natural reserves. In situ conservation to most people meant natural forests in protected areas. In the last several decades, most advocates for the conservation of forest genetic resources in North America concluded that in situ conservation had significant advantages over ex situ conservation.

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Both ex situ and in situ conservation can provide for future economic values, such as the discovery of new products, like taxol (Wheeler – Hehnen 1993). But, in situ conservation has other values, such as ecologic: forests provide services through the carbon cycle and many other geochemical and hydrologic cycles. Esthetic values: forests enrich our world, both by their own beauty and because of the many creatures they shelter which, by the way, it may be our moral duty to protect, according to most of the world's major religions. In situ conservation does all this with a minimum of input and expense.

However, in the future, probably no temperate forest will be truly natural and wild, even in North America. They will not be natural because society will have to move species and forests to prevent extinctions due to rapid climate change combined with limited seed dispersal. Although forest species and genetic resources cannot be maintained solely in seed banks, nevertheless, they will not be maintained without seed banks either, or at least without some form of ex situ conservation. Assisted colonization will be necessary to prevent the loss of genetic diversity and even species extinctions, but assisted colonization (or reforestation or some other term), also will be necessary to restore forests and the ecosystem services that they provide as current forests are reduced by climate change.

### 1.1 Gene Conservation and Conservation Genetics

To facilitate discussion of forest conservation, some terminology needs to be clarified; in particular, the phrases 'gene conservation' versus 'conservation genetics'. Gene conservation is about the preservation of genes for their future utility to breeders. That can be accomplished ex situ, in bottles and bags – seed banks.

Conservation genetics is about the genetic conditions for survival, reproduction, and evolution in response to changing environments. This is about maintaining healthy forests, which cannot be done in bottles. However, genetically healthy forests serve the purposes of gene conservation just as well or better than seed banks. Conservationists have talked far too much about gene conservation and far too little about conservation genetics.

### 1.2 Genetics and Extinction

External pressures threaten the survival of species, populations, and genetic resources, and therefore, threaten the forests themselves. These threats are usually human-caused. Among these external pressures, the most important may be habitat destruction, exploitation, introduced pests and diseases, pollution, and climate change. What exactly do these threats do? It is so simple, it is almost trivial. Their effect is to fragment large populations and reduce them in size. When populations are small enough, they are classed as threatened or endangered.

Whatever the external factors (development, over-harvest, etc.) that begin the march toward extinction, genetic processes end it. The pioneering conservation biologists, Michael Gilpin and Michael Soulé (1986), developed an analogy to a whirlpool or vortex (*Figure 1*). The external threats reduce population size and fragment larger, more extensive populations into smaller units. Small populations lose genetic diversity as a result of random genetic drift. Loss of genetic diversity limits adaptation to changing conditions, which leads to even smaller populations. The smaller population, the more inbreeding, even if mating is completely at random, because the choice of mates is reduced. Inbreeding results in loss of fitness in most organisms, and the population becomes even smaller. Fragmentation increases separation among subpopulations, which means less gene flow within the metapopulation, and genetic diversity can no longer be maintained, contributing to the reduction in size. Demographic variation becomes more likely in small populations, ratcheting them still lower in size. And so on in a feedback

circle, until these stochastic processes drive the population to extinction.

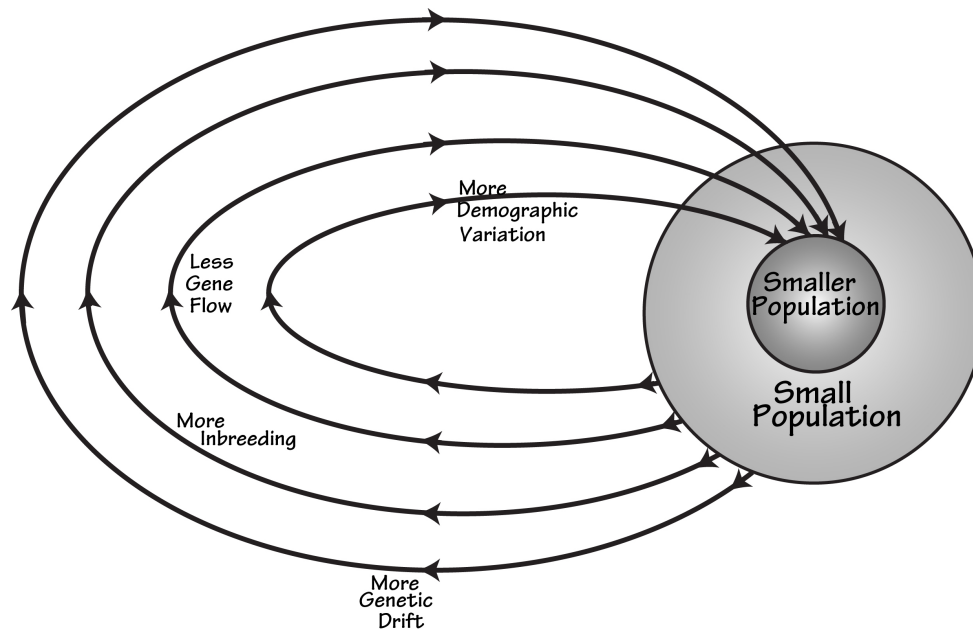


Figure 1. The genetic extinction vortex (Gilpin – Soulé 1986). External threats – urban and agricultural development, climate change, invasive species and diseases, overexploitation, and other factors – reduce available habitat and fragment species into smaller population. The smaller the population, the more genetic drift, which reduces diversity. Diversity cannot be replaced by gene flow because the fragments are isolated by distance. The reduction in genetic diversity limits adaptation to environmental changes. The smaller the population, the more inbreeding and inbreeding reduces fitness. All of these stochastic genetic processes operate along with demographic stochasticity and tend to further reduce population size in a positive feedback cycle until extinction is inevitable. All extinctions, with the exception of catastrophic extinction, may be the result of genetic factors in the final analysis.

This is documented in the case of the greater prairie chicken (*Tympanuchus cupido*) where even habitat improvement could no longer save the subpopulation in Illinois, USA (Westemeier et al. 1988), and in the Glanville fritillary (*Melitaea cinxia*), the first report of extinction linked to lack of genetic diversity and inbreeding in natural populations in the Aland Islands (Saccheri et al. 1998).

### 1.3 Genetics in Conservation

If genetics is the final factor in the destruction of forest species, genetic knowledge can also help in conservation. Some of the ways are: clarifying taxonomy; guiding the choice of where to place reserves; and diagnosing problems, such as lack of diversity, lack of gene flow, or excessive inbreeding.

The most basic way genetics enters into the conservation decision is through taxonomy. We must know what is out in the forest before we can even think about ways to save it. What should be saved? For example, *Picea mexicana* and *Picea martinezii* were not recognized as species eight years ago. The foremost authority on conifers (Farjon 2001) treated *Picea mexicana* as just a few, isolated, Mexican populations of a more common northern species, *Picea engelmannii*; and *Picea martinezii* was considered identical to *Picea chihuahuana*.

Without taxonomic status, there can be no protection, neither under law nor through public awareness.

We now know from genetic studies using markers, both isozymes and from DNA, that *Picea mexicana* is very different from *Picea engelmannii* (Figure 2). The data indicate that *Picea martinezii* and *Picea chihuahuana* have been separate species for 2 to 3 million years (Ledig et al. 2004).

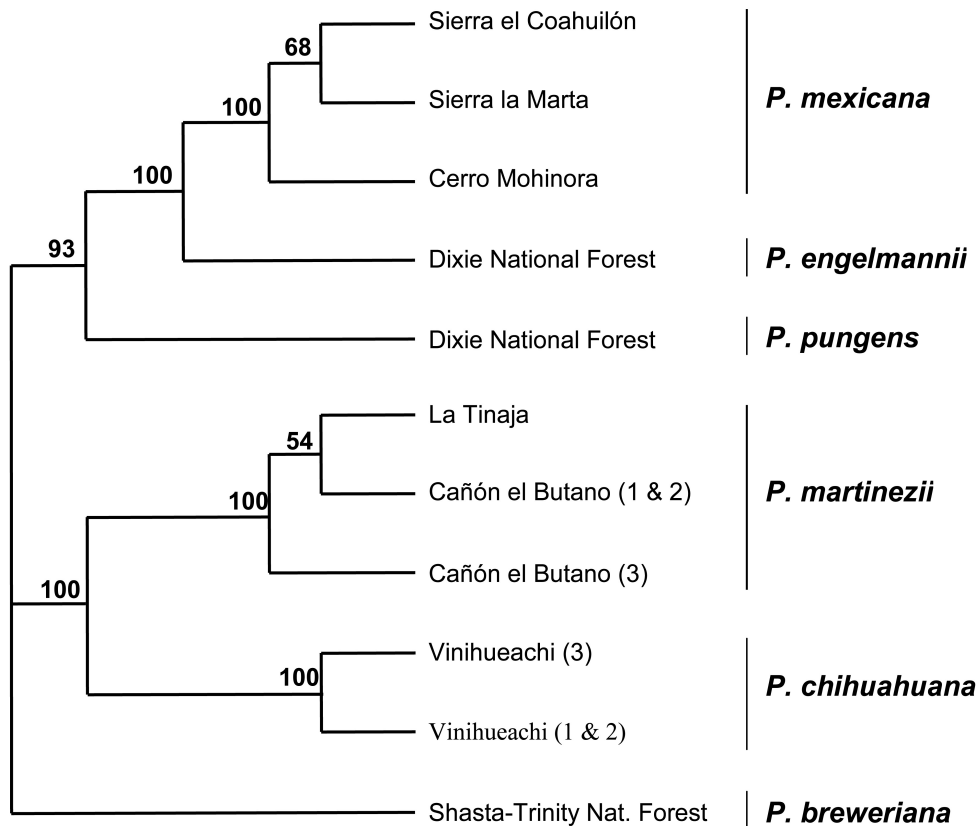


Figure 2. Neighbor-joining phylogenetic tree based on dissimilarity distance (Nei – Li 1985)

Figure 2 demonstrates that *Picea chihuahuana*, *P. martinezii*, and *P. mexicana* are separate species and that they are distinct from *P. engelmannii*. *P. pungens* is sometimes confused with *P. engelmannii* but the two are obviously distinct. *P. breweriana* was used as an outgroup to anchor the tree. Numbers near nodes are percentage of 1000 bootstrap replicates that justify the node (Ledig et al. 2004).

## 2. RESULT: CASE EXAMPLES – MEXICAN SPRUCES

The Mexican spruces are largely unknown to most foresters, even in Mexico. There are three species of spruce in México (Figure 3a,b,c). They have highly fragmented ranges, small populations, and are relicts of past glacial periods. Localized, fragmented species are always more at risk of extinction than widespread species, such as Canada's transcontinental spruces.



3a: *Picea mexicana*:  
3 populations spread over 676 km,  
tallest peaks – 3350–3550 m, < 4,000 trees



3b: *Picea chihuahuana*:  
39 populations spread over 687 km,  
ravines at 2155–2990 m,  
24,211 trees > 2 m tall



3c: *Picea martinezii*:  
6 populations spread over 147 km,  
at elevations 1820–2515 m < 2,000 trees

Figure 3. Photos and some data on the rare, little-known Mexican spruces, which occur in remote areas of the Sierra Madre Oriental and Sierra Madre Occidental

Studies of the Mexican spruces began because of the North American Forest Commission and its Forest Genetic Resources Working Group (FGRWG), which includes three delegates from each country in North America – Canada, México, and the US. *Picea chihuahuana* first drew our attention. However, all the Mexican spruces are wonderful models to study the effects of fragmentation and population size on genetic processes. The FGRWG undertook studies of the Mexican spruces in a spirit of international cooperation.

A great deal of international cooperation was needed. Many colleagues and I worked together and as a result learned a lot about these rare spruces. The project was begun largely thanks to Teobaldo Eguiluz, the founding director of the Centro de Genética Forestal in Chapingo. My late colleague, Basilio Bermejo, shouldered much of the burden when he became director of the Centro de Genética Forestal. However, Celestino Flores deserves most of the credit for carrying out extensive investigations in the mountains of Mexico.

*Picea mexicana* is the rarest of the Mexican spruces (Ledig et al. 2000). It occurs in only three locations. Two locations are in the Sierra Madre Oriental, the eastern mountain range of Mexico. One location is on Sierra la Marta, where most of the population was destroyed by fire 30 years ago. Another population is on Sierra el Coahuilon, only 5 km from Sierra la Marta. These two peaks are among the highest in the Sierra Madre Oriental. The third location is on Cerro Mohinora, 676 km away in the Sierra Madre Occidental, the western mountain range of Mexico. Cerro Mohinora is the highest peak in the State of Chihuahua.

Like *Picea mexicana*, *Picea martinezii* also occurs in the Sierra Madre Oriental. When I began work on the Mexican spruces, we knew of only two populations. These were discovered in 1984 by Glafiro Alanís and a visiting German professor, Burkhardt Müller-Using, at the Universidad Autónoma Nuevo León in Linares (Müller-Using – Alanís 1984, Müller-Using – Lässig 1986). One location was at a site called La Trinidad, a population of about 350 trees at the foot of El Butano, a cliff that rises over 200 m above the spruce. Another, separated from the first by 147 km, had about 68 trees. Both sites are in the State of Nuevo León. Later, Celestino Flores discovered four other groups of trees near Aramberri, a village in the middle of the desert at the base of a high sierra that provides refuge for remnants of the North American Arcto-Tertiary forest (Ledig et al. 2000).

*Picea chihuahuana* is more widespread than the other two Mexican spruces. We have found 39 populations (Ledig et al. 2000). They are spaced over 687 km north-south in the Sierra Madre Occidental – north and south of the famous Copper Canyon country, Cañon del Cobre. Chihuahua spruce almost always occurs in steep arroyos where the sun may not reach until noon.

The map (Figure 4) gives some idea of how fragmented these three species are. All of these species are considered endangered because of the small numbers of populations and the small numbers of trees. Manuel Mápula and Celestino Flores counted and measured every tree of *Picea chihuahuana* and all saplings and seedlings above 0.3 m tall (Ledig et al. 2000). There are less than 25,000 trees in the 39 stands.

Data on the other two species are not precise, but *Picea martinezii* certainly has fewer than 2000 trees, probably less than 1000. *Picea mexicana* has only three stands and probably less than 4000 trees.

There are other demographic reasons to be worried about these species. Reproduction is scarce. For *Picea chihuahuana*, on which we have good data, the ratio of seedlings and saplings to trees is less than in northern spruces, such as *Picea rubens* and *Picea engelmannii* (Table 1).

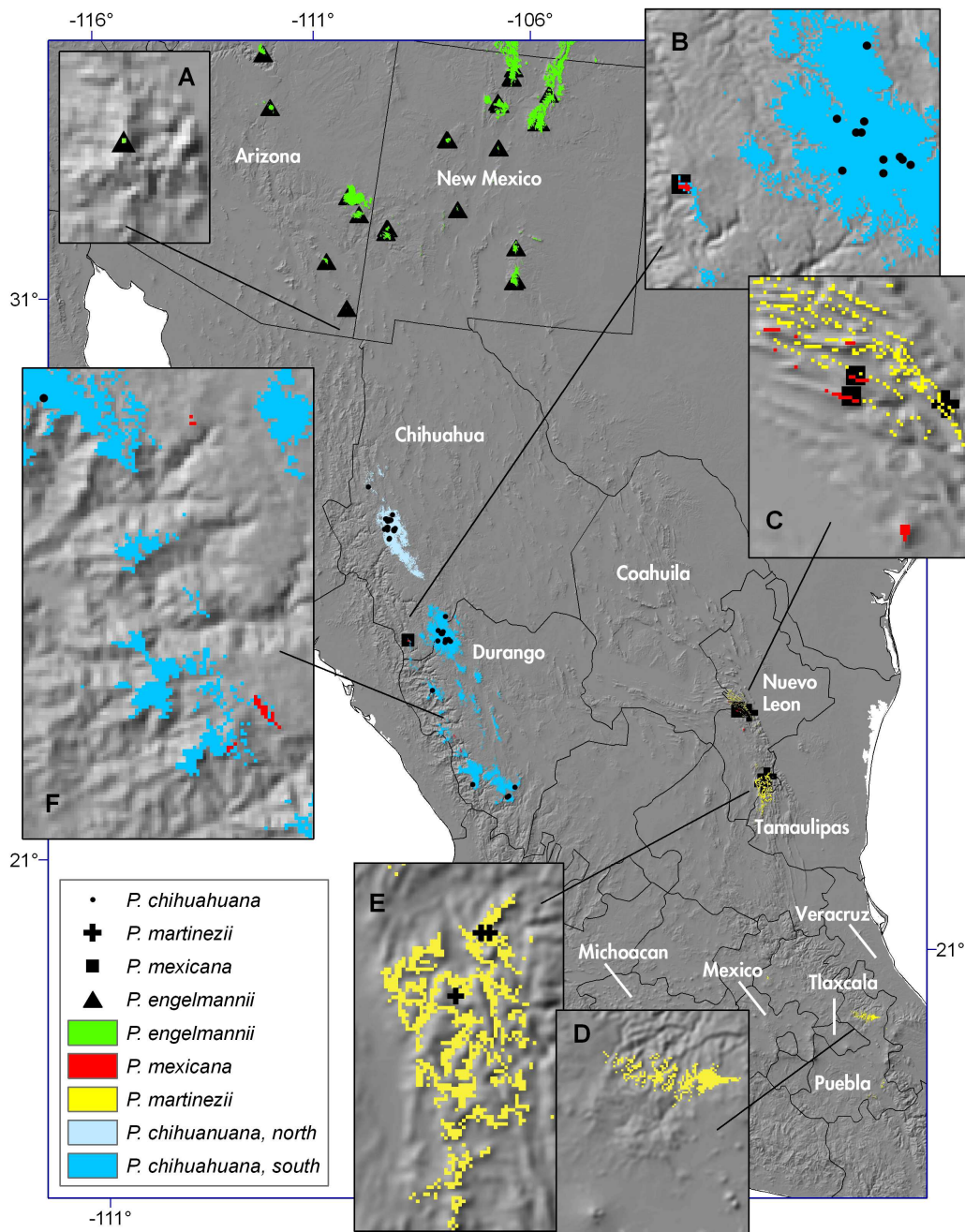


Figure 4. Map of Mexico and the extreme southwestern United States showing all the present locations of *Picea chihuahuana* (●), *P. martinezii* (□), *P. mexicana* (■), and for comparison, locations of *P. engelmannii* (▲) in the southwestern United States. The areas predicted to be climatically suitable for the two mitotypes of *P. chihuahuana* are in light blue (northern mitotype) and dark blue (southern mitotype). The yellow is where the climate is predicted suitable for *P. martinezii* and the red is predicted to be climatically suitable for *P. mexicana*. The insets magnify detail in significant areas. See Ledig et al. (2010) for details on the modeling procedure.

Table 1. The ratio of seedlings and saplings to trees (>2 m height) in *Picea chihuahuana*, *P. rubens*, and *P. engelmannii*. Data for the latter two species are from Burns and Honkala (1990).

Species	Mean	Range
<i>Picea chihuahuana</i>	0.59 ( $\pm 0.05$ )	0.09 – 1.47 <sup>1</sup>
<i>P. rubens</i>	13.02	1.87 – 26.85
<i>P. engelmannii</i>	2.34	0.24 – 7.33

<sup>1</sup> Omitting an outlier of 3.18, a stand which had been recently harvested, leaving predominantly seedlings and saplings.

Why is reproduction scarce? Seed germination may be an explanation, but not the ultimate explanation. The highest value we obtained for seed germination was 54% in seeds from one of the largest stands of *Picea chihuahuana*, one which has over 2600 trees and is only a few kilometers from a stand with over 3500 trees (Ledig, unpublished data); in other words, a large, healthy population. Seeds from other, smaller populations had lower rates, approaching zero in many small stands. In the two *Picea martinezii* stands of about 60 and 350 trees, germination averaged 7%. Much older seeds of the widespread U.S. species, *Picea engelmannii* (about 20 years old when tested) had substantially higher germination rates, about 85%. Therefore, some of the reason for the low seedling-sapling:tree ratio of *Picea chihuahuana* might be a result of low seed germinability.

## 2.1 Conservation Genetics and the Mexican spruces

We used molecular markers, mostly isozymes, to analyze genetic variation in all three spruces (Ledig et al. 1997, 2000, 2002), providing extensive knowledge of their population genetic structure. I've mentioned above that the data showed convincingly that the Mexican spruces are phylogenetically distinct from each other and from the US *Picea engelmannii* (Ledig et al. 2004).

We also know that genetic variation is lower than normal for conifers. What does this tell managers? That they should concentrate protection on the populations with the greatest genetic variation because those populations have the greatest potential for adaptive evolution.

We know that today chance – random genetic drift – is the most important genetic process in these populations, overwhelming natural selection. In these situations, mutations reach high frequency even as the population loses genetic variation. And these mutations reduce fitness because the vast majority are deleterious. What does this tell managers? Managers should help the populations increase in size through silvicultural methods and enrichment plantings so that genetic drift is less important.

We know that exchange of genes among populations by pollen or by seed dispersal is near zero, especially, in *Picea chihuahuana*. Therefore, much of the genetic variation is among populations. What does this tell managers? Managers should encourage gene flow and maintain as many populations as possible.

We have looked at the mating system – the proportion of self-fertilization and outcrossing – and found that selfing is very high, sometimes 100%. This is completely unique in conifers. The result is inbreeding and a great loss in fitness. This inbreeding is the cause of low seed yields and low germination rates, which explains why regeneration is scarce. What does this tell managers? Managers should encourage outcrossing.

There is a common thread to these management suggestions. If we encouraged gene flow among populations, it would increase their genetic variation and reduce inbreeding and reduce genetic drift. There are several ways to do this. We could connect populations with migration corridors to promote gene flow. However, the stands are separated by great distances and intervening habitat is likely to be unsuitable for these species; e.g., *Picea mexicana* is restricted to only the highest peaks in the Sierra Madre Oriental and the Sierra Madre Occidental and these ranges are very distant from one another. No migration corridor is possible. Another method would be to pollinate one population with pollen from another. However, anyone who has cross-pollinated trees knows that this is wildly impractical. The most practical way of encouraging gene flow and increasing genetic diversity is by enrichment plantings. That is, collect seeds from various populations, germinate the seeds and grow seedlings from them in a forest nursery, and, finally, interplant the seedlings among different stands. When these grow to tree size, they should naturally intercross with the locals, restoring genetic diversity and eliminating the effects of genetic drift and inbreeding.

## 2.2 Climate Change and the Mexican Spruces

The management suggestions outlined above would be sufficient to restore genetic health if the Mexican spruces existed in a static world. However, the world is not static. Change, climate change in the past, is the reason the Mexican spruces have highly fragmented ranges and small populations. During the last glacial maximum, spruce in México extended at least 700 km further south to the Basin of México (Clisby – Sears 1955, Lozano-García et al. 1983). Today, after Holocene warming, they are mere relicts.

Foresters and conservationists must consider the effects of climate change projected for this century and beyond (Mátyás 2006). Assisted colonization – relocation – will be necessary to conserve genetic resources and prevent extinctions. Assisted colonization has been hotly debated in the last decade (see the discussion in Ledig et al. 2012), and I will not rehash that here. Assuming that assisted colonization is accepted, our first guess might be that species must be moved up in elevation or northward. However, *Picea mexicana*, for example, is already at the very top of the tallest peaks in the Sierra Madre Oriental and Sierra Madre Occidental. Where could it go? To answer that question, one must know the future distribution of climatic niches.

For projections of the effect of climate change, I am especially indebted to Jerry Rehfeldt and Cuauhtémoc Sáenz. Cuauhtémoc Sáenz developed spline climatic models for all of México (Sáenz-Romero et al. 2010) and Jerry Rehfeldt has calculated and modeled the future climate for all these rare spruces (Ledig et al. 2010).

We modeled the present fundamental climatic niches for all three Mexican spruces and for southwestern populations of *Picea engelmannii* (Figure 4). For this purpose, *Picea chihuahuana* was divided into two genetically different groups – north and south – called mitotypes because they differ in their mitochondrial DNA (Jaramillo-Correa et al. 2006).

The model correctly predicts where *Picea mexicana* and *Picea martinezii* now grow in the northern Mexican States of Coahuila and Nuevo León. However, it also shows that many other sites are climatically suitable, such as a peak called Cerro Potosí in southern Nuevo León predicted suitable for *Picea mexicana*. The reason these species do not grow everywhere the climate is suitable is because these projections show the fundamental climatic niche, not the realized niche. The realized niche may be affected, in part, by soils or by interactions with other species – competitors, insect pests, and pathogens.

The model correctly predicts *Picea mexicana* on Cerro Mohinora in the western Mexican State of Chihuahua, but indicates that conditions lower on the mountain might be right for

*Picea chihuahuana* as well. However, it also shows suitable habitat for *Picea mexicana* southward on some high ridges in the State of Durango, where it does not now occur.

For *Picea martinezii*, the model predicts suitable habitat in many areas where it is not actually found in the northern States of Mexico, Coahuila and Nuevo León and on the border of the States of Nuevo León and Tamaulipas. Note that the present climate far south in the northern part of the State of Puebla in central Mexico is also predicted to be suitable for *Picea martinezii*, but it does not occur there.

We also projected the situation for 2060 (Figure 5) using Global or General Climate Models (GCMs). GCMs predict future climates. By 2060, the suitable habitat for each species shrinks. In fact, the fundamental niche for *Picea chihuahuana* disappears in Chihuahua. The model shows both mitotypes overlapping near the Chihuahua-Durango border – the northern mitotype on the eastern side and the southern mitotype on the western side of the Sierra Madre Occidental. On Cerro Mohinora, *Picea chihuahuana* replaces *Picea mexicana*.

*Picea mexicana* also disappears near the Coahuila-Nuevo León border on Sierra la Marta and Sierra el Coahuilon. In fact, in 2060, its habitat is gone – completely! There is no suitable habitat for *Picea mexicana* in just 50 years.

For *Picea martinezii*, the climate niche shrinks in the States of Nuevo León, Coahuila, and Tamaulipas. However, it expands to the south in the east-central Mexican States of Veracruz, Puebla, and elsewhere in the Trans-Mexican Volcanic Belt (a belt of active vulcanism and high volcanic peaks that runs east-west across central Mexico). Peaks in the Volcanic Belt can reach 5636 m in elevation compared to only about 3500 in the Sierra Madre Oriental. The climate niche for *Picea martinezii* also appears for the first time in the State of México and in eastern Michoacán, both in central Mexico.

Notice that habitat does not open up in the north of México nor in the southwestern US for any of the three spruces.

By 2090, the climate for *Picea chihuahuana* is predicted to shrink even more drastically to a small area in the border region of the States of Chihuahua and Durango (Ledig et al. 2010). The climate suitable for *Picea martinezii* is almost gone in the area near the border of the northern States of Coahuila and Nuevo León, and has shrunk badly near the border of the States of Nuevo León and Tamaulipas. However, a climate niche for *Picea martinezii* still is predicted around the volcanic peak, Orizaba, the highest peak in Mexico, in other mountains along the Puebla-Veracruz border, and on the eastern border of the central Mexican State of Michoacán.

Furthermore, in 2090 a climatic niche is predicted for *Picea mexicana* for the first time on the volcanic peaks Tláloc, Iztaccíhuatl, Popocatepetl, and La Malinche in the Trans-Mexican Volcanic Belt (Ledig et al. 2010). Suitable climate for *Picea martinezii* is predicted below *Picea mexicana* on La Malinche.

In conclusion, the situation in the northern States of Mexico (Coahuila, Nuevo León, and Tamaulipas) is grim. My suggestion to Mexican foresters has been to start test planting *Picea martinezii* and *Picea mexicana* on the high volcanic peaks now. If seed banks are not established for these species soon, it may be too late.

*Picea chihuahuana* is an even bigger problem because the models do not show a suitable climatic niche developing, even in the Trans-Mexican Volcanic Belt. Where can it find suitable habitat? From the projections, that is an unsolved question. Perhaps, no suitable climate will develop in Mexico.

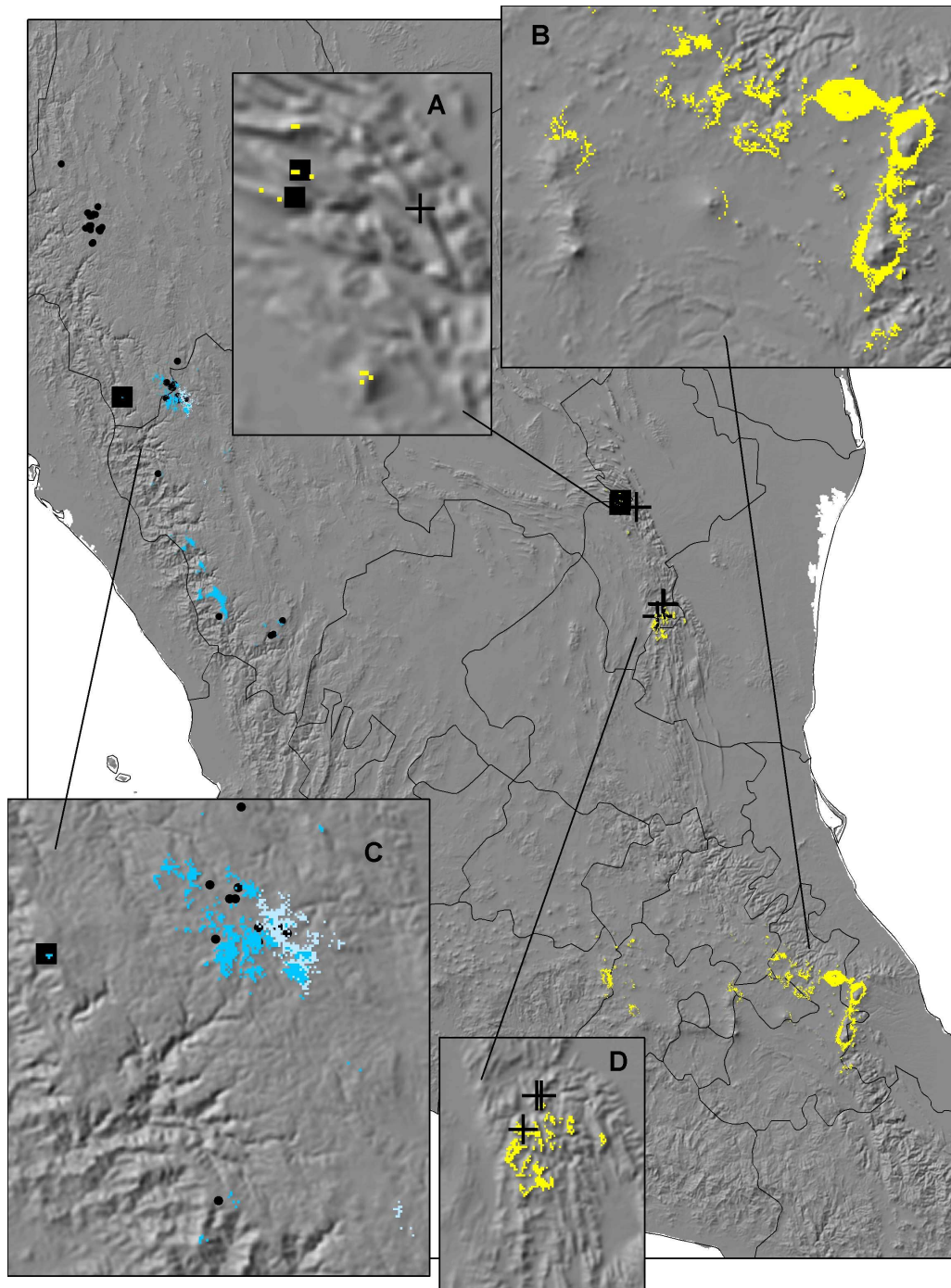


Figure 5. Composite mapping of six projections made from output of three General Circulation Models (GCMs) and two scenarios (pessimistic – business as usual – and optimistic – some restraints on carbon emissions) for the decade surrounding 2060 using the majority of votes cast by the Random Forests classification tree to determine presence or absence of four taxa. Light blue for the northern mitotype of *P. chihuahuana* and sky blue for the southern mitotype; yellow for *P. martinezii*; and red for *P. Mexicana*. The insets magnify detail in significant areas. See Ledig et al. (2010) for details on the modeling procedure.

### 3 CASE EXAMPLE – *PICEA BREWERIANA*

*Picea breweriana* is my last example. *Picea breweriana* is native only to the Klamath-Siskiyou Mountains of the West Coast of the United States – in the States of California and Oregon. The range is fragmented (Figure 6). According to fossil evidence, *Picea breweriana* was once a part of the Arcto-Tertiary forest (Wolfe 1964, Axelrod 1987). The Arcto-Tertiary forest spanned western North America.

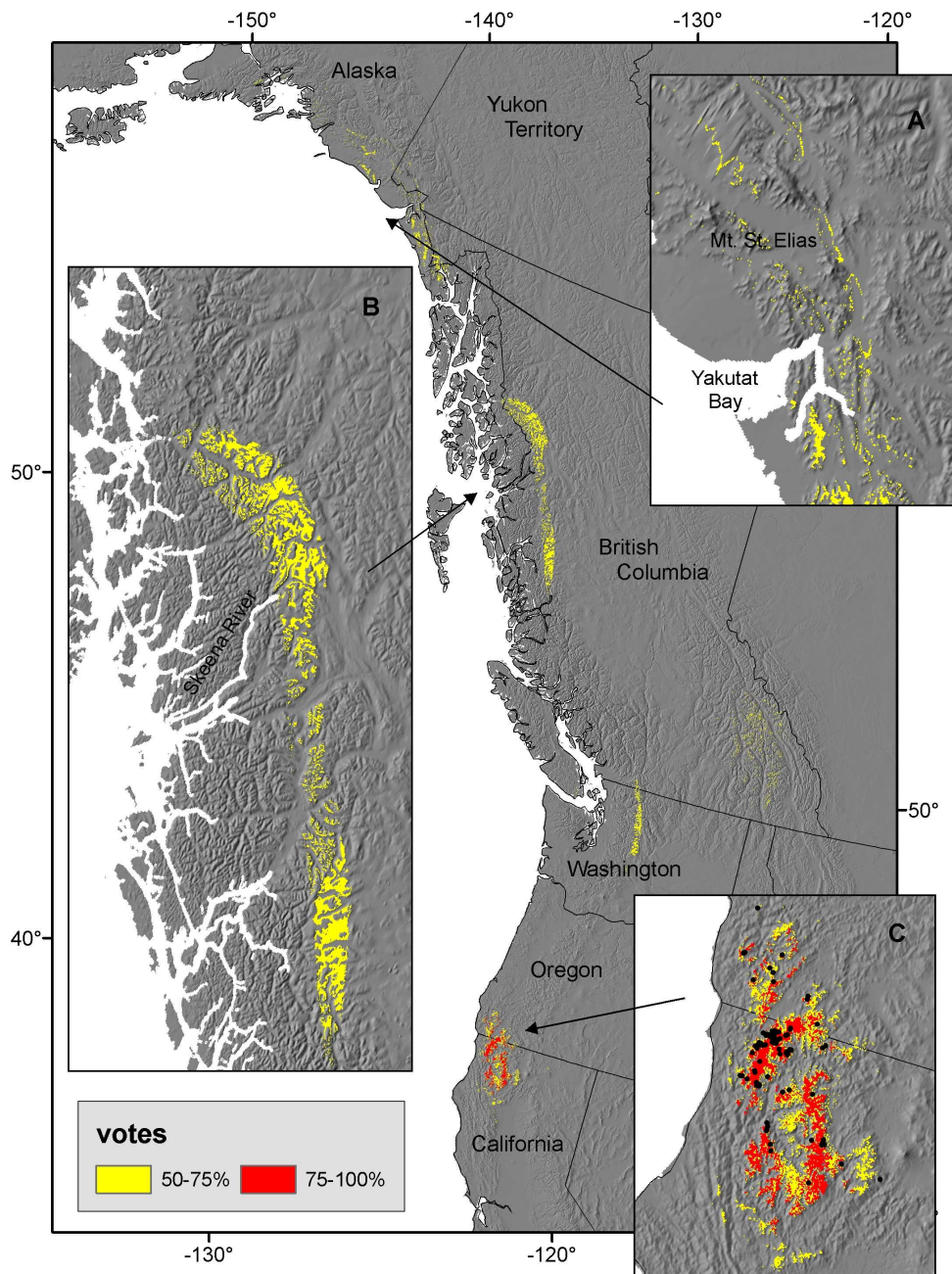


Figure 6. Map of northwestern coastal North America showing the range of *Picea breweriana* (●) and areas of suitable climate as modeled by the Random Forests classification tree. Yellow means the climate was deemed suitable by one General Climate Model (GCM), blue by two GCMs, and red means the climate was deemed suitable by all three GCMs used in the modeling approach. See Ledig et al. (2012) for details on the modeling procedure.

*Picea breweriana* has moderate levels of genetic diversity for a conifer, except in its northernmost outlying population in Oregon (Ledig et al. 2005). It is highly outcrossing – on average 92%, despite low stand density in several of our samples. Even when highly isolated trees are compared to those in dense clusters, there is no increase in the level of selfing. But, there is fairly high differentiation and low gene flow among populations. The high outcrossing rate is in striking contrast to that in the equally fragmented Mexican spruces.

The genetic analysis is mostly good news with regard to *Picea breweriana*. That is, genetic diversity is moderate – not high, but not low either. And the rate of outcrossing is high, which is very promising. The bad news is that at least some populations may have suffered loss of genetic variation because of genetic drift, and gene exchange among populations is low, which tends to isolate them, particularly those in Oregon. However, compared to the Mexican spruces, genetic analysis suggests that it should be quite simple to maintain viable populations of *Picea breweriana* in situ. Nevertheless, because of the high level of differentiation, I would again suggest that managers encourage gene flow, probably by exchanging seedlings among stands.

But what about climate change? Certainly, *Picea breweriana*, like the Mexican spruces, responded to past climate changes. *Picea breweriana* occurred all over the western United States 10 million years ago, before the climate became more arid in the post-Miocene. Its present habitat is a small fraction of its former range.

As he did for the Mexican spruces, Jerry Rehfeldt also modeled the fundamental climate niche of *Picea breweriana*; Figure 6 includes its predicted present climatic niche (Ledig et al. 2012).

Figure 7 is constructed with Global Climate Models (GCM) for the decade 2060. By 2060, there will be almost no suitable climatic niche in the lower United States for *Picea breweriana*. Only one GCM has it clinging to a few ridgetops. By 2090 (not shown; see Ledig et al. 2012) even these small areas of projected habitat are predicted to disappear.

Conversely, climate in northern British Columbia, the Yukon Territory, and southern coastal Alaska may be suitable for *Picea breweriana*. In Figure 7, blue means the climate was deemed suitable by two GCMs. And if the map could be seen in magnification, it would reveal a few red pixels; i.e., habitat suitable according to three GCMs. Note that *Picea breweriana* does seem to match our first notions of where to move species – north – in contrast to the situation in the Mexican spruces. The lesson is that every species and climate combination could be unique.

Without assisted colonization, *Picea breweriana*, like the three species of Mexican spruces, may go extinct. Therefore, Barry Jaquish (British Columbia Ministry of Forests, Lands and Resource Operations, personal communications, 2012) is planning provenance plantings in the Prince Rupert area of British Columbia, using seed collections from 10 populations. *Picea breweriana* is an example in which international cooperation may actually save a species from extinction.

### 3.1 Extinction, Genetics, Climate Change, and Assisted Colonization

To summarize to this point: A massive wave of extinction will be upon us in a short time because of the many unique threats resulting from human activities (Pimm et al. 1995, Ward 1995). Both now and later we should work to maintain genetically healthy populations, because beyond some point, small populations will find themselves in the genetic vortex from which they cannot escape (Gilpin – Soulé 1986). Saving genetic resources in bottles is not the final answer, but it may be a necessary interim tool because many climate models suggest such extensive rearrangements (Williams – Jackson 2007) that assisted colonization will be absolutely necessary to prevent extinctions. And assisted colonization requires some mixture of in situ and ex situ conservation methods.

I began my career 50 years ago by advocating conservation in situ in natural forests. But, if forests are moved to exotic locales, this is, in fact, ex situ conservation? In fact, forests of the future may have no present analogue.

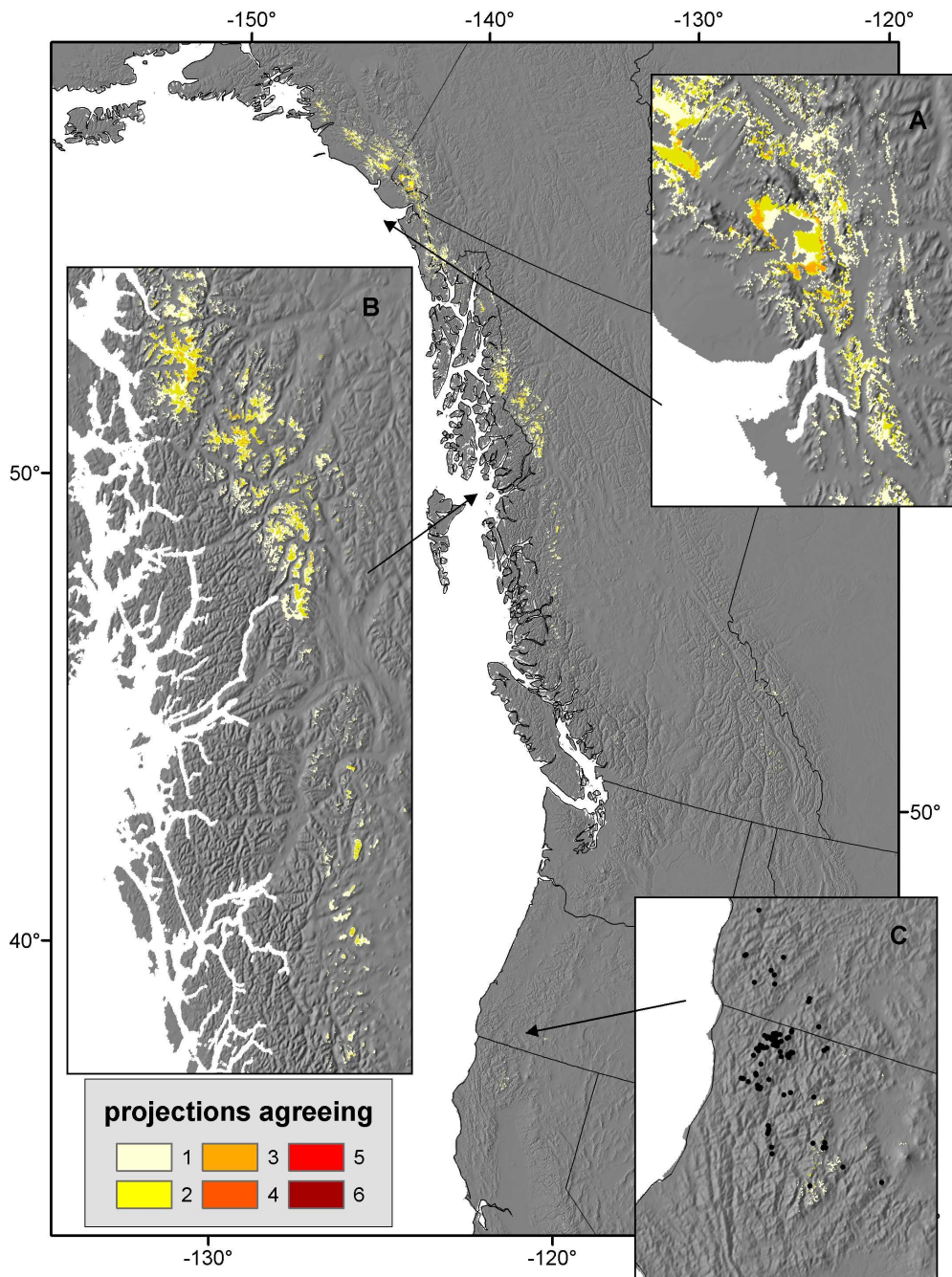


Figure 7. Composite mapping of the climatic niche of *Picea breweriana* made from the Random Forests bioclimate model for six projections using output of three GCMs and two scenarios (pessimistic – business as usual – and optimistic – some restraints on carbon emissions) for the decade surrounding 2090. Climate suitability uses the 50 % voting threshold. Insets show in detail the Yakutat Bay - Mt. St. Elias region of Alaska (A), the Nass-Skeena region of British Columbia (B), and the Klamath region of California and Oregon (C). Dots in C locate sites inhabited by *Picea breweriana* that were used for the present analysis. Shades of color code concurrence: lightest yellow, 1 projection; darkest red, 6 projections.

## 4 CONCLUSION

About 20 years ago, I wrote this (Ledig – Kitzmiller, 1992):

*“Foresters ... must be ready to act if the signal for global warming becomes clearer. To prepare, national governments should launch major programs of conservation to save native gene pools in seed banks, clone banks, or ex situ plantations.”*

The signal for global warming is now clear, but in the United States, we have not prepared. The reason for inaction is that many politicians ask whether forest species like the Mexican spruces and *Picea breweriana* have any real value? Why should we save them? The ancient Hindus and Buddhists had an answer, perhaps right, perhaps exaggerated. This story from India, for example, about a great scholar and physician, Jivak, inscribed on the wall of the National Botanic Institute, Lucknow, India.

*“Jivak, the ancient physician, when asked by his teacher to bring a plant that was quite useless, returned empty-handed, remarking that there was no such plant.”*

However, the value of a species – the value of a forest – need not be solely economic – a piece of wood or a log that we can sell, a medicine that we can market.

The greatest value is ecologic. Forests provide indispensable ecosystem services. They sequester carbon from the atmosphere, and that kept the carbon dioxide level in balance at roughly 280 ppm for millions of years. It is common knowledge that forests can offset the emissions from burning fossil fuels, but in the short term, declining forests may contribute to the problem of global warming. Today, much of the carbon added to the atmosphere comes from forests (Bowman et al. 2009). Burning forests to clear land for pastures, or wildfires, accounts for a significant share of the carbon added to the atmosphere (Zarin 2012), at least 10% to 20% of global emissions. And as forests decline directly or indirectly because of global warming, they will add more carbon to the atmosphere and sequester less; in the forests of northern California, carbon emissions from fire are predicted to more than double by the year 2085 (Westerling et al. 2011). The climate projections presented in *Figures 5 and 7* carry an ominous message that is not just about the North American spruces. The Mexican spruces are not the only species that will be endangered. México alone has, perhaps, more than 3000 woody species, and about 40% of these may be endemic (Rzedowski 1986). And beyond Mexico, species throughout the world are at risk. Assisted colonization is needed not only for rare species, but also for common species. Furthermore, assisted colonization is needed not just to prevent extinction of species and loss of genetic diversity; more importantly, it will be needed to *maintain forest cover* – call it restoration ecology.

The world may be embarking on a positive feedback cycle – a dangerous runaway situation (*Figure 8*). The increase in carbon dioxide from burning fossil fuels has resulted in global warming, which will lead to forest decline. Forest decline has two effects: less carbon will be sequestered and the fuel load will increase. Higher fuel load and higher temperatures lead to more and hotter fires, and that leads to still higher levels of carbon dioxide, accelerating global warming.

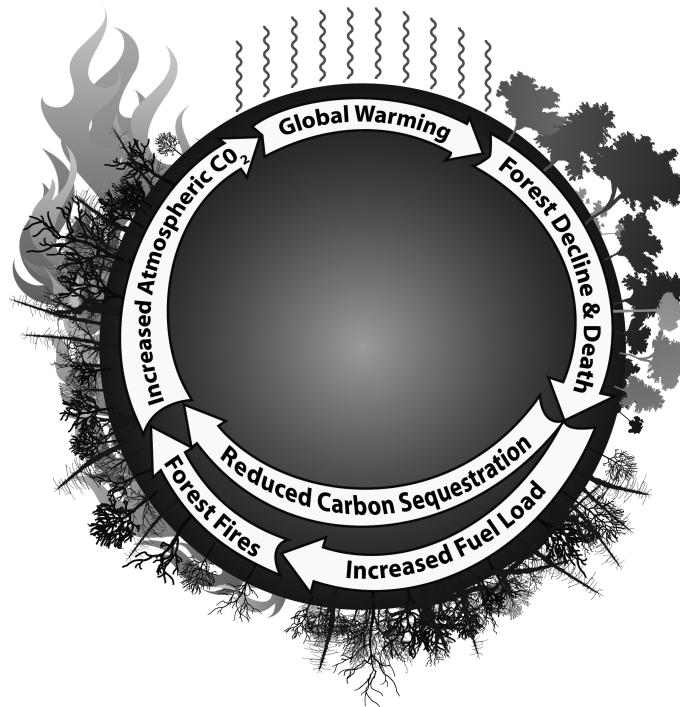


Figure 8. Hypothesized positive feedback loop leading to increased CO<sub>2</sub> through forest decline and wildfire

Global climate change confronts the world with a massive environmental crisis, and conserving some semblance of forest cover is a critical problem for the survival of civilization; for our survival, not just survival of the spruces. Although I realize this is alarmist, I am sincerely frightened for the future of our world. It may not be an exaggeration to liken the effects of global warming to the Four Horsemen of the Apocalypse. Coastal areas will flood, displacing millions of people. Agricultural productivity will decline in many areas, resulting in local famine. With the refugees displaced by flood and famine will come pestilence, and many countries will believe that war is their only option to gain needed resources – and they will have nothing to lose.

Jose Ortega y Gasset (1914) said it poetically in an essay he wrote about seeing the forest through the trees:

*“I am myself and what is around me, and if I do not save it, it shall not save me.”*

Foresters have skills in planting and managing forests, and a vital role to play in stabilizing our environment. This is a century when foresters, in their role as restoration ecologists, will be urgently needed.

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