

## 8. Vegetation and Climate

Plants are of utmost importance to life on earth, due to their ability to fix atmospheric carbon, provide oxygen and food for animals, and due to their stabilizing influence on tropical climate through transpiration and clouds (Chapter 7). Solar energy captured by plants is directly related to the mass of carbon in the biosphere, as expressed in *net primary productivity* (NPP, cf. Chapter 11), Vegetation plays a crucial role in the carbon cycle (Chapter 9), including carbon storage above and below ground, and in the formation of fossil fuel deposits.

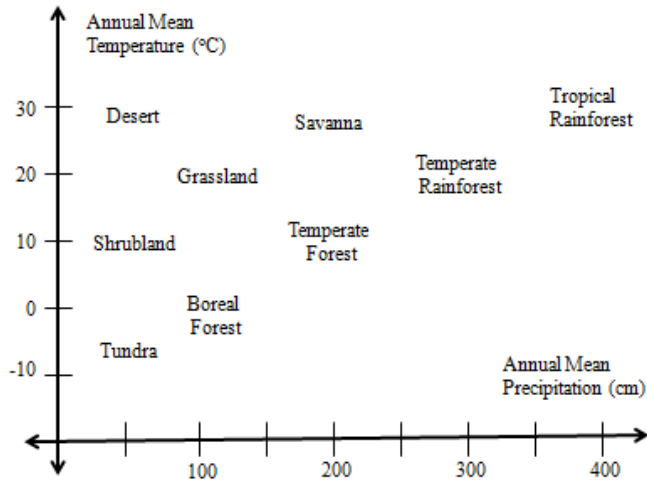
In this chapter, we first examine the relationship between regional plant types and climate, as defined by *biomes*. The distribution of tropical deforestations is described. We then explore the physiology of plants with the concepts of cold and warm-adapted plants and the *growing degree days* (*GDD*). This is followed by a discussion of the challenge to plants for latitudinal migration in the face of global warming, the “*CO<sub>2</sub> fertilization*” effect on plants, and damage by ozone.

### 8.1. Biomes

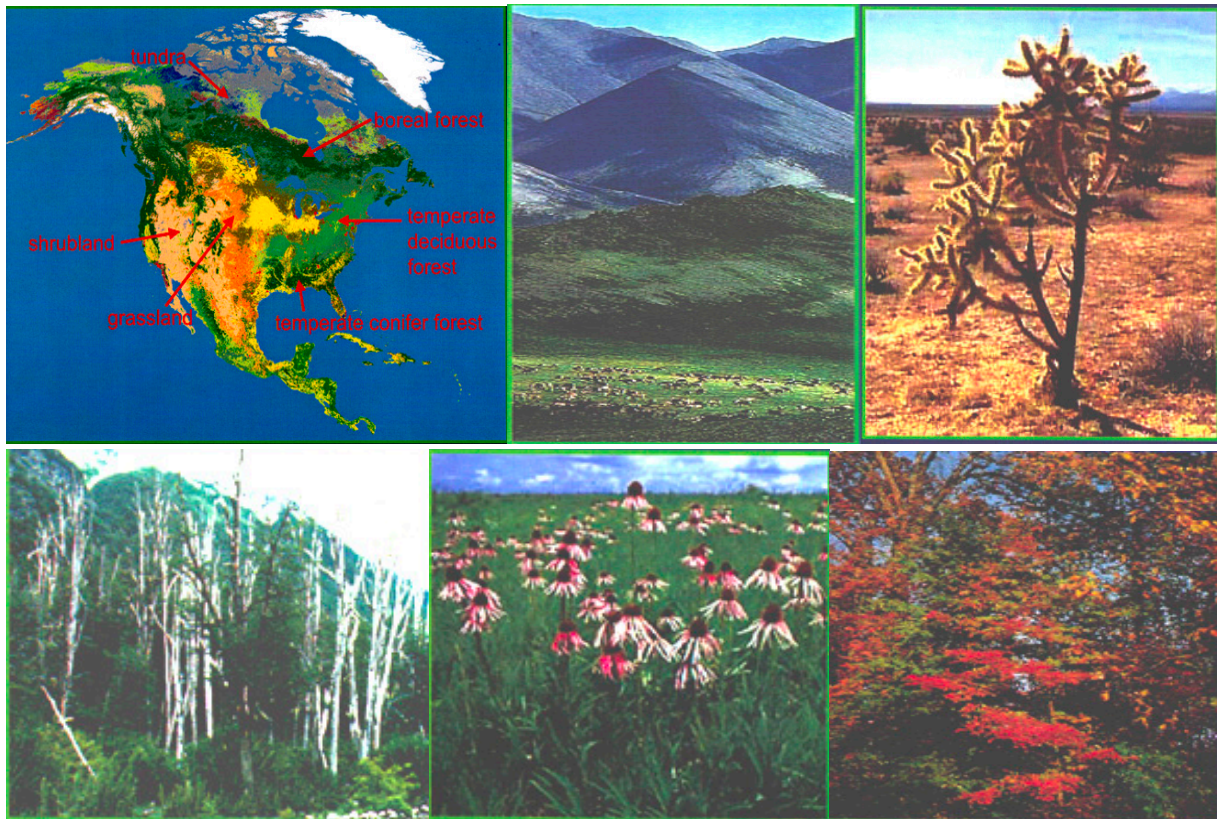
The type of vegetation found in a given part of the world is intimately linked with the local climate. Temperature controls photosynthesis, respiration, growth rate, reproduction, and water use of plants, while precipitation is crucial for photosynthesis and nutrient acquisition. In the early 1900s Vladimir Köppen capitalized on extensive observations of this intimate relationship between climate parameters and prevailing plant types to define a classification of climate/plant types or biomes. Although the strength of seasonal and daily variation is important, and latitudinal control on sunlight, soil type, nitrogen availability, and disturbance by fire, humans and animals are also important, the two primary variables used to define biomes are annually average temperature and annually averaged precipitation.

Figure 8.1 shows the biomes associated with each temperature/rainfall combination. Note that no biomes exist in the lower right of the diagram, because cold air cannot hold enough moisture to precipitate that much. With annual precipitation amounts of less than 100 cm/yr, the coldest regions ( $< 0^{\circ}\text{C}$ ) support small plants such as kinnikinnik in the tundra (Figs. 8.2b and 8.3a), while temperate regions ( $\sim 10\text{-}15^{\circ}\text{C}$ ) support shrubland, such as in the Sahel (Fig. 8.4a). Hot and dry regions ( $\sim 30^{\circ}\text{C}$ ) are deserts, with very sparse plants (Fig. 8.2c). Note the large deserts in Africa, Asia, and Australia (Figs. 8.4a, 8.3a, b).

With annual precipitation in the range  $\sim 100\text{-}150$  cm/yr, at cold high latitude temperatures ( $\sim 0^{\circ}\text{C}$ ) the boreal forest biome dominates (Fig. 8.2b, 8.3a), while at higher temperatures grasslands thrive (Fig. 8.2e). The soil carbon storage content of the extensive grassland biomes in each continent (Figs. 8.2-8.4) is  $\sim 25\%$  of the world total. With annual rainfall near 200 cm/yr, temperate forests (Fig. 8.2f) dominate the temperate regions, and savanna occurs in hot climates  $\sim 30^{\circ}\text{C}$  (Figs. 8.2a – 8.4).

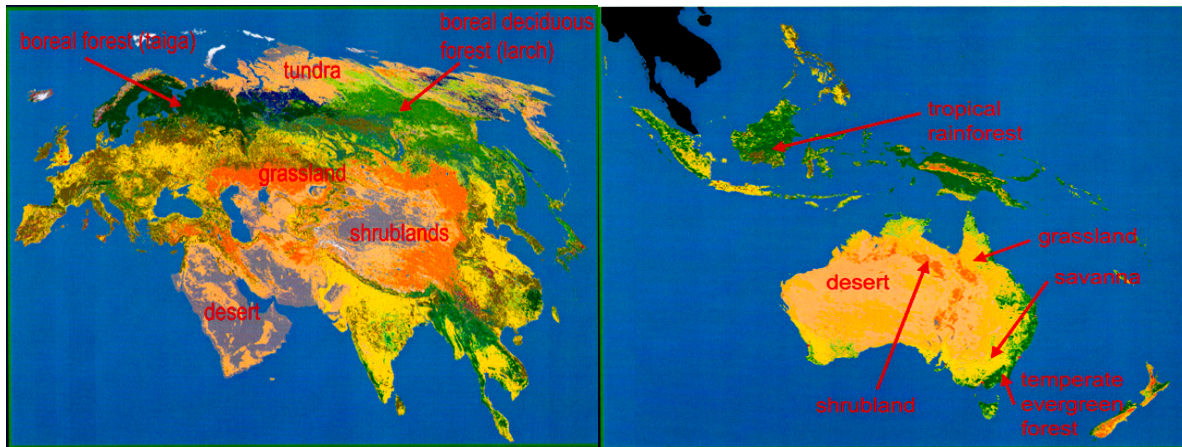


**Figure 8.1.** Biomes plotted as a function of annually averaged temperature and precipitation, following Köppen's classification system.

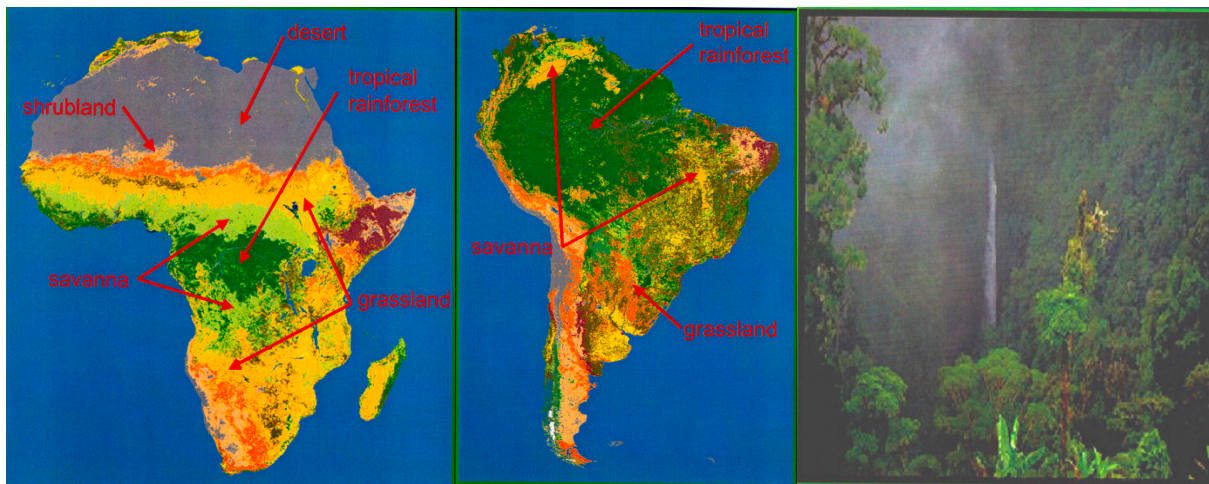


**Figure 8.2.** a) North American biomes with b) caribou grazing on very short vegetation in the *tundra*, c) cholla in the Mojave *Desert*, d) *boreal forest* biome, typified by spruce, larch and birch, e) Echinacea blooming in the tall *grassland* prairie, and f) autumn colors in the *temperate deciduous forest*.

With annual rainfall of 300 cm/yr or higher one finds temperate rainforest in the midlatitudes of southeast Australia (Fig. 8.3b), southwest Chile, and northwest North America. In hot climates ( $\sim 30^{\circ}\text{C}$ ) with abundant rainfall, tropical rainforests dominate in Southeast Asia, Amazonia, Central Africa, and Indonesia (Figs. 8.3 and 8.4).



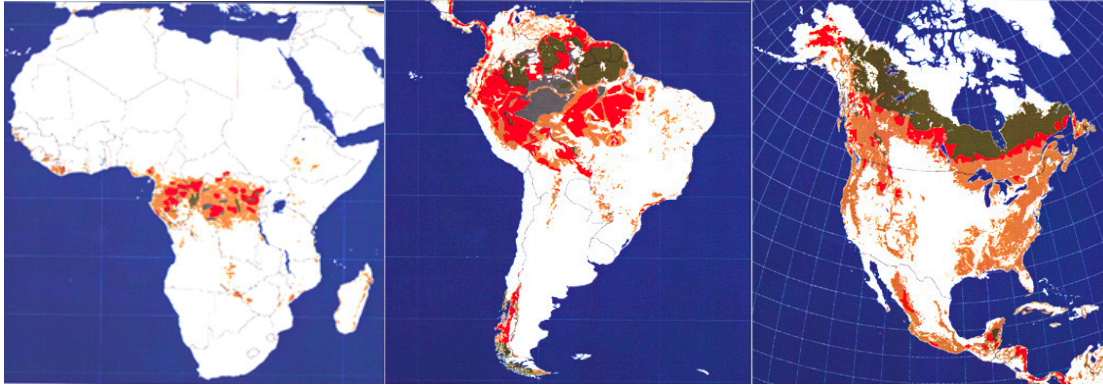
**Figure 8.3.** Biomes in a) Asia and b) Oceania.



**Figure 8.4.** Biomes in a) Africa, b) South America, and c) example of *tropical rainforest*, with lush, complex canopies.

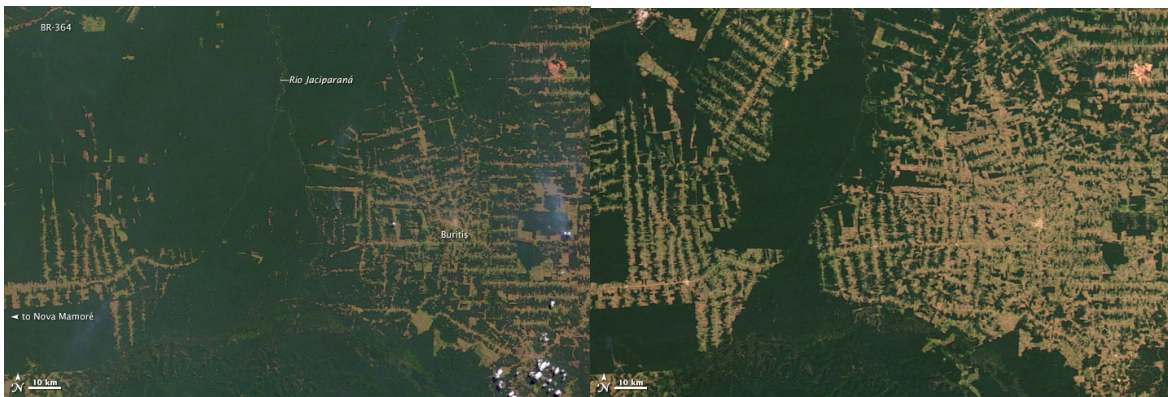
## 8.2. Deforestation

During the 1980s and 1990s the Amazon was being deforested at a rate of 10,000 – 30,000 km<sup>2</sup> per year. Figure 8.5 shows the current extent of areas with moderate to high threat by logging in Central Africa, South America, and North America. Note the extensive logging taking place along the southern edge of the boreal forest. Approximately 25-50% of the world's tropical rainforests have already been cut down.



**Figure 8.5.** Estimation of the threat to global forests by logging, with green indicating little threat and red indicating a moderate to high threat (World Resources Institute).

The characteristic “fishbone” pattern of deforestation in Rondonia, a region of south central Amazonia, is shown for the period 2000-2012 in Fig. 8.6. Roads and spur roads are built for colonizing homesteads and farms.



**Figure 8.6.** Changes in land cover over a part of Rondonia from July 30, 2000 (left) to July 18, 2012 (right) as seen by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on NASA’s Terra satellite. Intact forest is deep green, while cleared areas are tan (bare ground) or light green (crops, pasture, or occasionally, second-growth forest).

The 2015 United Nations Climate Change Conference, COP 21 or CMP 11 was held in Paris, France, from 30 November to 12 December 2015. It was the 21st yearly session of the Conference of the Parties (COP) to the 1992 United Nations Framework Convention on Climate Change (UNFCCC) and the 11th session of the Meeting of the Parties to the 1997 Kyoto Protocol. As part of the recent Paris climate treaty of 2015, Brazil has set a goal of cutting no more than 75% of their rainforest.

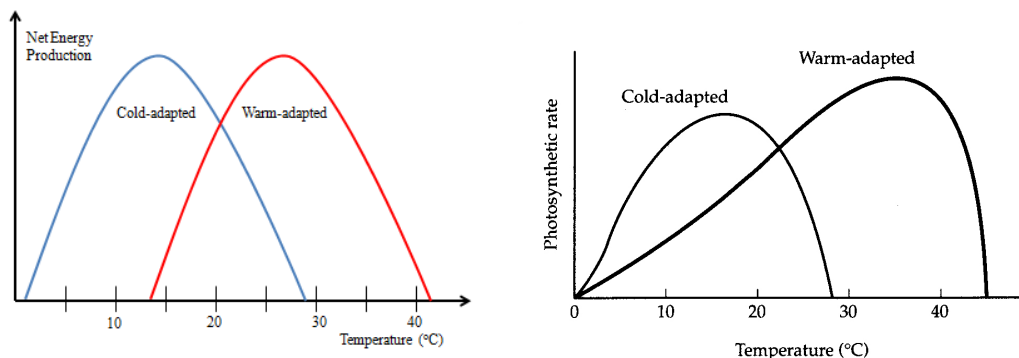
If one considers the role of forests in feedback to climate change, it is useful to distinguish the regional feedback of a boreal forest from that of a tropical rainforest. A reduced tropical rainforest will cause less evapotranspiration, few clouds, and heating of the soil, so deforestation of the rainforest will exacerbate regional warming. But a reduced boreal forest,

because winter is a major factor in the annual average at high latitudes, will trap less heat, so deforestation of the boreal forest would reduce regional warming.

## 8.2. Plant physiology

A plant's rate of photosynthesis increases with temperature until reaching an optimal range, then it drops off at higher temperatures (Fig. 8.7a). Some plants, such as the spruce tree of the boreal forest, are well-adapted to living in cold environments, while others, such as the lime tree, are adapted to living in warm environments (Gates, 1993). Each plant must produce more energy by photosynthesis than it uses in respiration in order to thrive. If net energy production gets too low the plant will fail. If it gets too cold photosynthesis becomes inefficient. If it gets too hot, plants use more energy than they produce and net energy production, so photosynthesis declines. Schematic diagrams of the net energy production for a typical cold-adapted and a typical warm-adapted plant are shown in Fig. 8.7.

A cold adapted plant might start photosynthesizing at 5°C, with maximum net energy production near 10-15°C, but becomes less and less efficient at higher temperatures (Fig. 8.7b). Temperate zone plants have optima between 15°C and 30°C. Warmer temperatures increase the growth rates of most plants if they are to the left of their peak and have enough water and nutrients. The radial growth rate of Scots pine increases by 50% when mean July temperatures increase from 14°C to 17°C (Cannell et al., 1989). A warm adapted plant might do best at temperatures near 35°C, but with a rapid decline above 40°C (Fig. 8.7b). Perhaps there is an interesting similarity with coral bleaching in that when temperatures get too high, the photosynthetic dinoflagellates are much less efficient, similar to the abrupt high temperature drop-off in Fig. 7b, so the coral animal expels the zooxanthellae.



**Figure 8.7.** Schematic diagrams of net energy production as a function of temperature for a cold-adapted plant (left) and a warm-adapted plant (right) (from Gates 1993).

Individual plants within a given species may vary somewhat with respect to their viable temperature range. Collectively, there is a probability distribution for a given species that corresponds to a temperature range for its viability. Since temperature decreases poleward and upward into the mountains, this implies that there is a preferred latitude and altitude range for each given species. A given plant can optimize their enzyme systems for shifts in temperature

of a few degrees, and tolerance varies among individuals in a population. Yet each community has its upper and lower limits and faces a challenge to migration from climate change.

One way to estimate the geographical range of a given species is in terms of its range in *growing-degree-days (GDD)*. For a given species there is a certain threshold temperature above which it will grow (and another threshold temperature above which it will not grow). If a daily average temperature exceeds the minimum threshold by 5°C then 5 GDD are accumulated for that day. A plant needs to accumulate a certain number of GDD during the growing season to survive the winter, and must accumulate a higher number of GDD to have progeny (Table 8.1). If the daily average temperature exceeds the upper threshold, then growth stops. This corresponds to an upper bound on accumulated GDD. For example, tundra plants typically need to accumulate 200-700 GDD during the growing season, but require 700-1600 to create seeds. Boreal forest spruce trees need to accumulate 600-1300 GDD. Lime trees require 2,000 GDD to bear fruit. Most tropical rainforest trees need more than 10,000 GDD (Table 8.1).

Physiognomy	Growing degree-days (GDD)	
	Reproductive	Vegetative
Broadleaved deciduous	2800–2100	2100–1700
Evergreen coniferous	2300–1500	1500–900
Deciduous coniferous	1900–1100	1100–700
Tundra	1600–700	700–200

(From Woodward, 1992.)

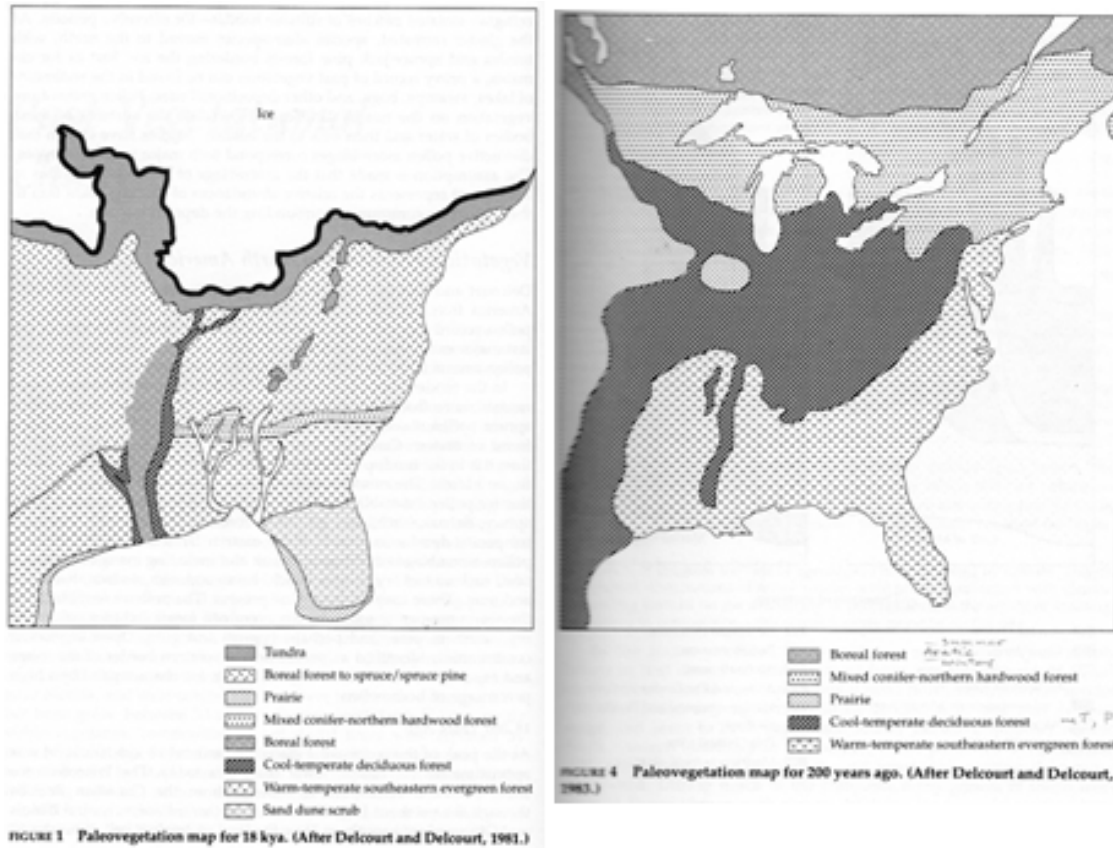
**Table 8.1.** Comparison of growing degree day (GDD) ranges for survival to the next year (vegetative) and the larger amounts needed for producing seeds (reproductive), for four different biomes (Gates, 1993).

The concept of GDD allows farmers to estimate when a crop is likely to need harvesting, as well as allowing scientists to diagnose present and future geographical ranges for species viability. We expect that, under a 4 K greenhouse warming scenario, the boreal forest will have to migrate northward at least 500 km, requiring a rate of more than 50 km/yr.

Other aspects of global warming are also relevant for plant growth and reproduction. Many plants require vernalization – sufficient winter chilling – in order to break dormancy at the most auspicious time in the spring. Warmer winters could interfere with this process. In addition, many plants require a large enough diurnal temperature range for seed germination to occur. But nights are getting warmer, reducing the temperature range. There is also the concern that warmer autumns may not induce enough cold hardening to prepare plants for a sudden arctic blast.

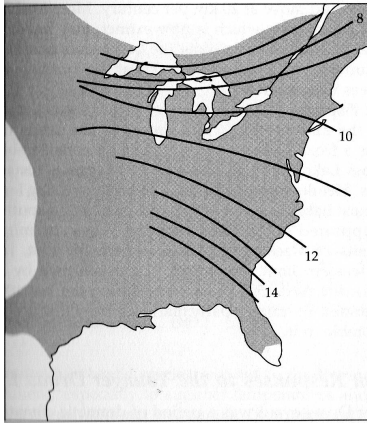
### 8.3. Plant migration

The distribution of biomes determined from pollen evidence is shown for 18 kybp and 200 ybp in Fig. 8.8. Note the presence of a broad swath of boreal forest across the central United States during the last glacial maximum, which is now confined to north of Lake superior. The temperate deciduous forest which now dominates the Ohio Valley region emerged from a refugium along the Mississippi valley. The warm temperate southeast woodland biome spread from Florida throughout the southeast.

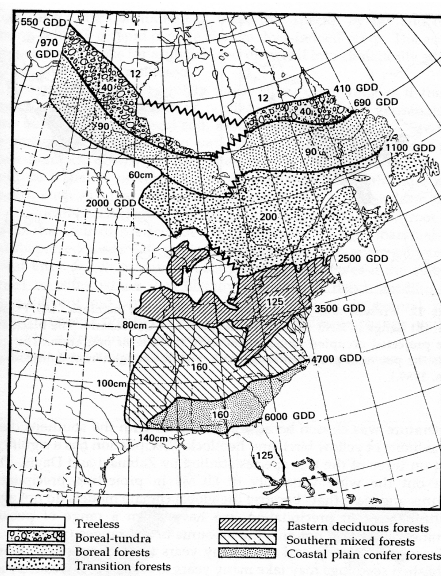
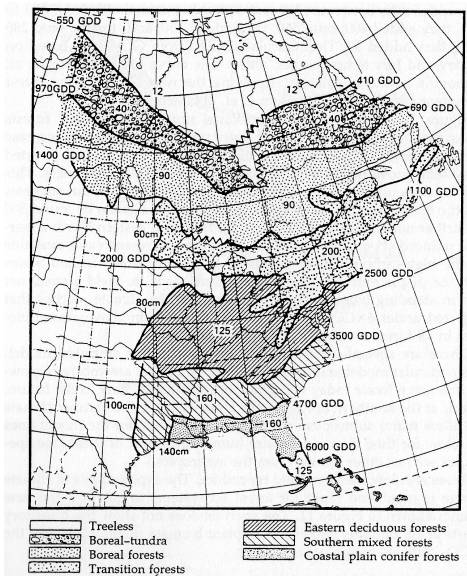
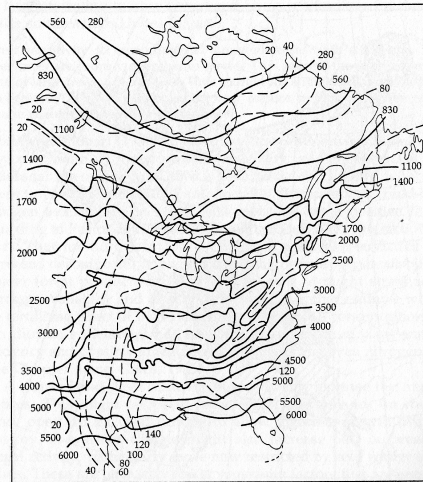
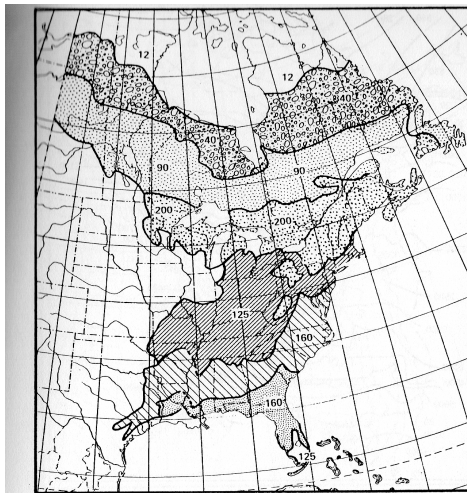


**Figure 8.8.** Comparison of biome distributions determined from pollen evidence for a) 18 kybp and b) 200 ybp (Gates 1993, after Delcourt and Delcourt 1991).

An example of isochrones of pollen occurrence for oak is shown in Fig. 8.9. These change in Figs. 8.8 and 8.9 are consistent with a migration rate of  $\sim 1000$  km / 20,000 yr, or  $\sim 50$  m/yr. The average rates of Holocene range extensions in eastern North America ranged from  $\sim 100$  to 400 m/yr. These rates are much less than the 50 km/yr expected under global warming during this century.



**Figure 8.9.** Oak migration since the Last Glacial Maximum as indicated by isochrones of appearance of oak pollen, in kybp.

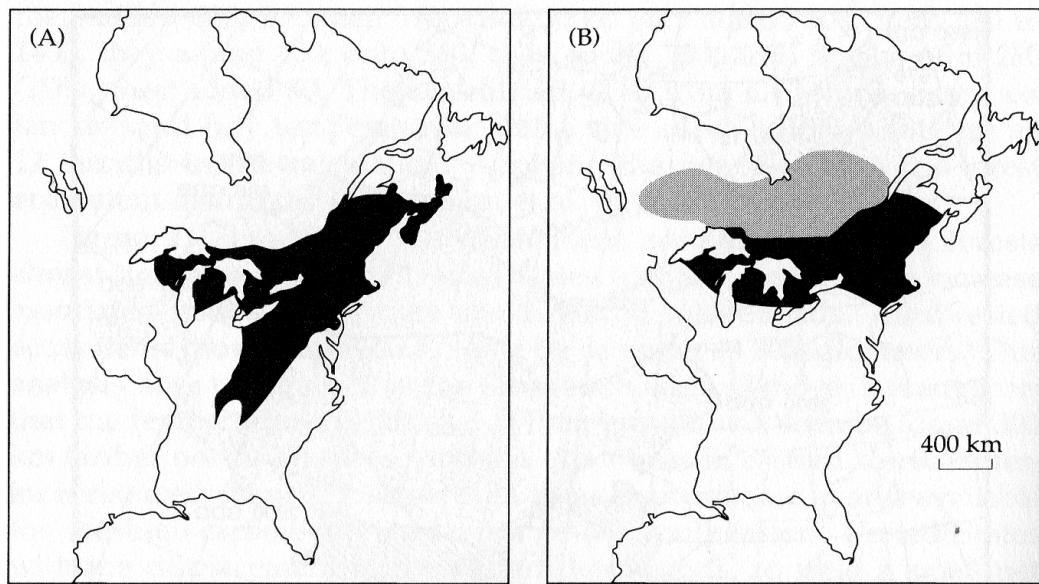


**Figure 8.10.** a) Present distribution of forest biomes in Eastern North America without human disturbance. The amount of standing biomass ( $10^3$  kg per hectare) in each region is indicated. b) Present distribution of growing-degree-days (GDD, solid contours) and annual precipitation (cm, dashed contours). The GDD contours, or isotherms, closely approximate the boundaries in



a). c) Potential forest biomes determined by GDD and precipitation for the present. d) Future potential forest biomes determined by GDD and precipitation for a 2xCO<sub>2</sub> scenario (Gates 1993, after Solomon et al., 1984).

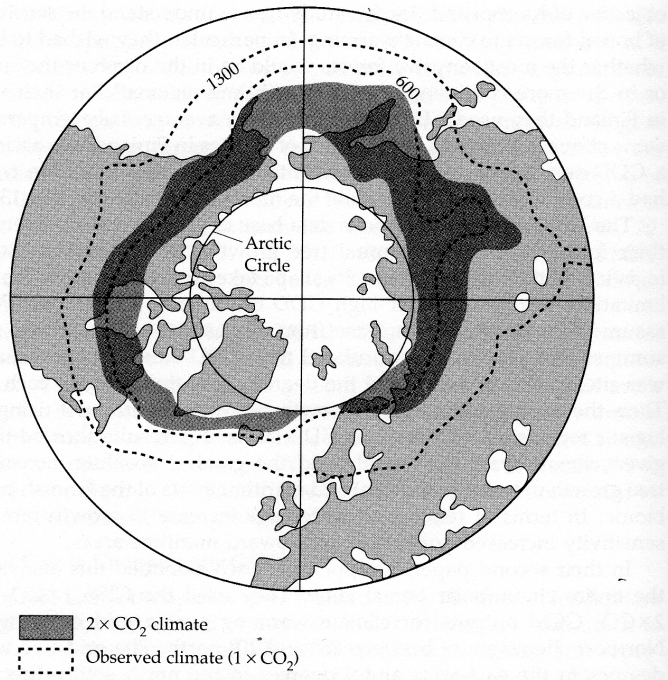
The distribution of present natural biomes in Eastern North America is shown in Fig. 8.10a. Fig. 8.10b shows the distribution of GDD, based on average isotherms, together with annual rainfall for the present climate. The GDD map is then used to generate a map of current biomes (Fig. 8.10c). It can be seen that the observed distribution of biomes agrees quite well with biomes generated from the GDD distribution. This supports the idea of using temperature maps from climate forecasts to make an educated guess regarding the likely future range for a given biome. Fig. 8.10d shows the distribution of biomes under a 2xCO<sub>2</sub> scenario. Note the significant poleward shift in biomes relative to Fig. 8.10a.



**Figure 8.11.** a) Present and b) future ranges for hemlock in 2090 under the GISS 2xCO<sub>2</sub> scenario. In b) the black area shows where hemlock is likely to be able to migrate, while gray shows where they could live but might not be able to migrate into (Gates 1993, after Zabinski and Davis, 1989).

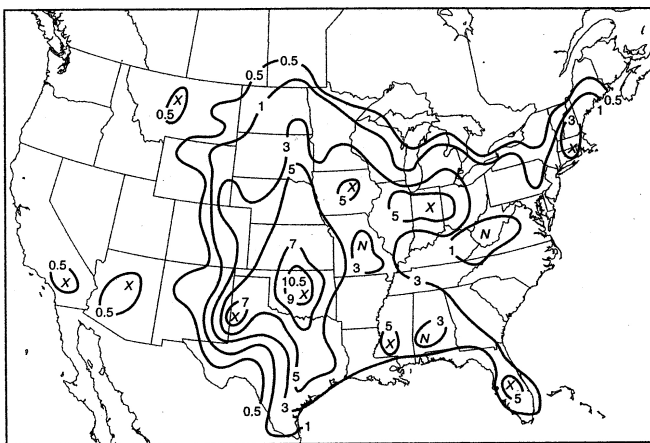
Using the same technique, the present and future distributions of each species can be mapped. The example of hemlock is shown in Figure 8.11. A comparison of estimated hemlock migration rates with anticipated latitudinal biome shifts suggests that the plant may not be able to migrate fast enough to keep up with climate change. Under global warming, plants may die off on the southern edge of a pre-existing biome and not be able to colonize at the leading edge of the new comfort zone efficiently. Of course, other plants are already growing in the target migration region, which may make it more challenging for migration.

The boreal forest biome shift is shown in Fig. 8.12. It may be compared with the current map of deforestation (Fig. 8.5c). It appears that logging is helping the boreal forest's southern edge migrate poleward. Given the 50 years required to maturity for reproduction in spruce trees, it seems challenging for the boreal forest's northern edge to migrate 50 km/yr.



**Figure 8.12.** Northern and southern boundaries of the boreal forest as defined by the 600 and 1300 GDD contours, for their current locations (dashed) and where they could exist under a  $2xCO_2$  warming scenario (black) (Gates 1993, after Kauppi and Posch 1988).

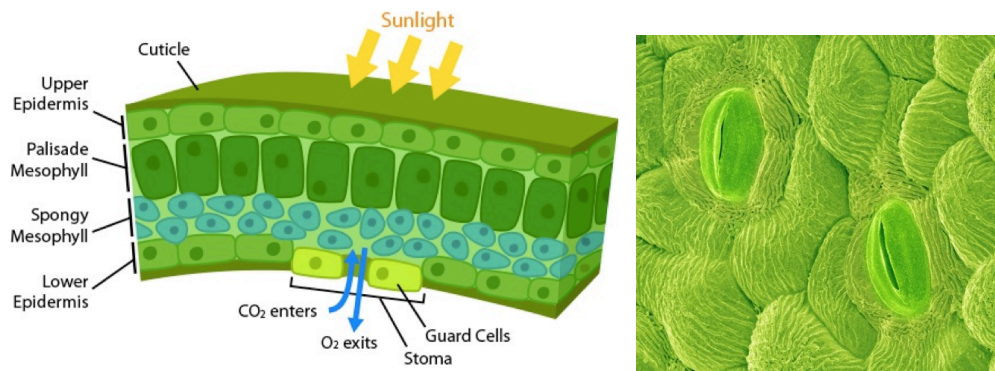
Other limitations to migration include the presence of roads, buildings, and farmland. What could aid migration rates? Squirrels can. People can. Perhaps on a century time scale tornados can facilitate seed dispersal. A map of tornado occurrence (Fig. 8.13) shows that, during 100 years, tornadoes are fairly likely to tear up a given patch of vegetation and spread seeds downwind. The cartoon in Fig. 8.13b suggests a possible conversation between “man” and “nature” where the assertion of power from the knowledge about the genome is countered with a reminder from Mr. Squirrel that we don’t yet know all that much about tornados, let alone mother nature.



**Figure 8.13.** a) The frequency of tornadoes defined by the number per year within a 91-km radius, for the period 1950-1979 (X = maximum, N = minimum; National Climatic Data Center). b) Imagined dialogue between Francis Crick, who has the power of the knowledge of DNA, and a scolding squirrel who reminds us that we don't know all there is to know about tornadoes yet.

#### 8.4. “CO<sub>2</sub> fertilization”, ozone, and the future

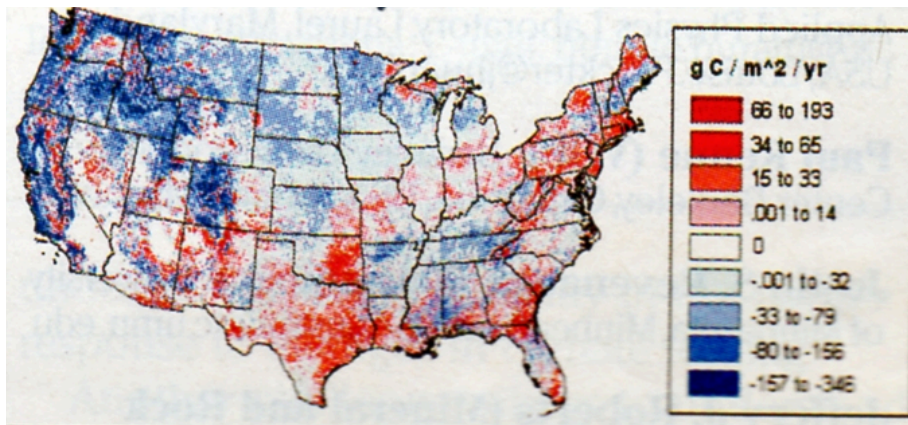
Plants in midlatitudes have distinctive metabolic pathways which are sensitive to atmospheric CO<sub>2</sub> concentration. Temperate plants are “C<sub>3</sub>” plants, which assimilate CO<sub>2</sub> into a 3-carbon chemical compound. The efficiency of photosynthesis can be improved by up to 50% by doubling the ambient amount of CO<sub>2</sub>. This is called “*carbon dioxide fertilization*”.



**Figure 8.14.** Carbon dioxide enters plants through stomata for use in photosynthesis, while O<sub>2</sub> exits (www). Increased atmospheric concentration of CO<sub>2</sub> can increase net photosynthesis for extratropical plants.

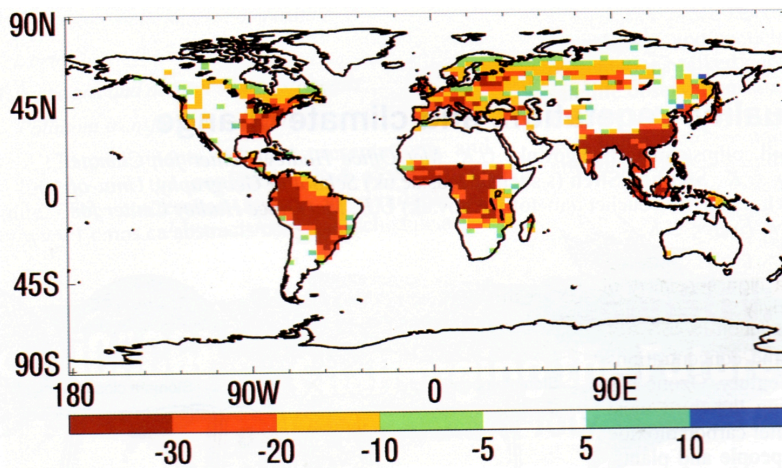
Figure 8.14 shows how gases are exchanged with the atmosphere – CO<sub>2</sub> comes in and O<sub>2</sub> and H<sub>2</sub>O go out through their stomata. If a plant is exposed to 2xCO<sub>2</sub> then it becomes ~50% more efficient at photosynthesis. The response to increased CO<sub>2</sub> is most pronounced under high levels of nutrients, water, and light (Bazzaz 1990).

Figure 8.15 shows where standing biomass has increased due to afforestation (red) and decreased due to logging (blue) during 1982-1997. Parts of New England are becoming afforested as old farmland returns to forests and shrubberier suburbs. Some of this increase may be due to carbon dioxide fertilization, and to more efficient photosynthesis at warmer temperatures. Much of the Southeast, Upper Midwest, and most of the West shows deforestation due to logging. Since forests help keep the air moist, deforestation of the west is likely to exacerbate problems associated with future warming and drying of the region. We will return to this topic in discussing the carbon cycle in Chapter 9.



**Figure 8.15.** Net ecosystem production in grams C per m<sup>2</sup> per year, as determined by the sum of observed carbon fluxes during 1982-1997, with gains from the atmosphere (afforestation) shown in red and losses to the atmosphere (deforestation) shown in blue (EoS transactions).

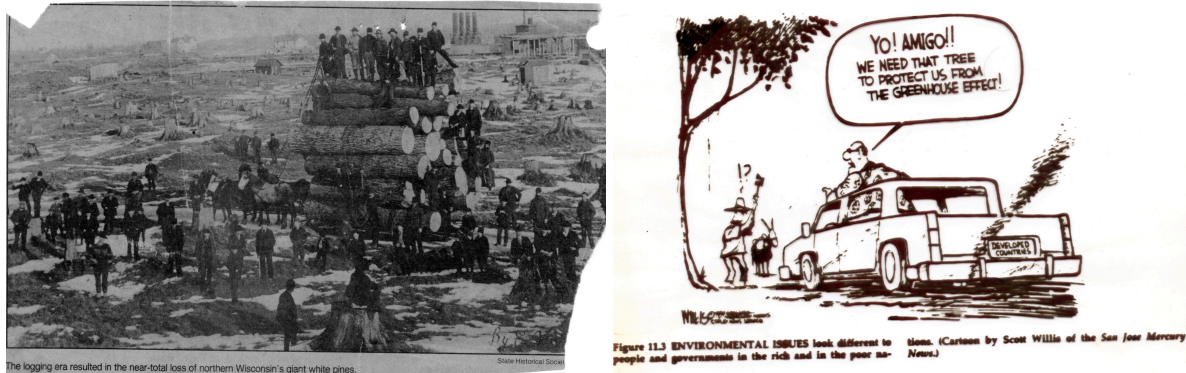
In addition to CO<sub>2</sub> affecting plant growth, other compounds in the air, such as acid rain and ozone, can affect vegetation. Although acid rain is moderating in most parts of the world, it is anticipated that the future increase in burning fossil fuel will cause a continued increase in tropospheric ozone. In polluted regions, ozone can enter the stomata (Fig. 8.14) and cause internal cellular damage as well as damage to the surface of the leaves. Some coupled climate models with a biosphere module suggest that increases in tropospheric ozone will cause a decrease in NPP by 20-30% in the tropical rainforests and other significant parts of the globe (Fig. 8.16).



**Figure 8.16.** The percent difference in the Net Primary Productivity of terrestrial vegetation for simulated ozone levels in the year 2100 minus NPP for ozone levels in the year 1900. Future ozone levels were based on a scenario without further air quality legislation (SRES A2) (NCAR Newsletter).

As the world proceeds into the future, with countries striving to come to grips with how best to cope with deforestation, it is important to remember that we've cut most of our old-

growth forests down already (Fig. 8.17a). This would seem to deflate the moral component behind pressuring tropical countries to save their rainforests. But the main aspect to keep in mind is that fossil fuel burning by industrialized countries contributes ~10 times more to atmospheric CO<sub>2</sub> increases than deforestation, so we need to keep a reasonable perspective about our responsibility.



**Figure 8.17.** a) The U.S. deforested much of its original forests (Northern Wisconsin in the late 1800s, Wisconsin State Historical Society). b) In addition to already having deforested much of North America, the amount of CO<sub>2</sub> from fossil fuel usage in the extratropics is an order of magnitude larger than that which results from deforestation of tropical rainforests.

## Key words

*Biomes*

*evapotranspiration*

*CO<sub>2</sub> fertilization*

*growing degree day (GDD)*

*net primary productivity (NPP)*

## References Cited

- Bazzaz (1990)  
 Cannell et al., 1989  
 Delcourt and Delcourt 1991  
 EoS transactions  
 Gates, D. M., 1993: *Climate Change and its Biological Consequences*. Sinauer Assoc., Inc., Sunderland, MA, 280 pp.  
 International Institute for Sustainable Development, 2015: "19th Session of the Conference of the Parties to the UNFCCC".  
 Kauppi and Posch 1988  
 NCAR newsletter  
 Solomon et al. 1984  
 World Resources Institute  
 Zabinski and Davis, 1989