

1 **3 Land Resources**

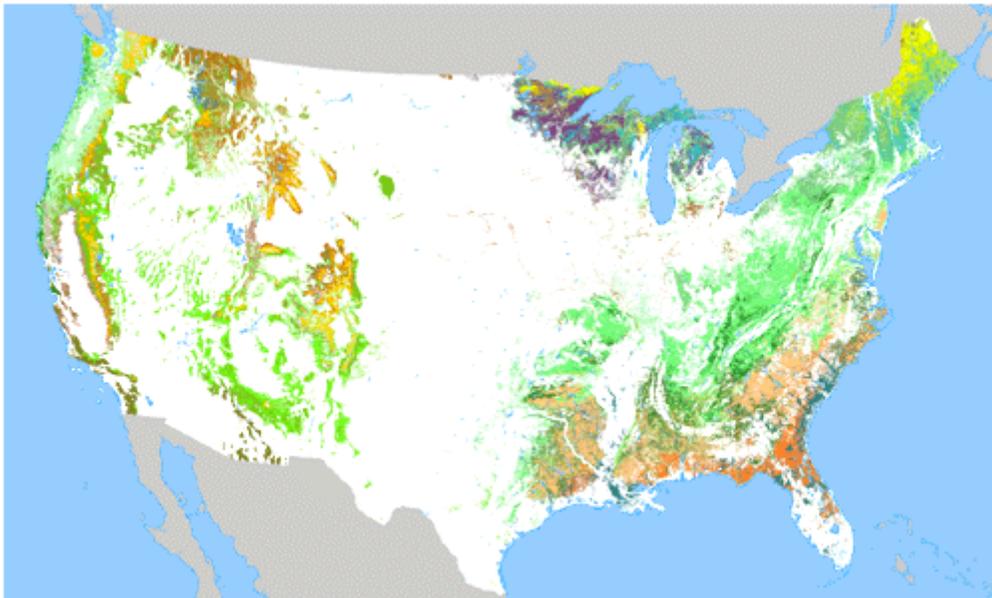
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MG Ryan, SR Archer, RA Birdsey, CN Dahm, LS Heath, JA Hicke, DY Hollinger,
TE Huxman, GS Okin, R Oren, JT Randerson, WH Schlesinger

6 **3.1 The effects of climate change on land resources**

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Forests are found in all 50 states but are most common in the humid eastern U.S., the west coast, at higher elevations in the interior west and southwest, and along riparian corridors in the plains states (Figure 3.1) (Zhu and Evans, 1994). Forested land occupies about 740 million acres, or about one-third of the United States. Forests in the eastern U.S. cover 380 million acres – 74 percent are broadleaf forests – with most of the land, 83 percent, privately owned. The 360 million acres of forest land in the western U.S. are mostly conifer forests (78 percent), and split between public (57 percent), and private ownership (nationalatlas.gov/articles/biology/a_forest.html).



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Figure 3.1 Distribution of forest lands in the continental U.S. by forest type. This map was derived from Advanced Very High Resolution Radiometer (AVHRR) composite images recorded during the 1991 growing season. Each composite covered the United States at a resolution of one kilometer. Field data collected by the Forest Service were used to aid classification of AVHRR composites into forest-cover types. Details on development of the forest cover types dataset are in Zhu and Evans (1994).

Forests provide many ecosystem services that are important to the wellbeing of the United States: watershed protection, water quality, and flow regulation; wildlife habitat and diversity, recreational opportunities, and aesthetic and spiritual fulfillment; raw material for wood and paper products; climate regulation, carbon storage, and air quality; biodiversity conservation. While not all of these services have easily quantified market values, all services have considerable economic value (Costanza et al. 1997; Daily et al. 2000; Krieger 2001; Millennium-Ecosystem-Assessment 2005), and Americans are strongly attached to their forests. A changing climate will alter forests and the services they provide – sometimes changes will be viewed as beneficial, but often they will be viewed as detrimental.

Arid lands are defined by low, and highly variable precipitation, and are found in the United States in the subtropical hot deserts of the Southwest and the temperate cold deserts of the Intermountain West (Figure 3.2). Arid lands provide many of the same ecosystem services as forests (with the exception of raw materials for wood and paper products), and support a large ranching industry. These diverse environments are also valued for their wildlife habitat, and plant and animal diversity, their regulation of water flow and quality, their opportunities for outdoor recreation, and their open spaces for expanding urban environments. A changing climate will alter arid lands and their services. Compared with forests, arid lands face additional challenges related to changing climate: the legacy of historical land use and the sensitivity of arid lands to future land use; the widespread presence and success of exotic invasive species in changing arid ecosystems and their disturbance patterns (especially fire); and the very slow growth of many of the species that hinders recovery from disturbance.

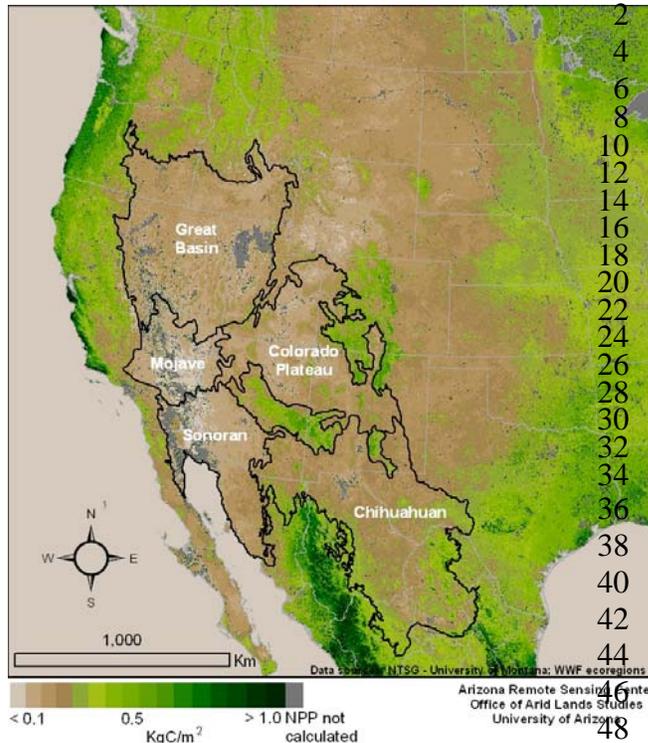


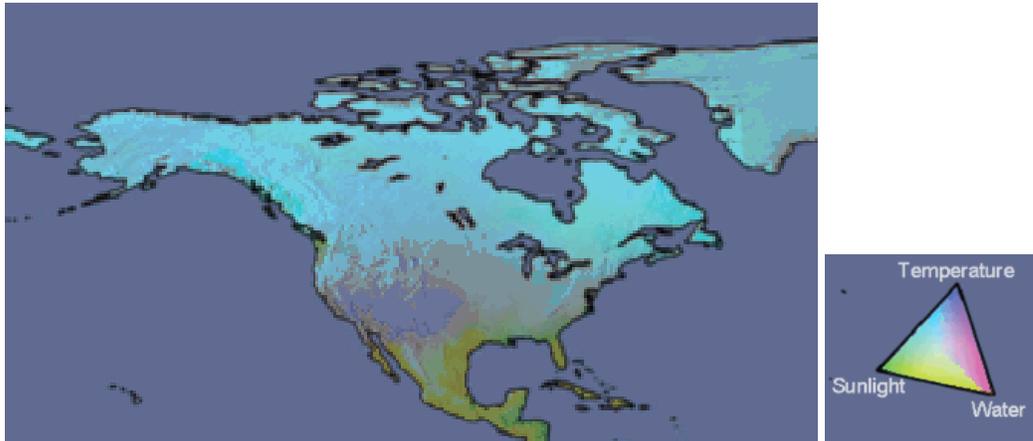
Figure 3.2 The five major North American deserts, outlined on a 2006 map of net primary productivity (NPP). Modeled NPP was produced by the Numerical Terradynamic Simulation Group (<http://www.ntsug.umt.edu/>) using the fraction of absorbed photosynthetically active radiation measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite and land cover-based radiation use efficiency estimates Running et al. (2000). Desert boundaries based on Olson et al. (2001).

Climate strongly influences both forests and arid lands. Climate shapes the broad patterns of ecological communities, the species within them, their productivity, and the ecosystem goods and services they provide – the interaction of

49 vegetation and climate is a fundamental tenet of ecology. Many studies show how
 50 vegetation has changed with climate over the past several thousand years, so we know
 51 that changes in climate will change vegetation. Given a certain climate and long enough
 52 time, we can generally predict the ecological communities that will result. However,
 53 predicting the effects of a changing climate on forests and arid lands for the next few
 54 decades is challenging, especially with regard to the rates and dynamics of change. Plants
 55 in these communities can be long-lived; hence, changes in species composition may lag
 56 behind changes in climate. Furthermore, seeds and conditions for better-adapted
 57 communities are not always present.

58
 59 Past studies linking climate and vegetation may also provide poor future predictions
 60 because the same physical climate may not occur in the future, and because many factors
 61 other than the physical climate may be changing as well. CO₂ is increasing in the
 62 atmosphere, nitrogen deposition is much larger than in the past, and appears to be
 63 increasing, ozone pollution is locally increasing, and species invasions from other
 64 ecosystems are widespread. These factors cause important changes themselves, but their
 65 interactions are difficult to predict. This is particularly so because these interactions
 66 represent novel combinations beyond our experience base.

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Figure 3.3 Potential limits to vegetation net primary production based on fundamental physiological limits by sunlight, water balance, and temperature. From Boisvenue and Running (2006).

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Disturbance (such as drought, storms, insect outbreaks, and fire) is part of the ecological history of most ecosystems, and influences ecological communities and landscapes.

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Climate affects the timing, magnitude, and frequency of many of these disturbances, and a changing climate will bring changes in disturbances to forests and arid lands (Dale et al.

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2001). Trees and arid land vegetation can take from decades to centuries to re-establish after a disturbance. Therefore, changes in disturbance regimes caused by climate-change

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can affect land resources (Dale et al. 2001). Both human-induced and natural

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disturbances shape ecosystems by influencing species composition, structure, and

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function (such as productivity, water yield, erosion, carbon storage, and susceptibility to future disturbance). In forests, more than 55 million acres are currently impacted by

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disturbance, with the largest being insects and pathogens (Dale et al. 2001). These

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disturbances cause an estimated economic loss of 3.7 billion dollars (Dale et al. 2001). In

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the past several years, scientists have learned that the magnitude and impact of these

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disturbances and their response to climate rivals that expected from changes in

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temperature and precipitation (Dale et al. 2001).

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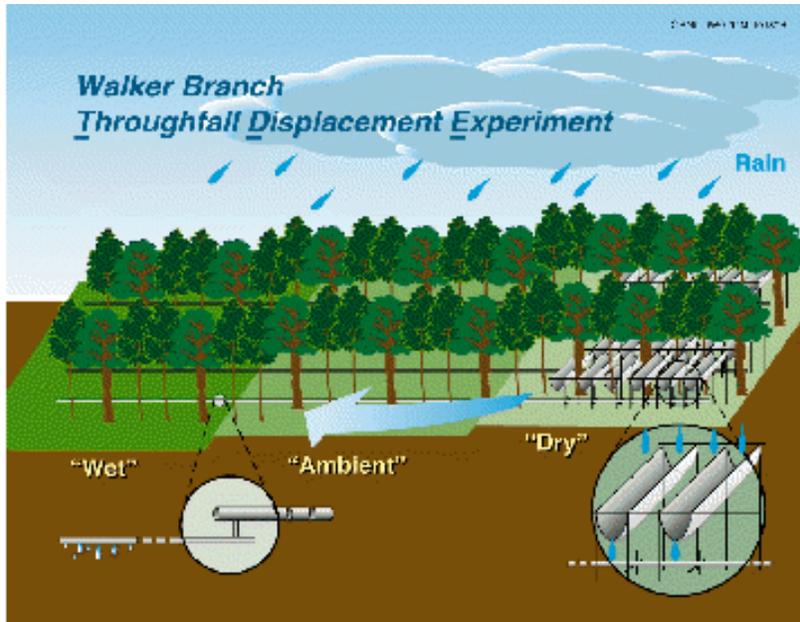
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3 **Figure 3.4** Aerial view of extensive attack by mountain pine beetle in lodgepole pine forests in British
4 Columbia. Photo by Lorraine Maclauchlan, Ministry of Forests, Southern Interior Forest Region.
5 (http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/bbphotos.htm)
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7 Disturbance may reset and rejuvenate some ecosystems in some cases; and, cause
8 enduring change in others. For example, climate may favor the spread of invasive exotic
9 grasses into arid lands where the native vegetation is too sparse to carry a fire. When
10 these areas burn, they typically convert to non-native monocultures and the native
11 vegetation is lost. In another example, drought may weaken trees and make them
12 susceptible to insect attack and death – a pattern that recently occurred in the Southwest.
13 In these forests, drought and insects converted large areas of mixed pinyon-juniper
14 forests into juniper forests. However, fire is an integral component of many forest
15 ecosystems, and many forests (such as the lodgepole pine forests that burned in the
16 Yellowstone fires of 1988) depend on fire to regenerate many species. So, climate effects
17 on disturbance will likely shape future forests and arid lands as much as the effects of
18 climate itself.
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20 Disturbances and changes to the frequency or type of disturbance present challenges to
21 resource managers. Many disturbances command quick action, public attention, and
22 resources. Surprisingly, most resource planning in the United States does not consider
23 disturbance, even though disturbances are common, and preliminary information exists
24 on the frequency and areal extent of disturbances (Dale et al. 2001). Disturbances in the
25 future may be larger and more common than those experienced historically, and planning
26 for disturbances should be encouraged (Dale et al. 2001; Stanturf et al. 2007).
27

28 Current trends in climate that affect forests and arid lands show that the United States has
29 warmed in Alaska, the Interior West and Southwest, and in the Northern states. The

1 Southeast has cooled. Over the past hundred years, precipitation has declined in the
2 Interior West, the Southwest, and the eastern portions of the Southeast (Figs. 1.5 and 1.6).
3 Climate models project that these trends will continue.
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Figure 3.5 Direct manipulation of precipitation in the Throughfall Displacement experiment at Walker Branch (Oak Ridge National Laboratory).



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Figure 3.6 FACE ring at the Rhinlander FACE facility, Rhinlander, WI.

Our goal in this chapter is to predict how forests and arid lands will respond to predicted changes in climate over the next few decades. We will discuss the effects of climate and its components on the structure and function of forest and arid land ecosystems. We will

1 also highlight the effects of climate on disturbance and how these disturbances change
2 ecosystems.

3.2 *Brief Summary of Key Points from the Literature*

3.2.1 Forests

Climate strongly affects forest productivity and species composition. Forest productivity in the United States has increased two to eight percent in the past two decades, but separating the role of climate from other factors causing the increase is complicated and varies by location. Some factors that act to increase forest growth are observed greater precipitation in the Midwest and Lake States, observed increases in nitrogen deposition, an observed increase in temperature in the Northern U.S. that lengthens the growing season, changing age structure of forests, and management practices. These factors interact, and identifying the specific cause of a productivity change is complicated by insufficient data. Even in the case of large forest mortality events, such as fire and insect outbreaks, attributing a specific event to climate or a change in climate may be difficult because of interactions among factors. For example, in the widespread mortality of pinyon pine in the Southwest, intense drought weakened the trees, but generally, the Ips beetle killed them.

In addition to the direct effects of climate on tree growth, climate also affects the frequency and intensity of natural disturbances such as fire, insect outbreaks, ice storms, and windstorms. These disturbances have important consequences for timber production, water yield, carbon storage, species composition, invasive species, and public perception of forest management. Disturbances also draw management attention and resources. Because of observed warmer and drier climate in the West in the past two decades, forest fires have grown larger and more frequent during that period. Several large insect outbreaks have recently occurred or are occurring in the United States. Increased temperature and drought likely influenced these outbreaks, but other factors, such as a more uniform forest age structure, which is a legacy of logging, or climate-induced fires in the late 1800s and early 1900s, or fire suppression since, may also play a role.

Atmospheric CO₂ elevated to 550 parts per million toward the end of this century will increase forest productivity and carbon storage in forests, with the carbon primarily being stored in live trees. Average productivity increase for a variety of experiments was 23 percent. The response of tree growth and carbon storage to elevated CO₂ depends on site fertility, water availability, and perhaps stand age, with fertile, younger stands responding more strongly.

Forest inventories can detect long-term changes in forest growth and species composition, but they have limited ability to attribute changes to specific factors, including climate. Combining forest inventories with experimental data, remote sensing, and models is a promising new approach. Monitoring of disturbances affecting forests is

1 currently ineffective, fragmented, and generally unable to attribute disturbances to
2 specific factors, including climate.

3 **3.2.2 Arid Lands**

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5 Plants and animals in arid lands live near their physiological limits, so slight changes in
6 temperature and precipitation will substantially alter the composition, distribution, and
7 abundance of species, and the products and services that arid lands provide. Observed
8 and projected decreases in the frequency of freezing temperatures, lengthening of the
9 frost-free season, and increased minimum temperatures will alter plant species ranges and
10 shift geographic and elevational boundaries of the Great Basin, Mojave, Sonoran, and
11 Chihuahuan Deserts. The extent of these changes will also depend on changes in
12 precipitation and fire. Increased drought frequency will put arid systems at risk for major
13 changes in vegetation cover. Losses of vegetative cover coupled with increases in
14 precipitation intensity and climate-induced reductions in soil aggregate stability will
15 dramatically increase potential erosion rates. Transport of eroded sediment to streams
16 coupled with changes in the timing and magnitude of minimum and maximum flows will
17 affect water quality, riparian vegetation and aquatic fauna. Wind erosion will have
18 continental-scale impacts on downwind ecosystems, air quality, and human populations.

19

20 The response of arid lands to climate change will be strongly influenced by interactions
21 with non-climatic factors at local scales. Climate effects should be viewed in the context
22 of these other factors, and simple generalizations should be viewed with caution. Climate
23 will strongly influence the impact of land use on ecosystems and how ecosystems
24 respond. Grazing has traditionally been the most extensive land use in arid regions.
25 However, land use has significantly shifted to exurban development and recreation since
26 1950. Arid land response to climate will thus be influenced by new environmental
27 pressures related to air pollution and N-deposition, motorized off-road vehicles, feral
28 pets, and horticultural invasives, in addition to grazing.

29

30 Emissions of VOC gases by plants have increased because of the displacement of native
31 grasslands by desert shrubs. However, the implications for tropospheric ozone and
32 aerosol production are not yet known. Non-native plant invasions will likely have a major
33 impact on future VOC emissions and how arid land ecosystems respond to climate and
34 climate change. Exotic grasses generate large fuel loads that predispose arid lands to
35 more frequent and intense fire than historically occurred. Such fires can radically
36 transform diverse desert scrub, shrub-steppe, and desert grassland/savanna ecosystems
37 into monocultures of non-native grasses. This process is well underway in the Cold
38 Desert region, and is in its early stages in Hot Deserts. Because of their profound impact
39 on the fire regime and hydrology, invasive plants in arid lands may trump direct climate
40 impacts on native vegetation.

41

42 Given the concomitant changes in climate, atmospheric CO₂, nitrogen deposition, and
43 species invasions, novel wildland and managed ecosystems will likely develop. In novel
44 ecosystems, species occur in combinations, and relative abundances that have not

1 occurred previously in a given biome. In turn, novel ecosystems present novel challenges
2 for conservation and management.

3 **3.3 Summary of Findings and Conclusions**

4 **3.3.1 Forests**

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6 A changing climate will very likely change forest productivity. Current and projected
7 changes in temperature and precipitation are likely to lower forest productivity in the
8 Interior West, the Southwest, eastern portions of the Southeast, and Alaska, and increase
9 forest productivity in the Northeastern U.S., the Lake States, and in western portions of
10 the Southeast. However, projected increases in hurricanes and ice storms will likely act to
11 lower productivity in the Southeast and Northeast, and exacerbate or offset changes
12 caused by temperature and precipitation.

13
14 Temperature increases have lengthened, and will continue to lengthen, the growing
15 season, and will very likely yield warmer winters, particularly in Alaska, the West, and
16 northern continental United States. These temperature increases will likely lead to larger,
17 more frequent forest fires in the western U.S., and possibly for portions of the East as
18 well. Where increased temperatures and forests coincide, the range and frequency of
19 large insect outbreaks will likely increase. More disturbances in the future will likely
20 lower carbon storage in forests in the coming decades, counteracting the projected effect
21 of increasing CO₂.

22
23 Elevated CO₂ will very likely increase forest photosynthesis, but the response to CO₂ will
24 be lower for infertile forests and perhaps for older forests. Nitrogen deposition (most
25 prominent in the eastern U.S.) will very likely increase forest productivity and the
26 response of forest growth to the rise in atmospheric CO₂. The interactions of elevated
27 CO₂, temperature, precipitation, ozone pollution, and nitrogen deposition are likely to be
28 important in determining forest growth and species composition, but the net result of
29 these interactions is poorly understood.

30 **3.3.2 Arid Lands**

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32 U.S. deserts will likely expand to the north, east, and upward in elevation in response to
33 changing temperatures. Simultaneously, arid lands may contract in their southern borders.
34 Higher temperatures predicted to co-occur with more severe drought portend increased
35 mortality for the dominant woody vegetation typical of North American deserts and will
36 encourage establishment of exotic annual grasses. Proliferation of exotic grasses will
37 predispose sites to more frequent and more intense fires that kill native woody plants and
38 charismatic flora, such as Saguaro cactus. The interaction of climate, fire, and invasive
39 grasses will likely determine the future plant distribution in U.S. arid lands.

40
41 Water strongly limits plant productivity in arid lands, and projected reductions in
42 precipitation will very likely lower productivity and carbon storage. Even though annual
43 carbon storage per unit area is low in arid lands, their large extent yields a considerable

1 contribution to global carbon storage. The risk of loss of carbon from these ecosystems is
2 high; greatest losses will likely be associated with desertification processes and annual
3 plant invasions. Arid land soils are often deficient in nitrogen, so expected erosional
4 losses of soil nitrogen will further restrict productivity. Nitrogen losses possibly will be
5 partially offset by greater nitrogen deposition. Emissions of VOC gases by plants will be
6 elevated by higher temperatures and greater water stress, but displacement of high-
7 emitting shrubs by low-emitting non-native grasses may counteract this.

8
9 Floods and droughts that structure arid riverine corridors are likely to increase in number
10 and intensity. The net result of climate warming will be greater depletion of water along
11 riverine corridors. The balance of competition between native and non-native species in
12 riparian zones will continue to shift in favor of non-native species as temperatures
13 increase, as the timing and amount of precipitation shifts, and as the intensity of
14 disturbances is magnified.

15
16 Higher temperatures and decreased soil moisture will likely reduce the stability of soil
17 aggregates, making the surface more erodible. Climate change will likely further increase
18 erosion by reducing vegetation cover. Increases in precipitation intensity and the
19 proportion of precipitation delivered in high-intensity storms will likely accelerate water
20 erosion from uplands and delivery of nutrient-rich sediment to riparian areas. Increases in
21 wind speed and gustiness will likely increase wind erosion, dust emission, and transport
22 of nutrient-rich dust to downwind ecosystems, causing more rapid spring melt and shorter
23 availability of snowmelt for human use.

24 **3.3.3 Observing Systems**

25
26 Current observing systems can detect changes in growth and species composition in
27 forests and in some arid lands, but are inadequate to separate the effects of changes in
28 climate from other effects. There are few observing systems for monitoring wind and
29 water erosion, and for examining interactions among climatic and non-climatic drivers.
30 To identify climate effects would require a broad network, with many indicators, coupled
31 with a network of controlled experimental manipulations. A coordinated national network
32 that monitors ecosystem disturbance and recovery would greatly contribute to attributing
33 disturbances to a particular cause, and identifying the consequences of those
34 disturbances. However, no such network currently exists. Time-series of satellite
35 observations can identify disturbance, changes in productivity, and changes in land use.
36 Lack of assured continuity for satellite observations may jeopardize these observations in
37 the future.

39 **3.4 Observed Changes or Trends - Forests**

40 **3.4.1 Climate and Ecosystem Context**

41
42 Anyone traveling from the lowlands to the mountains will notice that species composition
43 changes with elevation and with it, the structure and function of these forest ecosystems.

1 Biogeographers have mapped these different vegetation zones and linked them with their
2 characteristic climates. The challenge facing scientists now is to understand how these
3 zones and the individual species within them will move with a changing climate, at what
4 rate, and with what effects on ecosystem function.

5
6 Temperature, water, and radiation are the primary abiotic factors that affect forest
7 productivity (Figure 3.3). Any response to changing climate will depend on the factors
8 that limit production at a particular site. For example, any site where productivity is
9 currently limited by lack of water or a short growing season will increase productivity if
10 precipitation increases and if the growing season lengthens. Temperature controls the rate
11 of metabolic processes for photosynthesis, respiration, and growth. Generally, plant
12 metabolism has an optimum temperature. Small departures from this optimum usually do
13 not change metabolism and short-term productivity, although changes in growing season
14 length may change annual productivity. Large departures and extreme events (such as
15 frosts in orange groves) can cause damage or tree mortality. Water controls cell division
16 and expansion (which promote growth), and stomatal opening, which regulates water loss
17 and CO₂ uptake in photosynthesis. Productivity will generally increase with water
18 availability in water-limited forests (Knapp et al. 2002). Radiation supplies the energy for
19 photosynthesis, and both the amount of leaf area and incident radiation control the
20 quantity of radiation absorbed by a forest. Nutrition and atmospheric CO₂ also strongly
21 influence forest productivity if other factors are less limiting (Boisvenue and Running
22 2006), and ozone exposure can lower productivity (Hanson et al. 2005). Human activities
23 have increased nitrogen inputs to forest ecosystems, atmospheric CO₂ concentration, and
24 ozone levels. The effects of CO₂ are everywhere, but ozone and N deposition are
25 common to urban areas, and forests and arid lands downwind from urban areas. The
26 response to changes in any of these factors is likely to be complex and dependent on the
27 other factors.

28
29 Forest trees are evolutionarily adapted to thrive in certain climates. Other factors, such as
30 fire and competition from other plants, also regulate species presence, but if climate alone
31 changes enough, species will move to suitable conditions or go locally extinct if suitable
32 conditions are unavailable (Woodward, 1987). One example of such a species shift is
33 sugar maple in the northeastern U.S. – suitable climate for it may move northward into
34 Canada and the distribution will likely follow (Chuine and Beaubien 2001), assuming the
35 species is able to disperse propagules rapidly enough to keep pace with the shifting
36 climatic zone. Because trees live for decades and centuries, it is likely that forest species
37 composition will take time to adjust to changes in climate.

38
39 Disturbances such as forest fires, insect outbreaks, ice storms and hurricanes also change
40 forest productivity, carbon cycling, and species composition – climate influences the
41 frequency and size of disturbances. Many features of ecosystems can be predicted by
42 forest age, and disturbance regulates forest age. After a stand-replacing disturbance,
43 forest productivity increases until the forest fully occupies the site or develops a closed
44 canopy, then declines to near zero in old age (Ryan et al. 1997). Carbon storage after a
45 disturbance generally declines while the decomposition of dead wood exceeds the
46 productivity of the new forest, then increases as the trees grow larger and the dead wood

1 from the disturbance disappears (Kashian et al. 2006). In many forests, species
2 composition also changes with time after disturbance. Susceptibility to fire and insect
3 outbreaks changes with forest age, but we do not know if the response of forest
4 productivity to climate, N deposition, CO₂, and ozone differs for old and young forests
5 because most studies have only considered young trees or forests. Changes in disturbance
6 prompted by climate change are likely as important as the changes in precipitation,
7 temperature, N deposition, CO₂, and ozone for affecting productivity and species
8 composition.

9 **3.4.2 Temperature**

10
11 Forest productivity in the United States has generally been increasing since the middle of
12 the 20th century (Boisvenue and Running 2006), with an estimated increase of two to
13 eight percent between 1982 and 1998 (Hicke et al. 2002b), but the causes of this increase
14 (increases in air and surface temperature, increasing CO₂, N deposition, or other factors)
15 are difficult to isolate (Cannell et al. 1998). These affects can be potentially disentangled
16 by experimentation, by analysis of species response to environmental gradients, planting
17 trees from seeds grown in different climates in a common garden, anomaly analysis, and
18 other methods. Increased temperatures will affect forest growth and ecosystem processes
19 through several mechanisms (Hughes 2000, Saxe et al. 2001) including effects on
20 physiological processes such as photosynthesis and respiration, and responses to longer
21 growing seasons triggered by thermal effects on plant phenology (e.g., the timing and
22 duration of foliage growth). Climate warming will be superimposed on interannual
23 temperature variations that already exceed several degrees, and may differ in the future.
24 Across geographical or local elevational gradients, forest primary productivity has long
25 been known to increase with mean annual temperature and rainfall (Leith 1975). This
26 result also generally holds within a species (Fries et al. 2000) and in provenance trials
27 where trees are found to grow faster in a slightly warmer location than that of the seed
28 source itself (Wells and Wakeley 1966, Schmidting 1994). In Alaska, where
29 temperatures have warmed strongly in recent times, changes in soil processes are similar
30 to those seen in experimental warming studies (Hinzman et al. 2005). In addition,
31 permafrost is melting, exposing organic material to decomposition and drying soils
32 (Hinzman et al. 2005).

33
34 Along with a general trend in warming, the length of the northern hemisphere growing
35 season has been increasing in recent decades (Menzel and Fabian 1999, Tucker et al.
36 2001). Forest growth correlates with growing season length (Baldocchi et al. 2001), with
37 longer growing seasons (earlier spring) leading to enhanced net carbon uptake and
38 storage (Black et al. 2000, Hollinger et al. 2004). The ability to complete phenological
39 development within the growing season is a major determinant of tree species range
40 limits (Chuine and Beaubien 2001). However, Sakai and Weiser (1973) have also related
41 range limits to the ability to tolerate minimum winter temperatures.

42 **3.4.3 Fire and Insect Outbreaks**

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1 Westerling et al. (2006) analyzed trends in wildfire and climate in the western U.S. from
2 1974 – 2004. They show that both the frequency of large wildfires and fire season length
3 increased substantially after 1985, and that these changes were closely linked with
4 advances in the timing of spring snowmelt, and increases in spring and summer air
5 temperatures. Much of the increase in fire activity occurred in mid-elevation forests in the
6 northern Rocky Mountains, and Sierra Nevada Mountains. Earlier spring snowmelt
7 probably contributed to greater wildfire frequency in at least two ways, by extending the
8 period during which ignitions could potentially occur, and by reducing water availability
9 to ecosystems in mid-summer, thus enhancing drying of vegetation and surface fuels
10 (Westerling et al. 2006). These trends in increased fire size correspond with an increased
11 cost of fire suppression (Calkin et al. 2005).

12
13 In boreal forests across North America, fire activity also has increased in recent decades.
14 Kasischke and Turetsky (2006) combined fire statistics from Canada and Alaska to show
15 that burned area more than doubled between the 1960s/70s and the 1980s/90s. The
16 increasing trend in boreal burned-area appears to be associated with a change in both the
17 size and number of lightning-triggered fires ($> 1000 \text{ km}^2$), which increased during this
18 period. In parallel, the contribution of human-triggered fires to total burned area
19 decreased from the 1960s to the 1990s (from 35.8 percent to 6.4 percent) (Kasischke and
20 Turetsky 2006). As in the western U.S., a key predictor of burned area in boreal North
21 America is air temperature, with warmer summer temperatures causing an increase in
22 burned area on both interannual and decadal timescales (Gillett et al. 2004, Duffy et al.
23 2005, Flannigan et al. 2005). In Alaska, for example, June air temperatures alone
24 explained approximately 38 percent of the variance of the natural log of annual burned
25 area during 1950-2003 (Duffy et al. 2005).

26
27 Insects and pathogens are significant disturbances of forest ecosystems in the United
28 States (Figure 3.4), costing \$1.5 billion annually (Dale et al. 2001). Extensive reviews of
29 the effects of climate change on insects and pathogens have reported many cases where
30 climate change has affected and/or will affect forest insect species range and abundance
31 (Ayres and Lombardero 2000; Malmström and Raffa 2000; Bale et al. 2002). This review
32 focused on forest insect species within the United States that are influenced by climate
33 and are ecologically or economically important.

34
35 Major outbreaks in recent years include: a mountain pine beetle (*Dendroctonus*
36 *ponderosae*) outbreak affected >10 million hectares (Mha) of forest in British Columbia
37 (Taylor et al. 2006), and 267,000 ha in Colorado (Colorado State Forest Service 2007);
38 more than 1.5 Mha was attacked by spruce beetle (*Dendroctonus rufipennis*) in southern
39 Alaska, and western Canada (Berg et al. 2006); >1.2 Mha of pinyon pine (*Pinus edulis*)
40 mortality occurred because of extreme drought, coupled with an Ips beetle outbreak in the
41 Southwest (Breshears et al. 2005); and millions of ha affected by southern pine beetle
42 (*Dendroctonus frontalis*), spruce budworm *Choristoneura fumiferana*), and western
43 spruce budworm (*Choristoneura occidentalis*) in recent decades in southeastern,
44 northeastern, and western forests, respectively (USDA Forest Service 2005). Ecologically
45 important whitebark pine (*Pinus albicaulis*) is being attacked by mountain pine beetle in
46 the Northern and Central Rockies (Logan and Powell 2001). For example, almost 70,000

1 ha, or 17 percent, of whitebark pine forest in the Greater Yellowstone Ecosystem is
2 infested by mountain pine beetle (Gibson 2006). Evident from these epidemics is the
3 widespread nature of insect outbreaks in forests throughout the United States.

4
5 Climate plays a major role in driving, or at least influencing, infestations of these
6 important forest insect species in the United States (e.g., Holsten et al. 1999; Logan et al.
7 2003a; Carroll et al. 2004; Tran et al. in press), and these recent large outbreaks are likely
8 influenced by observed increases in temperature. Temperature controls life cycle
9 development rates, influences synchronization of mass attacks required to overcome tree
10 defenses, and determines winter mortality rates (Hansen et al. 2001b; Logan and Powell
11 2001; Hansen and Bentz 2003; Tran et al. in press). Climate also affects insect
12 populations indirectly through effects on hosts. Drought stress, resulting from decreased
13 precipitation and/or warming, reduces the ability of a tree to mount a defense against
14 insect attack (Carroll et al. 2004, Breshears et al. 2005), though this stress may also cause
15 some host species to become more palatable to some types of insects (Koricheva et al.
16 1998). Both temperature and precipitation variability influence epidemics, however, the
17 relative importance of each has yet to be determined.

19 *3.5 Possible Future Changes and Impacts - Forests*

20 **3.5.1 Warming**

21
22 A review of recent experimental studies found that rising temperatures would generally
23 enhance tree photosynthesis (Saxe et al. 2001), as a result of increased time operating
24 near optimum conditions, and because rising levels of atmospheric CO₂ increase the
25 temperature optimum for photosynthesis (Long 1991). Warming experiments, especially
26 for trees growing near their cold range limits, generally increase growth (Bruhn et al.
27 2000; Wilmking et al. 2004; Danby and Hik 2007). The experimental warming of soils
28 alone has been found to stimulate nitrogen mineralization and soil respiration (Rustad et
29 al. 2001). An important concern for all experimental manipulations is that the treatments
30 occur long enough to determine the full suite of effects. It appears that the large initial
31 increases in soil respiration observed at some sites decrease with time back toward
32 pretreatment levels (Rustad et al. 2001; Melillo et al. 2002). This result may come about
33 from changes in C pool sizes, substrate quality (Kirschbaum 2004; Fang et al. 2005), or
34 other factors (Davidson and Janssens 2006).

35
36 A general response of leaves, roots, or whole trees to short-term increases in plant
37 temperature is an approximate doubling of respiration with a 10°C temperature increase
38 (Ryan et al. 1994, Amthor 2000). Over the longer term, however, there is strong evidence
39 for temperature acclimation (Atkin and Tjoelker 2003; Wythers et al. 2005), which is
40 probably a consequence of the linkage of respiration to the production of photosynthate
41 (Amthor 2000). One negative consequence of warming for trees, is that it can increase the
42 production of isoprene and other hydrocarbons in many tree species (Sharkey and Yeh
43 2001) – compounds that may lead to higher levels of surface ozone and increased plant
44 damage. Physiologically, the overall result of the few degrees of warming expected over

1 the next few decades is likely a modest increase in photosynthesis and tree growth
2 (Hyvonen et al. 2007). However, where increased temperature coincides with decreased
3 precipitation (western Alaska, Interior West, Southwest), forest growth is expected to be
4 lower (Hicke et al. 2002b).

5
6 For the projected temperature increases over the next few decades, most studies support
7 the conclusion that a modest warming of a few degrees Celsius will lead to greater tree
8 growth in the United States. There are many causes for this enhancement including direct
9 physiological effects, a longer growing season, and potentially greater mineralization of
10 soil nutrients. Because different species may respond somewhat differently to warming,
11 the competitive balance of species in forests may change. Trees will probably become
12 established in formerly colder habitats (more northerly, higher altitude) than at present.

13 **3.5.2 Changes in Precipitation**

14
15 Relationships between forest productivity and precipitation have been assessed using
16 continental gradients in precipitation (Webb et al. 1983; Knapp and Smith 2001),
17 interannual variability within a site (Hanson et al. 2001), and by manipulating water
18 availability (Hanson et al. 2001). Forest productivity varies with annual precipitation
19 across broad gradients (Webb et al. 1983; Knapp and Smith 2001), and with interannual
20 variability within sites (Hanson et al. 2001). Some of these approaches are more
21 informative than others for discerning climate change effects.

22
23 Gradient studies likely poorly predict the response to changes in precipitation, because
24 site-specific factors such as site fertility control the response to precipitation (Gower et al.
25 1992, Maier et al. 2004). The response of forest productivity to interannual variability
26 also likely poorly predicts response to precipitation changes, because forests have the
27 carbohydrate storage and deep roots to offset drought effects over that time, masking any
28 effects which might be apparent over a longer-term trend.

29
30 The effects of precipitation on productivity will vary with air temperature and humidity.
31 Warmer, drier air will evaporate more water and reduce water availability faster than
32 cooler, humid air. Low humidity also promotes the closure of stomata on leaves, which
33 reduces photosynthesis and lowers productivity even where soil water availability is
34 abundant.

35
36 Manipulation of water availability in forests allows an assessment of the direct effects of
37 precipitation (Figure 3.5). Two experiments where water availability was increased
38 through irrigation showed only modest increases in forest production (Gower et al. 1992;
39 Maier et al. 2004), but large increases with a combination of irrigation and nutrients. In
40 contrast, forest productivity did not change when precipitation was increased or reduced
41 33 percent, but with the same timing as natural precipitation (Hanson et al. 2005). Tree
42 growth in this precipitation manipulation experiment also showed strong interannual
43 variability with differences in annual precipitation. Hanson et al. (2005) conclude that
44 "differences in seasonal patterns of rainfall within and between years have greater

1 impacts on growth than percentage changes in rainfall applied to all rainfall events."
2

3 No experiments have assessed the effect of changes in precipitation on forest tree species
4 composition. Hanson et al. (2005) showed that growth and mortality changed in response
5 to precipitation manipulation for some smaller individuals, but we do not know if these
6 changes will lead to composition changes. However, one of the best understood patterns
7 in ecology is the variation of species with climate and site water balance. So, if
8 precipitation changes substantially, it is highly likely that species composition will
9 change (Breshears et al. 2005). However, we have limited studies with which to predict
10 the rate of change and the relationship with precipitation amount.

11
12 Drought is a common feature of all terrestrial ecosystems (Hanson and Weltzin 2000),
13 and generally lowers productivity in trees. Drought events can have substantial and long-
14 lasting effects on ecosystem structure, species composition and function by differentially
15 killing certain species or sizes of trees (Hanson and Weltzin 2000; Breshears et al. 2005),
16 weakening trees to make them more susceptible to insect attacks (Waring 1987), or by
17 increasing the incidence and intensity of forest fires (Westerling et al. 2006).

18
19 If existing trends in precipitation continue, forest productivity will likely decrease in the
20 Interior West, the Southwest, eastern portions of the Southeast, and Alaska. Forest
21 productivity will likely increase in the northeastern U.S., the Lake States, and in western
22 portions of the Southeast. An increase in drought events will very likely reduce forest
23 productivity wherever these events occur.

24 **3.5.3 Elevated Atmospheric CO₂ and Carbon Sequestration** 25

26 The effects of increasing atmospheric CO₂ on carbon cycling in forests are most
27 realistically observed in FACE (Figure 3.6) experiments. These experiments have
28 recently begun to provide time-series sufficiently long for assessing the effect of CO₂
29 projected for the mid-21st century on some components of the carbon cycle. The general
30 findings from a number of recent syntheses using data from the three American and one
31 European FACE sites (King et al. 2004; Norby et al. 2005; McCarthy et al. 2006a;
32 Palmroth et al. 2006) show that North American forests *will* absorb more CO₂ and *might*
33 retain more carbon as atmospheric CO₂ increases. The increase in the *rate* of carbon
34 sequestration will be highest (mostly in wood) on nutrient-rich soils with no water
35 limitation, and will decrease with decreasing fertility and water supply. Several yet
36 unresolved puzzles prevent a definitive assessment of the effect of elevated CO₂ on other
37 components of the carbon cycle in forest ecosystems:

- 38
- 39 ▪ Although total carbon allocation to belowground increases with CO₂ (King et al.
40 2004; Palmroth et al. 2006), there is only equivocal evidence of CO₂-induced
41 increase in soil carbon (Jastrow et al. 2005; Lichter et al. 2005).
- 42 ▪ Older forests can be strong carbon sinks (Stoy et al. 2006), and older trees absorb
43 more CO₂ in elevated CO₂ atmosphere, but wood production of these trees show
44 limited or only transient response to CO₂ (Körner et al. 2005).

- 1 ▪ When responding to CO₂, trees require and obtain more nitrogen (and other
2 nutrients) from the soil. Yet, despite appreciable effort, the soil processes
3 supporting such increased uptake have not been identified, leading to the
4 expectation that nitrogen availability may increasingly limit the response to
5 elevated CO₂ (Finzi et al. 2002; Luo et al. 2004; de Graaff et al. 2006; Finzi et al.
6 2006; Luo et al. 2006).

7
8 To understand the complex processes controlling ecosystem carbon cycling under
9 elevated CO₂, and solve these puzzles, longer time-series are needed (Walther 2007).

10
11 ***Major findings on specific processes leading to these generalities***

12
13 Net primary production (NPP) is defined as the balance between canopy photosynthesis
14 and plant respiration. Canopy photosynthesis increases with atmospheric CO₂, but less
15 than expected based on physiological studies because of negative feedbacks in leaves
16 (biochemical down-regulation) and canopies (reduced light, and conductance with
17 increasing LAI; (Saxe et al. 2001; Schäfer et al. 2003; Wittig et al. 2005). On the other
18 hand, plant respiration increases only in proportion to tree growth and amount of living
19 biomass – that is, tissue-specific respiration does not change under elevated CO₂
20 (Gonzelez-Meller et al. 2004). The balance between these processes, NPP, increases in
21 stands on moderately fertile and fertile soils. The short-term (<10 years), median
22 response among the four “forest” FACE experiments was an increase of 23±2 percent
23 (Norby et al. 2005). Although the average response was similar among these sites that
24 differed in productivity (Norby et al. 2005), the within-site variability in the response to
25 elevated CO₂ can be large (<10 percent to >100 percent). At the Duke FACE site, this
26 within-site variability was related to nitrogen availability (Oren et al. 2001; Finzi et al.
27 2002; Norby et al. 2005). The absolute magnitude of the additional carbon sink varies
28 greatly among years; at the Duke FACE, much of this variability is caused by droughts
29 and disturbance events (McCarthy et al. 2006a).

30
31 The enhancement of NPP at low LAI is largely driven by an enhancement in LAI,
32 whereas at high LAI, the enhancement reflects increased light-use efficiency (Norby et al.
33 2005, McCarthy et al. 2006a). The sustainability of the NPP response and the partitioning
34 of carbon among plant components may depend on soil fertility (Curtis and Wang 1998;
35 Oren et al. 2001; Finzi et al. 2002). NPP in intermediate fertility sites may undergo
36 several phases of transient response, with CO₂-induced enhancement of stemwood
37 production dominating initially followed by fine-root production after several years (Oren
38 et al. 2001; Norby et al. 2004). In high productivity plots, the initial response so far
39 appears sustainable (Körner 2006).

40
41 Carbon partitioning to pools with different turnover times is highly sensitive to soil
42 resources. With increasing soil nutrient supply, LAI of stands under elevated CO₂
43 become increasingly greater than that of stands under ambient CO₂. This response affects
44 carbon allocation to other pools. ANPP increases with LAI (McCarthy et al. 2006a) with
45 no additional effects of elevated CO₂. The fraction of ANPP allocated to wood, a
46 moderately slow turnover pool, increases with LAI in broadleaf FACE experiments (from

1 ~50 percent at low LAI, to a maximum of 70 percent at mid-range LAI), with the effect
2 of elevated CO₂ on allocation entirely accounted for by changes in LAI. In pines,
3 allocation to wood decreased with increasing LAI (from ~65 percent to 55 percent), but
4 was higher (averaging ~68 percent versus 58 percent) under elevated CO₂ (McCarthy et
5 al. 2006a). Despite the increased canopy photosynthesis, there is no evidence of increased
6 wood production in pines growing on very poor, sandy soils (Oren et al. 2001).

7
8 Total carbon allocation belowground (TBCA), and CO₂ efflux from the forest floor
9 decrease with increasing LAI, but the enhancement under elevated CO₂ is approximately
10 constant (~22 percent) over the entire range of LAI (King et al. 2004; Palmroth et al.
11 2006). About a third of the extra carbon allocated belowground under elevated CO₂ is
12 retained in litter and soil storage at the U.S. FACE sites (Palmroth et al. 2006). At Duke
13 FACE, a third of the incremental carbon sequestration is found in the forest floor. The
14 CO₂-induced enhancement in fine root and mycorrhizal fungi turnover have not
15 translated to a significant net incremental storage of carbon in the mineral soil
16 (Schlesinger and Lichter 2001; Jastrow et al. 2005; Lichter et al. 2005). A recent meta-
17 analysis (Jastrow et al. 2005), incorporating data from a variety of studies in different
18 settings, estimated a median CO₂-induced increase in the rate of soil C sequestration of
19 5.6 percent (+19 g C m⁻² y⁻¹). A longer time-series is necessary to separate the treatment
20 signal of soil C accumulation from the background noise in the C pool of real forest soil
21 (McMurtrie et al. 2001).

22
23 In summary, canopy photosynthesis will likely increase with rising concentrations of
24 atmospheric CO₂. In moderate to high fertility sites, aboveground biomass production
25 will be the dominant sink for the extra photosynthate fixed under elevated CO₂. In low to
26 moderately-low fertility sites, the extra photosynthate fixed under elevated CO₂ will be
27 allocated belowground, where heterotrophic organisms will rapidly cycle most of the
28 extra carbon back to the atmosphere.

29 **3.5.4 Interactive effects including O₃, N deposition, and forest age**

30
31 Ozone is produced from photochemical reactions of nitrogen oxides and volatile organic
32 compounds. Ozone can damage plants (Ashmore 2002) and lower productivity, and these
33 responses have been documented for U.S. forests (Matyssek and Sandermann 2003;
34 Karlsson et al. 2004). In the United States, controls on emissions of nitrogen oxides and
35 volatile organic compounds are expected to reduce the peak ozone concentrations that
36 currently cause the most plant damage (Ashmore 2005). However, background
37 tropospheric concentrations may be increasing as a result of increased global emissions of
38 nitrogen oxides (Ashmore 2005). These predicted increases in background ozone
39 concentrations may reduce or negate the effects of policies to reduce ozone
40 concentrations (Ashmore 2005). Ozone pollution will modify the effects of elevated CO₂
41 and any changes in temperature and precipitation (Hanson et al. 2005), but these
42 interactions are difficult to predict because they have been poorly studied.

43
44 Nitrogen deposition in the eastern U.S. and California can exceed 10 kg N ha⁻¹ yr⁻¹ and
45 likely has increased 10 to 20 times above pre-industrial levels (Galloway et al. 2004).

1 Forests are generally limited by nitrogen availability, and fertilization studies show that
2 this increased deposition will enhance forest growth and carbon storage in wood (Gower
3 et al. 1992; Albaugh et al. 1998; Adams et al. 2005). However, chronic nitrogen inputs
4 over many years could lead to 'nitrogen saturation' (a point where the system can no
5 longer use or store nitrogen), a reduction in forest growth, and increased levels of nitrate
6 in streams (Aber et al. 1998; Magill et al. 2004). Increased nitrogen availability from
7 nitrogen deposition will enhance the productivity increase from elevated CO₂ (Oren et al.
8 2001) and the positive effects of changes in temperature and precipitation. Overall, the
9 effects of nitrogen deposition might exceed those of elevated CO₂ (Körner 2000).

10
11 Forest growth changes with forest age (Ryan et al. 1997), likely because of reductions in
12 photosynthesis (Ryan et al. 2004). Because of the link of forest growth with
13 photosynthesis, the response to drought, precipitation, nitrogen availability, ozone, and
14 elevated CO₂ may also change with forest age. Studies of elevated CO₂ on trees have
15 been done with young trees (which show a positive growth response), but the one study
16 on mature trees showed no growth response (Körner et al. 2005). This is consistent with
17 model results found in an independent study (Kirschbaum 2005). Tree size or age may
18 also affect ozone response (older trees may be more resistant, Grulke and Miller 1994),
19 and response to drought (older trees may be more resistant, Irvine et al. 2004).

20 **3.5.5 Fire frequency and severity**

21
22 Several lines of evidence suggest that large, stand-replacing wildfires will likely increase
23 in frequency over the next several decades because of climate warming (Figure 3.7).
24 Chronologies derived from fire debris in alluvial fans (Pierce et al. 2004) and fire scars in
25 tree rings (Kitzberger et al. 2007) provide a broader temporal context for interpreting
26 contemporary changes in the fire regime. These longer-term records unequivocally show
27 that warmer and drier periods during the last millennium are associated with more
28 frequent and severe wildfires in western forests. GCM projections of future climate
29 during 2010-2029 suggest that the number of low humidity days (and high fire danger
30 days) will increase across much of the western U.S. – allowing for more wildfire activity
31 with the assumption that fuel densities and land management strategies remain the same
32 (Flannigan et al. 2000; Brown et al. 2004). Flannigan et al. (2000) used two GCM
33 simulations of future climate to calculate a seasonal severity rating, related to fire
34 intensity and difficulty of fire control. Depending on the GCM used, forest fires in the
35 Southeast are projected to increase from 10 to 30 percent and 10 to 20 percent in the
36 Northeast by 2060. Other biome models used with a variety of GCM climate projections
37 simulate a larger increase in fire activity and biomass loss in the Southeast, sufficient to
38 convert the southernmost Southeast forests to savannas (Bachelet et al. 2001).



1
2
3 **Figure 3.7** Ponderosa pine after the Hayman fire in Colorado, June 2002.
4

5 By combining climate-fire relationships derived from contemporary records with GCM
6 simulations of future climate, Flannigan et al. (2005) estimated that future fire activity in
7 Canadian boreal forests will approximately double by the end of this century for model
8 simulations in which fossil fuel emissions were allowed to increase linearly at a rate of
9 one percent per year. Both Hadley Center and Canadian GCM simulations projected that
10 fuel moisture levels will decrease and air temperatures will increase within the
11 continental interior of North America because of forcing from greenhouse gases and
12 aerosols.
13

14 Santa Ana winds and human-triggered ignitions play an important role in shaping the fire
15 regime of Southern California shrublands and forests (Keeley and Fotheringham 2001;
16 Westerling et al. 2004). Santa Ana winds occur primarily during fall and winter and are
17 driven by large scale patterns of atmospheric circulation – specifically by a high pressure
18 system over the Great Basin and, simultaneously, a low pressure system offshore of
19 Southern California and Mexico (Raphael 2003; Conil and Hall 2006). By correlating
20 Santa Ana events with these larger-scale patterns of atmospheric circulation, Miller and
21 Schlegel (2006) assessed how Santa Ana events may change in the future using output
22 from GCMs. The total number of annual Santa Ana events was not predicted to change
23 substantially over the next 30 years. However, for one of the GCM simulations (using the
24 Geophysical Fluid Dynamics Laboratory version 2 model) there was a shift in the
25 seasonal cycle in the mid to latter half of the 21st century, with fewer Santa Ana events
26 occurring in September and more occurring in December (Miller and Schlegel 2006). The

1 implication of a shift in the seasonal cycle of Santa Ana conditions for the Southern
2 California fire regime remains uncertain.

3
4 Future increases in fire emissions across North America will have important
5 consequences for climate forcing agents, air quality, and ecosystem services. More
6 frequent fire will increase emissions of greenhouse gases and aerosols (Amiro et al. 2001)
7 and increase deposition of black carbon aerosols on snow and sea ice (Flanner et al.
8 2007). Even though many forests will regrow and sequester the carbon released in the
9 fire, forests burned in the next few decades can be sources of CO₂ for decades and not
10 recover the carbon lost for centuries (Kashian et al. 2006) – an important consideration
11 for slowing the increase in atmospheric CO₂. In boreal forests, the warming effects from
12 fire-emitted greenhouse gases may be offset at regional scales by increases in surface
13 albedo caused by a shift in the stand age distribution (Randerson et al. 2006). Future
14 changes in boreal forest fires in Alaska and Canada will have consequences for air quality
15 in the central and eastern U.S. because winds often transport carbon monoxide, ozone,
16 and aerosols from boreal fires to the south (McKeen et al. 2002, Morris et al. 2006,
17 Pfister et al. 2006). Increased burning in boreal forests and peatlands also has the
18 potential to release large stocks of mercury currently stored in cold and wet soils
19 (Turetsky et al. 2006). These emissions may exacerbate mercury toxicities in northern
20 hemisphere food chains caused by coal burning.

21 **3.5.6 Insect outbreaks**

22
23 Rising temperature is the aspect of climate change most influential on forest insect
24 species through changes in insect survival rates, increases in life cycle development rates,
25 facilitation of range expansion, and effects on host plant capacity to resist attack (Ayres
26 and Lombardero 2000; Malmström and Raffa 2000; Bale et al. 2002). Future northward
27 range expansion attributed to warming temperatures has been predicted for mountain pine
28 beetle (Logan and Powell 2001) and southern pine beetle (*Dendroctonus frontalis*)
29 (Ungerer et al. 1999). Future range expansion of mountain pine beetle has the potential of
30 invading jack pine (*Pinus banksiana*), a suitable host that extends across the boreal forest
31 of North America (Logan and Powell 2001). Increased probability of spruce beetle
32 outbreak (Logan et al. 2003a) as well as increase in climate suitability for mountain pine
33 beetle attack in high-elevation ecosystems (Hicke et al. 2006) has been projected in
34 response to future warming. The combination of higher temperatures with reduced
35 precipitation in the Southwest has led to enhanced tree stress, and also affected Ips beetle
36 development rates; continued warming, as predicted by climate models, will likely
37 maintain these factors (Breshears et al. 2005).

38
39 Indirect effects of future climate change may also influence outbreaks. Increasing
40 atmospheric CO₂ concentrations may lead to increase ability of trees to recover from
41 attack (Kruger et al. 1998). Enhanced tree productivity in response to favorable climate
42 change, including rises in atmospheric CO₂, may lead to faster recovery of forests
43 following outbreaks, and thus a reduction in time to susceptibility to subsequent attack
44 (Fleming 2000). Although eastern spruce budworm (*Choristoneura fumiferana*) life
45 cycles are tightly coupled to host tree phenology even in the presence of climate change,

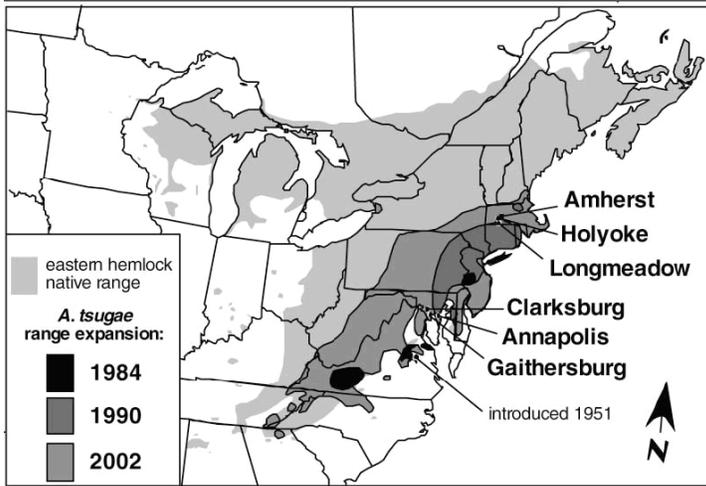
1 enemy populations that are significant in governing epidemic dynamics are not expected
2 to respond to climate change in a synchronized way (Fleming 2000). Changing fire
3 regimes in response to climate change (Flannigan et al. 2005) will affect landscape-scale
4 forest structure, which influences susceptibility to attack (Shore et al. 2006).

5
6 Nonnative invasive species are also significant disturbances to forests in the United
7 States. Although little has been reported on climate influences on these insects, a few
8 studies have illustrated climate control. The hemlock woolly adelgid (*Adelges tsugae*) is
9 rapidly expanding its range in the eastern United States, feeding on several species of
10 hemlock (Box 1). The northern range limit of the insect in the United States is currently
11 limited by low temperatures (Parker et al. 1999), suggesting range expansion in the event
12 of future warming. In addition, the hemlock woolly adelgid has evolved greater resistance
13 to cold conditions as it has expanded north (Butin et al. 2005). The introduced gypsy
14 moth (*Lymantria dispar*) has defoliated millions of hectares of forest across the eastern
15 United States, with great efforts expended to limit its introduction to other areas (USDA
16 Forest Service 2005). Projections of future climate and gypsy moth simulation modeling
17 reveal substantial increases in probability of establishment in the coming decades (Logan
18 et al. 2003a).

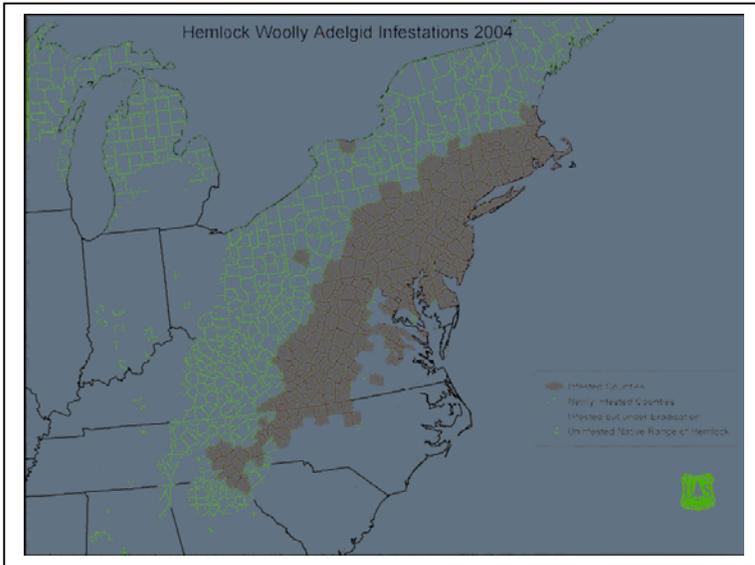
20 **BOX 1:** The Eastern Hemlock and its Woolly Adelgid.

21
22 Outbreaks in forests of insects and diseases affect forest structure and composition, leading to
23 altered cycling of matter and energy, and changes in biodiversity and ecosystem services. The
24 hemlock woolly adelgid (HWA, *Adelges tsugae* Armand), native to Asia, was first recorded in
25 1951 in Virginia, and has since spread, causing a severe decline in vitality and survival of eastern
26 hemlock (*Tsuga canadensis*) in North American forests (Maps 1 & 2, Stadler et al. 2006). Roads,
27 major trails, and riparian corridors provide connectivity enabling long-distance dispersal of this
28 aphid-like insect, probably by humans or birds (Koch et al. 2006). Although HWA is consumed
29 by some insect predators (Flowers et al. 2006), once it arrives at a site, complete hemlock
30 mortality is just a matter of time (Orwig et al. 2002; Stadler et al. 2005). Hemlock seedlings are
31 readily attacked and killed by the HWA, so damaged hemlock stands are replaced by stands of
32 black birch, black oaks, and other hardwoods, depending on site conditions (Brooks 2004; Small
33 et al. 2005; Sullivan and Ellison 2006). Plant biodiversity increases not only in the canopy;
34 considerable understory develops, including greater herb richness and abundance and increased
35 density of saplings of more species than found in the original forests; invasive shrubs and woody
36 vines of several species also expand in response to the improved light conditions (Goslee et al.
37 2005; Small et al. 2005; Eschtruth et al. 2006). Four insectivorous bird species have high affinity
38 for hemlock forest type, two of which, the blue-headed vireo and Blackburnian warbler, appeared
39 to specialize on certain habitats. Unchecked expansion of HWA could negatively impact several
40 million pairs from northeastern United States hemlock forests due to elimination of preferred
41 habitat (Tingley et al. 2002, Ross et al. 2004). Changes in canopy attributes upon replacement of
42 hemlock with deciduous broadleaf species alter the radiation regime, hydrology, and nutrient
43 cycling (Cobb et al. 2006; Stadler et al. 2006), and result in greater temperature fluctuations and
44 longer periods of times in which streams are dry (Snyder et al. 2002). These conditions reduce
45 habitat quality for certain species of fish. Brook trout (*Salvelinus fontinalis*) and brown trout
46 (*Salmo trutta*) were two to three times as prevalent in hemlock than hardwood streams (Ross et
47 al. 2003). Low winter temperature is the main factor checking the spread of HWA (Skinner et al.
48 2003). However, the combination of increasing temperature and the capacity of HWA to evolve
49 greater resistance to cold shock as it has expanded its range northward (Butin et al. 2005) means

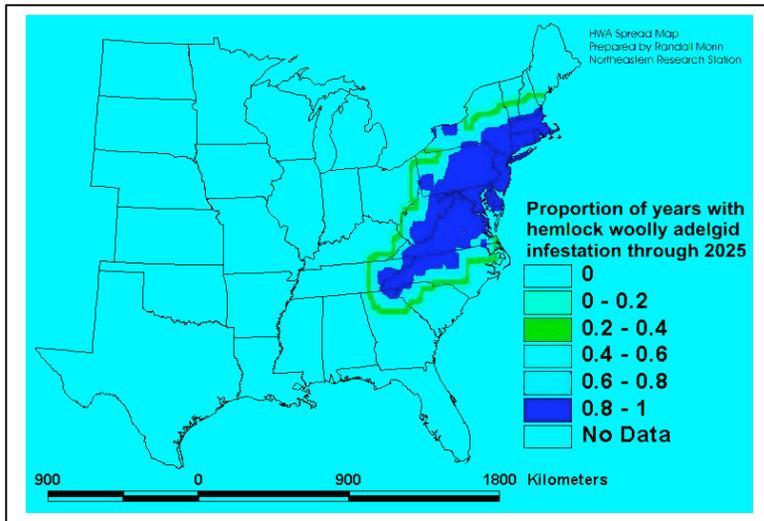
1 that stands that have been relatively protected by cold temperatures (Orwig et al. 2002) may fall
 2 prey to the insect in the not so distant future (Map 3).
 3



4
 5
 6 **Map 1.** Sample sites and range expansion of *Adelges tsugae* relative to the native range of eastern hemlock
 7 in North America. Map from Butin et al. 2005 (redrawn from USDA Forest Service and Little, 1971).
 8



9
 10
 11 **Map 2.** Onken B and Reardon R (compilers) (2005), Third Symposium on Hemlock Woolly Adelgid in the
 12 Eastern United States, Asheville, North Carolina. USDA Forest Service FHTET-2005
 13 01http://www.na.fs.fed.us/fhp/hwa/pub/2005_proceedings/frontcover.pdf
 14



1
2
3 **Map 3.** Hemlock Woolly Adelgid spread map prepared by Randall Marin, Northeastern Research Station,
4 U.S. Forest Service. Souto, D., Luther, T., Chianese, B., 1996. Past and current status of HWA in eastern
5 and Carolina hemlock stands. In: Salom, S.M., Tignor, T.C., Reardon, R.C. (Eds.), Proceedings of the First
6 Hemlock Woolly Adelgid Review, USDA For. Serv., Morgantown, WV, pp. 9-15.
7 <http://www.na.fs.fed.us/fhp/hwa/maps/hwaprojectedspreadmap.htm>

8
9 As important disturbances, insect outbreaks affect many forest ecosystem processes.
10 Outbreaks alter tree species composition within stands, and may result in conversion
11 from forest to herbaceous vegetation through lack of regeneration (Holsten et al. 1995).
12 Carbon stocks and fluxes are modified through a large decrease in living biomass and a
13 corresponding large increase in dead biomass, reducing carbon uptake by forests as well
14 as enhancing decomposition fluxes. In addition to effects at smaller scales, widespread
15 outbreaks have significant effects on regional carbon cycling (Kurz and Apps 1999;
16 Hicke et al. 2002a). Other biogeochemical cycles, such as nitrogen, are affected by
17 beetle-caused mortality (Throop et al. 2004). Defoliation, for example as related to gypsy
18 moth outbreaks, facilitates nitrogen movement from forest to aquatic ecosystems,
19 elevating stream nitrogen levels (Townsend et al. 2004).

20
21 Significant changes to the hydrologic cycle occur after a widespread insect epidemic,
22 including increases in annual water yield, advances in the annual hydrograph, and
23 increases in low flows (Bethlahmy 1974; Potts 1984). Water quantity is enhanced
24 through reductions in transpiration, in addition to reductions in snow interception, and
25 subsequent redistribution and sublimation. These effects can last for many years
26 following mortality (Bethlahmy 1974).

27
28 Interactions of outbreaks and fire likely vary with time, although observational evidence
29 is limited to a few studies (Romme et al. 2006). In central Colorado, number of fires, fire
30 extent, and fire severity were not enhanced following outbreaks of spruce beetle (Bebi et
31 al. 2003; Bigler et al. 2005; Kulakowski and Veblen in press). Other studies of the 1988
32 Yellowstone fire that followed two mountain pine beetle epidemics found mixed fire
33 effects, depending on outbreak severity and time since outbreak (Turner et al. 1999,
34 Lynch et al. 2006). A quantitative modeling study of fire behavior found mixed fire

1 effects following an outbreak of western spruce budworm (Hummel and Agee 2003);
2 more modeling studies that incorporate complete effects are needed to explore other
3 situations.

4
5 Multiple socioeconomic impacts follow severe insect outbreaks. Timber production and
6 manufacturing and markets may not be able to take advantage of vast numbers of killed
7 trees (Ferguson 2004), and beetle-killed timber has several disadvantages from a
8 manufacturing perspective (Byrne et al. 2006). Water quantity may be enhanced for a
9 period (Bethlahmy 1974). Perceived enhanced fire risk and views about montane
10 aesthetics following beetle-cause mortality influence public views of insect outbreaks,
11 which will drive public policy. Threats to ecologically important tree species may have
12 ramifications for charismatic animal species (e.g., influences of whitebark pine mortality
13 on the grizzly bear (*Ursus arctos horribilis*)) (Logan and Powell 2001). Impacts are
14 enhanced as human population, recreation, and tourism increase in forested regions
15 across the nation.

16 **3.5.7 Storms (hurricanes, ice storms, windstorms)**

17
18 Predictions of forest carbon (C) sequestration account for the effect of fires (e.g., Harden
19 et al. 2000), yet other wide-ranging and frequent disturbances, such as hurricanes (Figure
20 3.8) and ice storms, are seldom explicitly considered. Both storm types are common in
21 the southeastern United States, with an average return time of six years for ice storms
22 (Bennett 1959), and two years for hurricanes (Smith 1999). These, therefore, have the
23 potential for significant impact on C sequestration in this region, which accounts for ~20
24 percent of annual C sequestration in conterminous U.S. forests (Birdsey and Lewis 2002,
25 Bragg et al. 2003). Recent analysis demonstrated that a single category 3 hurricane and
26 severe ice storms could each transfer to the decomposable pool the equivalent of 10
27 percent of the annual U.S. C sequestration, with subsequent reductions in sequestration
28 caused by direct stand damage (McNulty 2002, McCarthy et al. 2006b). For example,
29 hurricanes Rita and Katrina together damaged a total of 2,200 ha and 63 million m³ of
30 timber volume (Stanturf et al. 2007).

31



1
2
3 **Figure 3.8** Forest damage from Hurricane Hugo. Andrew J. Boone, South Carolina Forestry Commission,
4 www.forestryimages.org.

5
6 Common forest management practices, such as fertilization and thinning, forest type, and
7 increasing atmospheric CO₂ levels can change wood and stand properties, and thus may
8 change vulnerability to ice storm damage. A pine plantation experienced a ~250 g C m⁻²
9 reduction in living biomass during a single ice storm, equivalent to ~30 percent of the
10 annual net ecosystem carbon exchange of this ecosystem. In this storm at the Duke
11 FACE, nitrogen fertilization had no effect on storm damage, conifer trees were more than
12 twice as likely to be killed by ice storm damages as leafless deciduous-broadleaf trees,
13 and thinning increased broken limbs or trees threefold. However, elevated CO₂ reduced
14 the storm damage to a third of that of the ambient CO₂ stand (McCarthy et al. 2006b).
15 Although this result suggests that forests may suffer less damage in a future ice storm
16 when atmospheric CO₂ is higher, future climate may create conditions leading to greater
17 ice storm frequency, extent and severity (da Silva et al. 2006), which may balance the
18 decreased sensitivity to ice damage under elevated CO₂. All of these predictions are very
19 uncertain (Cohen et al. 2001).

20 **3.5.8 Changes in Overstory Species Composition**

21
22 Several approaches can predict changes in biomes (major vegetation assemblages such as
23 conifer forests, and savanna/woodland) and changes in species composition or overstory
24 species communities (Hansen et al. 2001a). These approaches use either rules that define
25 the water balance, temperature, seasonality, etc. required for a particular biome, or

1 statistically link species distributions or community composition with climate envelopes.
2 These efforts have mostly focused on equilibrium responses to climate changes over the
3 next century (Hansen et al. 2001a), so predictions for the next several decades are
4 unavailable.

5
6 Bachelet et al. (2001) used the Mapped Atmosphere-Plant-Soil System (MAPPS) model
7 with the climate predictions generated by seven different global circulation models to
8 predict how biome distributions would change with a doubling of CO₂ by 2100. Mean
9 annual temperature of the United States increased from 3.3 to 5.8 °C for the climate
10 predictions. Predicted forest cover in 2100 declined by an average of 11 percent (range
11 for all climate models was +23 percent to -45 percent). The MAPPS model coupled to the
12 projected future climates predicts that biomes will migrate northward in the East and to
13 higher elevations in the West. For example, mixed conifer and mixed hardwood forests in
14 the Northeast move into Canada, and decline in area by 72 percent (range: -14 to -97
15 percent), but are replaced by eastern hardwoods. In the Southeast, grasslands or savannas
16 displace forests and move their southern boundaries northward, particularly for the
17 warmer climate scenarios. In the West, forests displace alpine environments, and the wet
18 conifer forests of the Northwest decline in area nine percent (range: 54 to + 21 percent),
19 while the area of interior western pines changes little. Species predictions for the Eastern
20 U.S. using a statistical approach showed that most species moved north 60-300 miles
21 (Hansen et al. 2001a).

22
23 Authors of these studies cautioned that these equilibrium approaches do not reflect the
24 transient and species-specific nature of the community shifts that are projected to occur.
25 Success in moving requires suitable climate, but also dispersal that may lag behind
26 changes in climate (Hansen et al. 2001a). Some species will be able to move quicker than
27 others will, and some biomes and communities may persist until a disturbance allows
28 changes to occur (Hansen et al. 2001a). The authors of these studies agreed that while
29 climate is changing, novel ecosystems will arise – novel because some species will
30 persist in place, some species will depart, and new species will arrive.

32 *3.6 Indicators and observing systems – Forests*

33 **3.6.1 Characteristics of Observing Systems**

34
35 Many Earth observing systems (Bechtold and Patterson 2005; Denning 2005) are
36 designed to allow for integration of multiple kinds of observations using a hierarchical
37 approach that takes advantage of the characteristics of each. A typical system uses remote
38 sensing to obtain a continuous measurement over a large area, coupled with statistically-
39 designed field surveys to obtain more detailed data at a finer resolution. Statistically, this
40 approach (known as “multi-phase” sampling) is more efficient than sampling with just a
41 single kind of observation or conducting a complete census (Gregoire and Valentine, in
42 press). Combining observed data with models is also common because often the variable
43 of interest cannot be directly observed, but observation of a closely-related variable may

1 be linked to the variable of interest with a model. Model-data synthesis is often an
2 essential component of Earth observing systems (Raupach et al. 2005).

3
4 To be useful, the system must observe a number of indicators more than once over a
5 period, and also cover a large-enough spatial scale to detect a change. The length of time
6 required to detect a change with a specified level of precision depends on the variability
7 of the population being sampled, the precision of measurement, and the number of
8 samples (Smith 2004). Non-climatic local factors, such as land use change, tend to
9 dominate vegetation responses at small scales, masking the relationship with climate
10 (Parmesan and Yohe 2003). A climate signal is therefore more likely to be revealed by
11 analyses that can identify trends across large geographic regions (Walther et al. 2002).

12 The relationship between biological observations and climate is correlational; thus, it is
13 difficult to separate the effects of climate change from other possible causes of observed
14 effects (Walther et al. 2002). Inference of causation can be determined with carefully
15 controlled experiments that complement the observations. Yet, observation systems can
16 identify some causal relationships and therefore have value in developing climate impact
17 hypotheses. Schreuder and Thomas (1991) determined that if both the potential cause and
18 effect variables were measured at inventory sample plots, a relationship could be
19 established if the variables are measured accurately, estimated properly, and based on a
20 large enough sample. But, in practice, additional information is often needed to
21 strengthen a case, for example, a complementary controlled experiment to verify the
22 relationship.

23 **3.6.2 Indicators of Climate Change Effects**

24
25 The species that comprise communities respond both physiologically and competitively
26 to climate change. One scheme for assessing the impacts of climate change on species
27 and communities is to assess the effects on: (1) the physiology of photosynthesis,
28 respiration, and growth; (2) species distributions; and (3) phenology, particularly life
29 cycle events such as timing of leaf opening. There may also be effects on functions of
30 ecosystems such as hydrologic processes.

31 *Effects on physiology*

32 Net primary productivity is closely related to indices of “greenness” and can be detected
33 by satellite over large regions (Hicke et al. 2002b). Net ecosystem productivity (NEP)
34 can be measured on the ground as changes in carbon stocks in vegetation and soil
35 (Boisvenue and Running 2006). Root respiration and turnover are sensitive to climate
36 variability and may be good indicators of climate change if measured over long enough
37 time periods (Atkin et al. 2000; Gill and Jackson 2000). Gradient studies show variable
38 responses of growth to precipitation changes along elevational gradients (Fagre et al.
39 2003). Climate effects on growth patterns of individual trees is confounded by other
40 factors such as increasing CO₂ and N deposition, so response of tree growth is difficult to
41 interpret without good knowledge of the exposure to many possible causal variables. For
42 example, interannual variability in NPP, which can mask long-term trends, can be
43 summarized from long-term ecosystem studies and seems to be related to interactions
44

1 between precipitation gradients and growth potential of vegetation (Knapp and Smith
2 2001).

3 4 ***Effects on species distributions***

5 Climate change affects composition and geographical distribution, and these changes are
6 observable over time by field inventories, remote sensing, and gradient studies. Both
7 range expansions and retractions are important to monitor (Thomas et al. 2006), and
8 population extinctions or extirpations are also possible. Range and vegetation density
9 changes have been observed in Alaska by field studies and remote sensing (Hinzman et
10 al. 2005). Detecting range and abundance shifts in wildlife populations may be
11 complicated by changes in habitat from other factors (Warren et al. 2001).

12 13 ***Effects on phenology***

14 Satellite and ground systems can document onset and loss of foliage, with the key being
15 availability of long-term data sets (Penuelas and Filella 2001). Growing season was
16 found significantly longer in Alaska based on satellite normalized difference vegetation
17 Index (NDVI) records (Hinzman et al. 2005). Schwartz et al. (2006) integrated weather
18 station observations of climate variables with remote sensing and field observations of
19 phenological changes using Spring Index phenology models. However, Fisher et al.
20 (2007) concluded that species or community compositions must be known to use satellite
21 observations for predicting the phenological response to climate change.

22 23 ***Effects on natural disturbances and mortality***

24 Climate change can affect forests by altering the frequency, intensity, duration, and
25 timing of natural disturbances (Dale et al. 2001). The correlation of observations of
26 changes in fire frequency and severity with changes in climate are well documented (e.g.,
27 Flannigan et al. 2000; Westerling et al. 2006), and the inference of causation in these
28 studies is established by in situ studies of fire and vegetation response, and fire behavior
29 models. Similar relationships hold for forest disturbance from herbivores and pathogens
30 (Ayres and Lombardero 2000; Logan et al. 2003b). Tree mortality may be directly caused
31 by climate variability, such as in drought (Gitlin et al. 2006).

32 33 ***Effects on hydrology***

34 Climate change will affect forest water budgets and these changes have been observed
35 over time by long-term stream gauge networks and research sites. Changes in permafrost
36 and streamflow in the Alaskan Arctic region are already apparent (Hinzman et al. 2005).
37 There is some evidence of a global pattern (including in the United States) in response of
38 streamflow to climate from stream-gauge observations (Milly et al. 2005). Inter-annual
39 variation in transpiration of a forest can be observed by sap flow measurements (Phillips
40 and Oren 2001; Wullschleger et al. 2001).

41 42 ***Causal variables***

43 It is important to have high-quality, spatially-referenced observations of climate, air
44 pollution, deposition, and disturbance variables. These are often derived from observation
45 networks using spatial statistical methods (e.g., Thornton et al. 2000).

1 **3.6.3 Current Capabilities and Needs**
 2

3 There are strengths and limitations to each kind of observation system: intensive
 4 monitoring sites such as Long Term Ecological Research (LTER) sites and protected
 5 areas; extensive observation systems such as Forest Inventory and Analysis (FIA) or the
 6 U.S. Geological Survey (USGS) stream-gauge network; and remote sensing. A national
 7 climate observation system may be improved by integration under an umbrella program
 8 such as the National Ecological Observatory Network (NEON), or Global Earth System
 9 of Systems (GEOSS) (see Table 3.1). Also, increased focus on “sentinel” sites, could
 10 help identify early indicators of climate effects on ecosystem processes, and provide
 11 observations of structural and species changes (NEON 2006).
 12

13 **Table 3.1 Current and Planned Observation Systems for Climate Effects on Forests**
 14

Observation System	Characteristics	Reference
Forest Inventory and Analysis (U.S. Forest Service)	Annual and periodic measurements of forest attributes at a large number (more than 150,000) of sampling locations. Historical data back to 1930s in some areas.	Bechtold and Patterson 2005
AmeriFlux (Department of Energy and other Agencies)	High temporal resolution (minutes) measurements of carbon, water, and energy exchange between land and atmosphere at about 50 forest sites. A decade or more of data available at some of the sites.	http://public.ornl.gov/ameriflux/
Long Term Ecological Research network (National Science Foundation)	The LTER network is a collaborative effort involving more than 1,800 scientists and students investigating ecological processes over long temporal and broad spatial scales. The 26 LTER Sites represent diverse ecosystems and research emphases	http://www.lternet.edu/
Experimental Forest Network (U.S. Forest Service)	A network of 77 protected forest areas where long-term monitoring and experiments have been conducted.	Lugo 2006
National Ecological Observation Network	The NEON observatory is specifically designed to address central scientific questions about the interactions of ecosystems, climate, and land use.	http://www.neoninc.org/
Global Terrestrial Observing System (GTOS)	GTOS is a program for observations, modelling, and analysis of terrestrial ecosystems to support sustainable development.	http://www.fao.org/gtos/

15
 16
 17 Intensive monitoring sites measure many of the indicators that are likely to be affected by
 18 climate change, but have mostly been located independently and so do not optimally
 19 represent either (1) the full range of forest condition variability, or (2) forest landscapes
 20 that are most likely to be affected by climate change (Hargrove et al. 2003). Forest
 21 inventories are able to detect long-term changes in composition and growth, but since
 22 they are limited in ability to attribute observed changes to climate, improvement in
 23 observing the potential causal variables associated with responses would help interpret

1 the results (Schreuder and Thomas 1991). Some additions to the list of measured
2 variables would also improve the inventory approach (The Heinz Center 2002; USDA
3 2003). Remote sensing, when coupled with models, can detect changes in vegetation-
4 response to climate variability (Running et al. 2004; Turner et al. 2004). Interpretation of
5 remote sensing observations is greatly improved by associating results with ground data
6 (Pan et al. 2006).

7
8 Maintaining continuity of remote sensing observations at appropriate temporal and spatial
9 scales must be a high priority. NASA's Earth Science division cannot support continued
10 operations of all satellites indefinitely, so it becomes a challenge for the community using
11 the measurements to identify long-term requirements for satellites, and provide a long-
12 term framework for critical Earth science measurements and products (NASA Office of
13 Earth Science 2004).

14
15 Another high-priority need is to improve ability to monitor the effects of disturbance on
16 forest composition and structure, and to attribute changes in disturbance regimes to
17 changes in climate. This will involve a more coordinated effort to compile maps of
18 disturbance events from satellite or other observation systems, to follow disturbances
19 with in situ observations of impacts, and to keep track of vegetation changes in disturbed
20 areas over time. There are several existing programs that could be augmented to achieve
21 this result, such as intensifying the permanent sample plot network of the FIA program
22 for specific disturbance events, or working with forest regeneration and restoration
23 programs to install long-term monitoring plots.

24 *3.7 How Changes in One System Affect Other Systems – Forests*

25
26 Disturbances in forests such as fire, insect outbreaks, and hurricanes usually kill some or
27 all of the trees and lower leaf area. These reductions in forest cover and leaf area will
28 likely change the hydrology of the disturbed areas. Studies of forest harvesting show that
29 removal of the tree canopy or transpiring surface will increase water yield, with the
30 increase proportional to the amount of tree cover removed (Stednick 1996). The response
31 will vary with climate and species, with wetter climates showing a greater response of
32 water yield to tree removal. For all studies, average water yield increased 2.5 mm for
33 each one percent of the tree basal-area removed (Stednick 1996). High-severity forest
34 fires can increase sediment production and water yield as much as 10 to 1000 times, with
35 the largest effects occurring during high-intensity summer storms (see review in
36 Benavides-Solorio and MacDonald 2001). An insect epidemic can increase annual water
37 yield, advance the timing annual hydrograph, and increase base flows (Bethlahmy 1974;
38 Potts 1984). Presumably, the same effects would occur for trees killed in windstorms and
39 hurricanes.

40
41 Disturbances can also affect native plant species diversity, by allowing opportunities for
42 establishment of non-native invasives, particularly if the disturbance is outside of the
43 range of variability for the ecosystem (Hobbs and Huenneke 1992). Areas most
44 vulnerable to invasion by non-natives are those areas that support the highest plant
45 diversity and growth (Stohlgren et al. 1999). In the western U.S., these are generally the

1 riparian areas (Stohlgren et al. 1998). We expect that disturbances that remove forest
2 litter or expose soil (fire, trees tipped over by wind) will have the highest risk for
3 admitting invasive non-native plants.

4 **3.8 Findings and Conclusions - Forests**

5 **3.8.1 Introduction**

6
7 Climate strongly influences forest productivity, species composition, and the frequency
8 and magnitude of disturbances that impact or reset forests. Below, we list the key points
9 from our literature review, coupled with the observed and projected trends in climate.
10 Four key findings stand out. First, we are already experiencing the effects of increased
11 temperature and decreased precipitation in the Interior West, the Southwest, and Alaska.
12 Forest fires are growing larger and more numerous, insect outbreaks are currently
13 impacting more than three times the area as fires and are moving into historically new
14 territory, and drought and insects have killed pinyon pine over large areas of the
15 Southwest. Second, an increased frequency of disturbance is at least as important to
16 ecosystem function as incremental changes in temperature, precipitation, atmospheric
17 CO₂, nitrogen deposition, and ozone pollution. Disturbances partially or completely reset
18 the forest ecosystems causing short-term productivity and carbon storage loss, allowing
19 better opportunities for invasive alien species to become established, and commanding
20 more public and management attention and resources. Third, interactions between
21 changing climate, changing atmospheric chemistry, disturbance, and forest ecosystems
22 are important, but poorly understood – so predicting the future of forest ecosystems is
23 difficult. Finally, we do not have the observing systems in place to separate the effects of
24 climate from those of other agents of change. We particularly lack a coordinated national
25 network for monitoring forest disturbance.

26 **3.8.2 Key Findings and Conclusions**

- 27
- 28 ▪ Climate effects on disturbances such as fire, insect outbreaks, and wind and ice
29 storms are very likely important in shaping ecosystem structure and function.
- 30
- 31 ▪ Temperature increases and drought have very likely influenced the massive insect
32 outbreaks in the past decade.
- 33
- 34 ▪ If warming continues as anticipated over the next 30 years:
 - 35 ○ The number of large, stand-replacing fires are likely to increase over the next
36 several decades.
 - 37 ○ The range and frequency of large insect outbreaks are likely to increase in the
38 next several decades.
 - 39 ○ Tree growth and forest productivity are likely to increase slightly on average,
40 and the growth season will very likely lengthen.
 - 41 ○ The impact of the expected warming on soil processes and soil carbon storage
42 is still unclear.

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- Rising CO₂ will very likely increase photosynthesis for forests.
 - On high fertility sites, this increased photosynthesis will likely increase wood growth and carbon stored in wood.
 - On low to moderate fertility sites, the increased photosynthesis will possibly be rapidly respired.
 - The response of photosynthesis to CO₂ for older forests is uncertain, but possibly will be lower than that of the younger forests that have been studied.
 - Effects of elevated CO₂ on soil carbon storage are poorly understood because soil carbon formation is slow. Long-term elevated CO₂ experiments are very likely necessary to predict soil responses
 - N deposition has very likely increased forest growth and will continue to do so. N deposition will likely increase the response of forest growth to CO₂.
 - If existing trends in precipitation continue (drier in the Interior West and Southwest, and higher in portions of the East), forest productivity will likely increase in portions of the eastern U.S. and decrease in portions of the western U.S. If the frequency of droughts increases, forest productivity will very likely be reduced and tree mortality likely increased where they occur.
 - Storm damage very likely reduces productivity and carbon storage. If projected increases in hurricanes and ice storms are realized, storm damage will very likely increase.
 - Monitoring the effects of climate change.
 - Current observing systems are very probably inadequate to separate the effects of changes in climate from other effects. Separating the effects of climate change would require a broad network of indicators, coupled with a network of controlled experimental manipulations.
 - Major indicators of climate change in forests are effects on physiology such as productivity, respiration, growth, net ecosystem exchange, and cumulative effects on tree rings, phenology, species distributions, disturbances, and hydrology. No national climate observation system provides measures of these indicators.
 - Major observation systems that can provide some information for forests include the USDA Forest Service FIA Program, AmeriFlux, USA National Phenology Network, LTER network and the upcoming National Ecological Observation Network, coupled with remote sensing.
 - No coordinated system exists for monitoring forest disturbance.

- 1 ○ The effects of climate change on disturbance and resulting species
2 composition, and the attribution of changes in disturbance to climate change is
3 one area where a well-designed observation system is a high priority need.
- 4 ○ A national climate observation system should be able to identify early
5 indicators of climate effects on ecosystem processes and observations of
6 structural and species changes.
- 7 ○ Large-scale experimental manipulations of climate, CO₂ and N have supplied
8 the most useful information on separating the effects of climate from site and
9 other effects. Experimental manipulations of precipitation and water
10 availability are rare, but supply critical information on long-term responses of
11 different species.
- 12

1 3.9 *Observed and Predicted Changes or Trends – Arid Lands*

2 **3.9.1 Introduction**

3

4 Arid lands occur in tropical, subtropical, temperate, and polar regions and are defined
5 based on physiographic, climatic and floristic features. Arid lands are characterized by
6 low (typically < 400 mm), highly variable annual precipitation, along with temperature
7 regimes where potential evaporation far exceeds precipitation inputs. In addition,
8 growing season rainfall is often delivered via intense convective storms, such that
9 significant quantities of water run off before infiltrating into soil; and precipitation falling
10 as snow in winter may sublimate or run off during snowmelt in spring while soils are
11 frozen. As a result of these combined factors, production per unit of precipitation can be
12 low. Given that many organisms in arid lands are near their physiological limits for
13 temperature and water stress tolerance, slight changes in temperature and precipitation
14 (e.g., higher temperatures that elevate potential evapotranspiration; more intense
15 thunderstorms that generate more run off) that affect water availability and water
16 requirements could have substantial ramifications for species composition and
17 abundance, and the ecosystem goods and services these lands can provide for humans.

18

19 The response of arid lands to climate and climate change is contingent upon the net
20 outcome of non-climatic factors interacting at local scales (Figure 3.9). Some of these
21 factors may reinforce and accentuate climate effects (e.g., livestock grazing); others may
22 constrain, offset or override climate effects (e.g., soils, atmospheric CO₂ enrichment, fire,
23 non-native species). Climate effects should thus be viewed in the context of other factors,
24 and simple generalizations regarding climate effects should be viewed with caution.
25 Today's arid lands reflect a legacy of historic land uses, and future land use practices will
26 arguably have the greatest impact on arid land ecosystems in the next two to five decades.
27 In the near-term, climate fluctuation and change will be important primarily as it
28 influences the impact of land use on ecosystems, and how ecosystems respond to land
29 use.

30

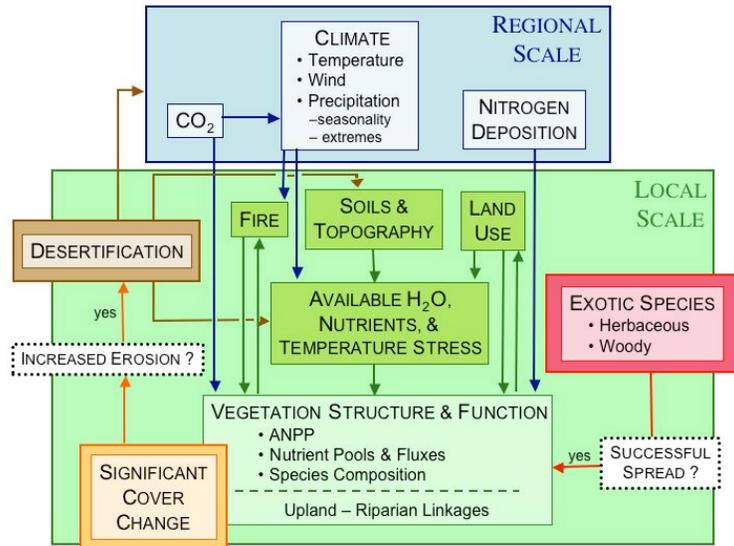


Figure 3.9 Organizational framework for interpreting climate and climate change effects on arid land ecosystems.

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3.9.2 Bio-Climatic Setting

4

5 Arid lands of the continental United States are represented primarily by the subtropical
6 Hot Deserts of the Southwest, and the temperate Cold Deserts of the Intermountain West
7 (Figure 3.2). The Hot Deserts differ primarily with respect to precipitation seasonality
8 (Figure 3.10). The Mojave Desert is dominated by winter precipitation (thus biological
9 activity in the cool season), whereas the Chihuahuan Desert is dominated by summer
10 precipitation (thus biological activity during hotter conditions). The hottest of the three
11 deserts, the Sonoran, is the intermediate, receiving both winter and summer precipitation.
12 The Cold Deserts are also dominated by winter precipitation, much of which falls as
13 snow, owing to the more temperate latitudes and higher elevations (West 1983). These
14 arid land formations are characterized by unique plants and animals, and if precipitation
15 seasonality changes, marked changes in species and functional group composition and
16 abundance would be expected.

17

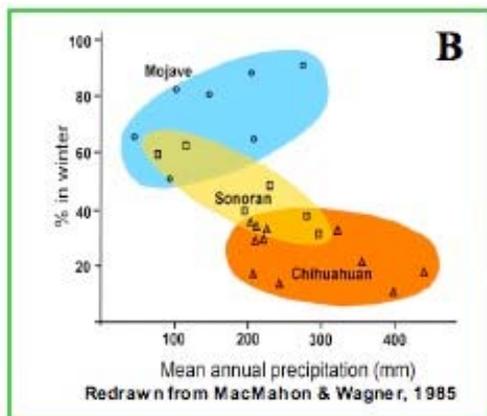
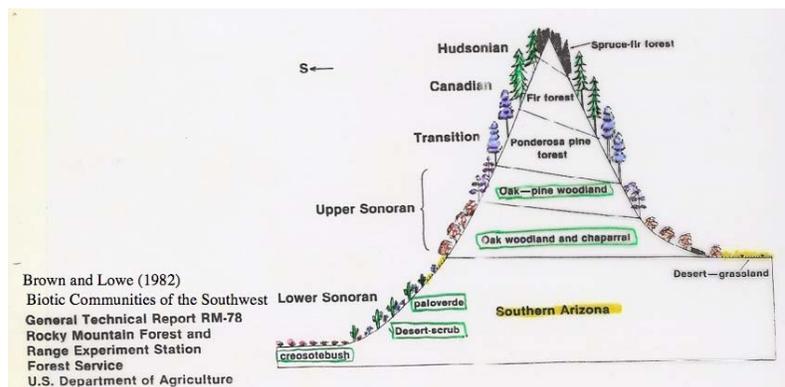


Figure 3.10 Mean annual precipitation and its seasonality in three Hot Deserts (from MacMahon and Wagner 1985).

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1 Such changes might first occur in the geographic regions where these formations and
 2 their major subdivisions interface. Extreme climatic events are major determinants of arid
 3 and semi-arid ecosystem structure and function (Holmgren et al. 2006). For example,
 4 while changes in temperature will affect levels of physiological stress and water
 5 requirements during the growing season, minimum temperatures during winter may be a
 6 primary determinant of species composition and distribution. In the Sonoran Desert, in
 7 addition to warm season rainfall, freezing temperatures strongly influence distributions of
 8 many plant species (Turner et al. 1995). The vegetation growing season, as defined by
 9 continuous frost-free air temperatures, has increased by on average about two
 10 days/decade since 1948 in the conterminous U.S., with the largest changes occurring in
 11 the West (Easterling 2002; Feng and Hu 2004). A recent analysis of climate trends in the
 12 Sonoran Desert (1960-2000) also shows a decrease in the frequency of freezing
 13 temperatures, lengthening of the frost-free season, and increased minimum temperatures
 14 (Weiss and Overpeck 2005). With warming expected to continue throughout the 21st
 15 Century, potential ecological responses may include contraction of the overall boundary
 16 of the Sonoran Desert in the southeast and expansion northward, eastward, and upward in
 17 elevation, and changes to plant species ranges. Realization of these changes will be co-
 18 dependent on what happens with precipitation and disturbance regimes (e.g., fire).

19
 20 The biotic communities that characterize many U.S. arid lands are influenced by Basin
 21 and Range topography. Thus, within a given bioclimatic zone, communities transition
 22 from desert scrub and grassland to savanna, woodland and forest along strong elevation
 23 gradients (Figure 3.11). Changes in climate will affect the nature of this zonation, with
 24 arid land communities potentially moving up in elevation in response to warmer and drier
 25 conditions. Experimental data suggest shrub recruitment at woodland-grassland ecotones
 26 will be favored by increases in summer precipitation, but unaffected by increases in
 27 winter precipitation (Weltzin and McPherson 2000). This suggests that increases in
 28 summer precipitation would favor down-slope shifts in this ecotone. Floristic and
 29 ecosystem process changes along these elevation gradients may precede those occurring
 30 on a regional basis, and as such, may be early indicators of climate change.



32
 33
 34 **Figure 3.11** Elevation life zones along an arid land elevation gradient (from Brown, 1994).
 35
 36

1 **3.9.3 Climate Influences at Local Scales**

2
3 Climate and atmospheric CO₂ influence communities at broad spatial scales, but
4 topography, soils, and landform control local variation in ecosystem structure and
5 function within a given elevation zone, making local vegetation very complex.
6 Topography influences water balance (south-facing slopes are drier), air drainage and
7 night temperatures, and routing of precipitation. Soil texture and depth affect water
8 capture, water storage, and fertility (especially nitrogen). These factors may interact with
9 water availability to limit plant production and control species composition. Plants that
10 can access water in deep soil or in groundwater depend less on precipitation for growth
11 and survival, but such plants may be sensitive to precipitation changes that affect the
12 recharge of deep water stores. If the water table increases with increases in rainfall or
13 decreased plant cover, soil salinity may increase and adversely affect vegetation
14 (McAuliffe 2003). To predict vegetation response to climate change, we need to
15 understand these complex relationships between soil, soil hydrology, and plant response.

16 **3.9.4 Climate and Disturbance**

17
18 Disturbances such as fire and grazing are superimposed against the backdrop of climate
19 variability, climate change, and spatial variation in soils and topography. The frequency
20 and intensity of a given type of disturbance will determine the relative abundance of
21 annual, perennial, herbaceous, and woody plants on a site. Extreme climate events such
22 as drought may act as triggers to push arid ecosystems experiencing chronic disturbances
23 such as grazing past desertification ‘tipping points’ (CCSP 4.2 2007; Gillson and
24 Hoffman 2007). An increase in the frequency of climate trigger events would put arid
25 systems increasingly at risk for major changes in vegetation cover. Climate is also a key
26 factor dictating the effectiveness of resource management plans and restoration efforts
27 (Holmgren and Scheffer 2001). Precipitation (and its interaction with temperature) plays
28 a major role in determining how plant communities are impacted by, and how they
29 respond to, a given type and intensity of disturbance. It is generally accepted that effects
30 of grazing in arid lands may be mitigated in years of good rainfall and accentuated in
31 drought years. However, this generalization is context dependent. Landscape-scale factors
32 such as rainfall and stocking rate affect grass cover in pre- and post-drought periods, but
33 grass dynamics before, during, and after drought varies with species-specific responses to
34 local patch-scale factors (e.g., soil texture, micro-topographic redistribution of water) (Yao
35 et al. 2006). As a result, a given species may persist in the face of grazing and drought in
36 some locales and be lost from others. Spatial context should thus be factored in to
37 assessments of how changes in climate will affect ecosystem stability (their ability to
38 maintain function in the face of disturbance (e.g., resistance)); and the rate and extent to
39 which they recover from disturbance (e.g., resilience). Advances in computing power,
40 geographic information systems, and remote sensing now make this feasible.

41
42 Disturbance will also affect rates of ecosystem change in response to climate change
43 because it reduces vegetation resistance to slow, long-term changes in climate (Cole
44 1985; Overpeck et al. 1990). Plant communities dominated by long-lived perennials may
45 exhibit considerable biological inertia and changes in community composition may lag

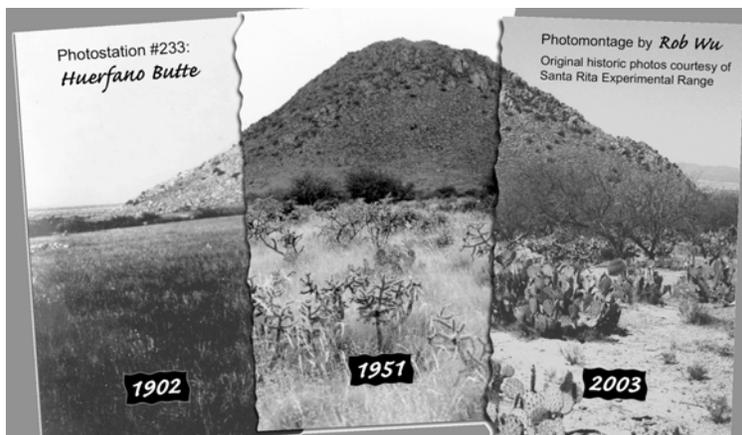
1 behind significant changes in climate. Species established under previous climate regimes
2 may thus persist in novel climates for long periods of time. Indeed, it has been suggested
3 that the desert grasslands of the Southwest were established during the cooler, moister
4 Little Ice Age but have persisted in the warmer, drier climates of the 19th and 20th
5 Centuries (Neilson 1986). Disturbances create opportunities for species better adapted to
6 the current conditions to establish. In the case of desert grasslands, livestock grazing
7 subsequent to Anglo-European settlement may have been a disturbance that created
8 opportunities for desert shrubs such as mesquite and creosote bush to increase in
9 abundance. Rates of ecosystem compositional change in response to climate change may
10 therefore depend on the type and intensity of disturbance, and the extent to which
11 fundamental soil properties (especially depth and fertility) are altered by disturbance.

12 **3.9.5 Desertification**

13

14 Precipitation and wind are agents of erosion. Wind and water erosion are primarily
15 controlled by plant cover. Reductions in plant cover by fire or grazing create
16 opportunities for accelerated rates of erosion; and loss of soils feeds back to affect species
17 composition in ways that can further reduce plant production and cover. Disturbances in
18 arid lands can thus destabilize sites and quickly reduce their ability to capture and retain
19 precipitation inputs. This is the fundamental basis for desertification, a long-standing
20 concern (Van de Koppel et al. 2002). Desertification involves the expansion of deserts
21 into semi-arid and subhumid regions, and the loss of productivity in arid zones. It
22 typically involves loss of ground cover and soils, replacement of palatable, mesophytic
23 grasses by unpalatable xerophytic shrubs, or both (Figure 3.12). There has been long-
24 standing controversy in determining the relative contribution of climatic and
25 anthropogenic factors as drivers of desertification. Local fence line contrasts argue for the
26 importance of land use (e.g., changes in grazing, fire regimes); vegetation change in areas
27 with no known change in land use argue for climatic drivers.

28



29

30

31 **Figure 3.12** Desertification of desert grassland (Santa Rita Experimental Range near Tucson, AZ).

32

33

34 Grazing has traditionally been the most pervasive and extensive climate-influenced land
35 use in arid lands (with the exception of areas where access to ground or surface water

1 allows agriculture; see Chapter 3.2). Large-scale, unregulated livestock grazing in the
2 1800s and early 1900s is widely regarded as contributing to widespread desertification
3 (Fredrickson et al. 1998). Grazing peaked around 1920 on public lands in the West; and
4 by the 1970s had been reduced by approximately 70 percent (Holechek et al. 2003).
5 These declines reflect a combination of losses in carrying capacity (ostensibly associated
6 with soil erosion, and reductions in the abundance of palatable species), and creation of
7 federally funded experimental ranges in the early 1900s (e.g., the Santa Rita
8 Experimental Range in Arizona, and the Jornada Experimental Range in New Mexico),
9 which are charged with developing stocking rate guidelines, the advent of the science of
10 range management, and federal legislation intended to regulate grazing (Taylor Grazing
11 Act 1934) and combat soil erosion (Soil Erosion Act 1935), and shifting of livestock
12 operations to higher rainfall regions. While livestock grazing remains an important land
13 use in arid lands, there has been a significant shift to exurban development and
14 recreation, reflecting dramatic increases in human population density since 1950 (Hansen
15 and Brown 2005). Arid land response to future climate will thus be mediated by new
16 suites of environmental pressures such as air pollution and N-deposition, motorized off-road
17 vehicles, feral pets, and horticultural invasives in addition to grazing.

18 **3.9.6 Biotic Invasions**

19
20 Arid lands of North America were historically characterized by mixtures of shrublands,
21 grasslands, and shrub-steppe or shrub-savanna. Since Anglo-European settlement, shrubs
22 have increased at the expense of grasses (Archer 1994). Causes for this shift in plant-life-
23 form abundance are the topic of active debate, but center around climate change,
24 atmospheric CO₂ enrichment, nitrogen deposition, and changes in grazing and fire
25 regimes (Archer et al. 1995; Van Auken 2000). In many cases, increases in woody plant
26 cover reflect the proliferation of native shrubs (e.g., mesquite, creosote bush); in other
27 cases, non-native shrubs have increased in abundance (e.g., tamarix). Historically, the
28 displacement of grasses by woody plants in arid lands was of concern due to its potential
29 impacts on stream flow and ground water recharge (Wilcox 2002), and livestock
30 production. More recently, the effects of this change in land cover has been shown to
31 have implications for carbon sequestration, and land surface-atmosphere interactions
32 (Schlesinger et al. 1990; Archer et al. 2001; Wessman et al. 2004). Warmer, drier
33 climates with more frequent and intense droughts are likely to favor xerophytic shrubs
34 over mesophytic native grasses, especially when native grasses are preferentially grazed
35 by livestock. However, invasions by non-native grasses are markedly changing the fire
36 regime in arid lands and impacting shrub cover.

37



1
2
3 **Figure 3.13** Top-down view of native sagebrush (*Artemisia tridentata*) steppe (right) invaded by cheatgrass
4 (*Bromus tectorum*), an exotic annual grass (left).
5
6

7 Non-native plant invasions, promoted by enhanced nitrogen deposition (Fenn et al. 2003),
8 will have a major impact on how arid land ecosystems respond to climate and climate
9 change. Once established, non-native annual and perennial grasses can generate massive,
10 high-continuity fine-fuel loads that predispose arid lands to fires more frequent and
11 intense than those with which they evolved (Figure 3.13). The result is the potential for
12 desert scrub, shrub-steppe, and desert grassland/savanna biotic communities to be quickly
13 and radically transformed into monocultures of invasive grasses over large areas. This is
14 already well underway in the Cold Desert region (Knapp 1998) and is in its early stages
15 in Hot Deserts (Williams and Baruch 2000; Kupfer and Miller 2005; Salo 2005; Mau-
16 Crimmins 2006). By virtue of their profound impact on the fire regime and hydrology,
17 invasive plants in arid lands will trump direct climate impacts on native vegetation where
18 they gain dominance. There is a strong climate-wildfire synchrony in forested ecosystems
19 of western North America (Kitzberger et al. 2007). As the areal extent of fire-prone
20 exotic grass communities increases, low elevation arid ecosystems will likely experience
21 similar climate-fire synchronization where none previously existed, and spread of low
22 elevation fires upslope may constitute a new source of ignition for forest fires. Exurban
23 development (Nelson 1992, Daniels 1999) will be a major source for exotic species
24 introductions by escape from horticulture.

25 **3.9.7 A Systems Perspective**

26

27 As reviewed in the preceding sections, the response of arid lands to climate and climate
28 change is contingent upon the net outcome of several interacting factors (Fig 3.9). Some
29 of these factors may reinforce and accentuate climate effects (e.g., soils, grazing); others
30 may constrain, offset or override climate effects (e.g., soils, atmospheric CO₂ enrichment,
31 fire, exotic species). Furthermore, extreme climatic events can themselves constitute
32 disturbance (e.g., soil erosion and inundation associated with high intensity rainfall
33 events and flooding; burial abrasion and erosion associated with high winds, mortality
34 caused by drought and extreme temperature stress). Climate effects should thus be
35 viewed in the context of other factors, and simple generalizations regarding climate

1 effects should be viewed with caution. This is not to say, however, that we do not have
2 data and theory to guide prediction of future outcomes. Today's arid lands reflect a
3 legacy of historic land uses, and future land use practices will arguably have the greatest
4 impact on arid land ecosystems in the next two to five decades. In the near-term, climate
5 fluctuation and change will be important primarily as it influences the impact of land use
6 on ecosystems and how ecosystems respond to land use. Given the concomitant changes
7 in climate, atmospheric CO₂, nitrogen deposition, and species invasions, it also seems
8 likely that novel wildland and managed ecosystems will develop (Hobbs et al. 2006). In
9 novel ecosystems, species occur in combinations and relative abundances that have not
10 occurred previously within our experience base in a given biome. These novel
11 ecosystems will present novel challenges and opportunities for conservation and
12 management.

13
14 The following sections will address specific climate/land use/land cover issues in more
15 detail. Section 3.10 will discuss climate and climate change effects on species
16 distributions and community dynamics and Section 3.11 will review the consequences for
17 ecosystem processes. Section 3.12 will focus on climate change implications for structure
18 and function of riparian and aquatic ecosystems in arid lands. Implications for wind and
19 water erosion will be reviewed in 3.13.

20 *3.10 Species Distributions and Community Dynamics*

21 **3.10.1 Climate-Fire Regimes**

22
23 The climate-driven dynamic of the fire cycle is likely to become the single most
24 important feature controlling future plant distributions in U.S. arid lands. Rising
25 temperatures, decreases in precipitation and a shift in its seasonality and variability, and
26 increases in atmospheric CO₂ and nitrogen deposition (Sage 1996) coupled with
27 invasions of exotic grasses (Brooks et al. 2004; Brooks and Berry 2006) will accelerate
28 the grass-fire cycle in arid lands and promote development of near monoculture stands of
29 invasive plants (D'Antonio and Vitousek 1992). The frequency of fire in the Mojave
30 Desert has dramatically increased over the past 20 years and effected a dramatic
31 conversion of desert shrubland to degraded annual-plant landscapes (Bradley et al. 2006,
32 Brooks and Berry 2006). Given the episodic nature of desert plant establishment and the
33 high susceptibility of the new community structure to additional fire, it will be
34 exceedingly difficult to recover native plant dominance. A similar conversion has
35 occurred in many Great Basin landscapes (Knapp 1995), and given the longer period of
36 non-native annual plant presence (Novak and Mack 2001), the pattern is much more
37 advanced and has lowered ecosystem carbon storage (Bradley et al. 2006). Contemporary
38 patterns in natural settings (Wood et al. 2006) and field experiments (Smith et al. 2000)
39 suggest non-native response to climate change will be extremely important in the
40 dynamics of arid land fire cycle, and changes in climate that promote fires will
41 exacerbate land cover change in arid and semi-arid ecosystems.

42
43 There is some debate as to how climate contributed to a non-native component of this
44 vegetation-disturbance cycle over the first half of the 20th century. For the upper

1 elevations in the Sonoran Desert, Lehmann lovegrass (*Eragrostis lehmanniana*), a
2 perennial African grass introduced for cattle forage and erosion control, has spread
3 aggressively and independently of livestock grazing (McClaran 2003). Its success relative
4 to native grasses appears related to its ability to more effectively utilize winter moisture
5 and greater seedling drought tolerance. Relatively wet periods associated with the Pacific
6 Decadal Oscillation appear to have been more important than increases in N-deposition
7 or CO₂ concentrations in the spread of the species (Salo 2005).

8
9 More recently, warm, summer-wet areas in northern Mexico (Sonora) and the
10 Southwestern U.S. have become incubators for perennial African grasses such as
11 buffelgrass (*Pennisetum ciliare*), purposely introduced to improve cattle forage in the
12 1940s. These grasses escape plantings on working ranches and, like exotic annual
13 grasses, initiate a grass-fire cycle (Williams and Baruch 2000). In the urbanized, tourism-
14 driven Sonoran Desert of southern Arizona, buffelgrass invasion is converting fireproof
15 and picturesque desert scrub communities into monospecific, flammable grassland.
16 Buffelgrass, like other neotropical exotics, is sensitive to low winter temperatures. The
17 main invasion of buffelgrass in southern Arizona happened with warmer winters
18 beginning in the 1980s, and its range will extend further north and upslope as minimum
19 temperatures continue to increase (Arriaga et al. 2004). This is complicated further by
20 ongoing germplasm research seeking to breed more drought- and cold-resistant varieties.
21 For example, a cold-resistant “Frio” variety of buffelgrass recently released by USDA-
22 Agricultural Research Service has been planted 40 km south of the Arizona border near
23 Cananea, Mexico. Escape of “Frio” north of the United States-Mexico border may extend
24 the potential niche of buffelgrass a few hundred meters in elevation and a few hundred
25 kilometers to the north.

26 **3.10.2 Drought and Vegetation Structure**

27
28 Over the past seventy-five years, the drought of the 1950s and the drought of the early
29 2000s represent two natural experiments for understanding plant community response to
30 future environmental conditions. While both had similar reductions in precipitation, the
31 1950s drought was typical of many Holocene period droughts throughout the Southwest,
32 whereas the drought that spanned the beginning of the 21st century was relatively hot
33 (with both greater annual temperatures and greater summer maximum temperatures)
34 (Breshears et al. 2005). The 1950s drought caused modest declines in the major shrubs in
35 the Sonoran Desert, whereas the 2000s drought caused much higher mortality rates in
36 numerous species, including the long-lived creosote bush (*Larrea tridentata*), which had
37 shown essentially no response to the 1950s drought (Bowers 2005). A similar pattern
38 was seen in comparing the two time periods for perennial species in the Mojave Desert,
39 where dry periods close to the end of the 20th century were associated with reductions in
40 shrubs and perennial grass species (Hereford et al. 2006). Thus, the greater temperatures
41 predicted to co-occur with drought portend increased mortality for the dominant woody
42 vegetation typical of North American deserts; and open the door for establishment of
43 exotic annual grasses. These patterns are mostly driven by changes in winter
44 precipitation, but in systems where summer rainfall is abundant, woody plant-grass
45 interactions may also be important. Given an increase in the frequency of these “global

1 warming type” droughts (e.g., Breshears et al. 2005), increases in summer active, non-
2 native C4 grasses (such as *Pennisetum ciliare* in the Sonoran Desert (Franklin et al.
3 2006)), and the increased probability of fire, a similar pattern of a wide-spread woody
4 vegetation conversion to degraded non-native grasslands can be anticipated for the hot
5 deserts of North America – a pattern similar to that already seen in the Great Basin
6 (Bradley et al. 2006).

7 **3.10.3 Plant Functional Group Responses**

8
9 Annual plants are a major source of plant diversity in the North American deserts
10 (Beatley 1967), but exotic annuals are rapidly displacing native annuals. The density of
11 desert annuals in the Sonoran Desert, at Tumamoc Hill in Tucson, AZ, has been reduced
12 by an order of magnitude since 1982 (from ~ 2,000 plants m⁻² to ~150 plants m⁻²)
13 (Venable and Pake 1999). Similar reductions have been recorded for the Nevada Test Site
14 (Rundel and Gibson 1996a). At the same time, there has been an increase in the number
15 of non-native annuals (Hunter 1991; Salo et al. 2005; Schutzenhofer and Valone 2006).
16 High CO₂ concentrations benefit non-native grasses more so than native species
17 (Huxman and Smith 2001, Nagel et al. 2004). Thus, when rainfall is relatively high in the
18 Mojave Desert, non-natives comprise about six percent of the flora and ~66 percent of
19 the community biomass, but when rainfall is restricted, they comprise ~27 percent of the
20 flora and > 90 percent of the biomass (Brooks and Berry 2006). Competition between
21 annuals and perennials for soil nitrogen during relatively wet periods can be intense
22 (Holzapfel and Mahall 1999). At the western fringe of the Mojave and Sonoran Deserts,
23 nitrogen deposition is tipping the balance toward the annual plant community (typically
24 non-native) with the resulting loss of woody native species (Wood et al. 2006).

25
26 Rising atmospheric CO₂ and increasing temperature are predicted to shift the competitive
27 ability of C3 versus C4 plants, altering the current pattern of C4 dominance in many
28 semi-arid ecosystems (Long 1991; Ehleringer et al. 1997; Poorter and Navas 2003).
29 Photosynthesis and stomatal conductance in mixed C3/C4 communities often show a
30 greater proportional response in C3 as compared to C4 species at elevated CO₂ (Polley et
31 al. 2002). However, community composition and productivity do not always reflect leaf
32 level patterns. It is likely that whole-system water budgets are significantly altered and
33 more effectively influence the competitive interaction as compared to any direct CO₂
34 effects on leaf function (Owensby et al. 1993; Polley et al. 2002).

35
36 Where C3 species have increased in abundance in elevated CO₂ experiments, the
37 photosynthetic pathway variation also reflected differences in herbaceous (C4) and
38 woody (C3) life forms. CO₂ enhancement of C3 woody plant seedling growth, as
39 compared to growth of C4 grasses, may facilitate woody plant establishment (Polley et al.
40 2003). Reduced transpiration rates from grasses under higher CO₂ may also allow greater
41 soil water recharge to depth, and favor shrub seedling establishment (Polley et al. 1997).
42 Changes in both plant growth and the ability to escape the seedling-fire-mortality
43 constraint are critical for successful shrub establishment in water-limited grasslands
44 (Bond and Midgley 2000). However, interactions with other facets of global change may
45 constrain growth form and photosynthetic pathway responses to CO₂ fertilization.

1 Increased winter temperatures would lengthen the C4 growing season. Greater primary
2 production at elevated CO₂ combined with increased abundance of non-native grass
3 species may alter fire frequencies (see 2.2.2.A). Nitrogen deposition may homogenize
4 landscapes, favoring grassland physiognomies over shrublands (Reynolds et al. 1993).
5 Changes in the occurrence of episodic drought may alter the relative performance of
6 these growth forms in unexpected ways (Ward et al. 1999). Predicting changes in C3
7 versus C4 dominance, or changes in grass versus shrub abundance in water-limited
8 ecosystems, will require understanding of multifactor interactions of global change.

9 3.10.4 Charismatic Mega Flora

10
11 Saguaro (*Carnegiea gigantea*) density is positively associated with high cover of
12 perennial vegetation (except for *Larrea tridentata*) and mean summer precipitation; but
13 total annual precipitation and total perennial cover are the best predictors of reproductive
14 stem density (Drezner 2006). Because of the importance of episodic freezing events, the
15 northeastern (high winter precipitation) and western (dry) portions of the southwestern
16 U.S. have lower saguaro densities than the southeastern (high summer precipitation)
17 areas, while the Northeast and Southeast both have very high reproductive stem densities
18 relative to the West. Despite predicted reductions in the number of freezing events (Weiss
19 and Overpeck 2005), predicted increases in annual temperature, loss of woody plant
20 cover from a greater frequency of ‘global warming-type’ droughts, and increasing fire
21 resulting from non-native grass invasions (Figure 3.14) suggest a restriction of the
22 Saguaro’s geographic range and reductions in abundance within its historic range.
23 The direct effects of rising CO₂ on climatic tolerance and growth of *Yucca brevifolia* also
24 suggest important shifts in this Mojave Desert species’ range (Dole et al. 2003). Growth
25 at elevated CO₂ improves the ability of seedlings to tolerate periods of cold temperature
26 stress (Loik et al. 2000). When applied to downscale climate outputs and included in the
27 rules that define species distribution, this direct CO₂ effect suggests the potential for a
28 slight increase in geographic range. However, like all long-lived, large-statured species in
29 the North American deserts, the frequency of fire will be a primary determinant of
30 whether this potential will be realized.



1
2 **Figure 3.14** Buffelgrass invasion of saguaro stand in the Tucson Mountains, Arizona (left); fire-damaged
3 saguaro (right). (Photos: Ben Wilder)
4

5 **3.11 Ecosystem Processes**

6 **3.11.1 Net Primary Production and Biomass**

7

8 Semi-arid and arid ecosystems of the western United States are characterized by low
9 plant growth (NPP), ranging from 20 to 60 g/m²/yr in the Mojave Desert of Nevada
10 (Rundel and Gibson 1996b) to 100 to 200 g/m²/yr (aboveground) in the Chihuahuan
11 Desert of New Mexico (Huenneke et al. 2002). In most studies, the belowground
12 component of plant growth is poorly characterized, but observations of roots greater than
13 nine meters deep suggest that root production could be very large and perhaps
14 underestimated in many studies (Canadell et al. 1996).
15

16 With water as the primary factor limiting plant growth, it is not surprising that the
17 variation in plant growth among desert ecosystems, or year-to-year variation within arid
18 ecosystems, is related to rainfall. Other factors, such as soil texture and landscape
19 position, also affect soil moisture availability and determine plant growth in local
20 conditions (Schlesinger and Jones 1984; Wainwright et al. 2002). Changes in the amount
21 and seasonal distribution of precipitation with global climate change can be expected to
22 have a dramatic impact on the dominant vegetation, NPP and carbon storage in arid
23 lands.
24

25 Jackson et al. (2002) found that plant biomass and soil organic matter varied
26 systematically in mesquite-dominated ecosystems across west Texas and eastern New
27 Mexico, demonstrating some of the changes that can be expected with future changes in
28 rainfall regimes. The total content of organic matter (plant + soil) in the ecosystem was
29 greatest at the highest rainfall, but losses of soil carbon in the driest sites were
30 compensated by increases in plant biomass, largely mesquite. Despite consistent
31 increases in aboveground carbon storage with woody vegetation encroachment, a survey
32 of published literature revealed no correlation between mean annual rainfall and changes
33 in soil organic carbon pools subsequent to woody plant encroachment (Asner and Archer
34 2007). Differences in soil texture, topography and historical land use across sites likely
35 confound assessments of precipitation influences on soil organic carbon pool responses to
36 vegetation change.

37 **3.11.2 Soil Respiration**

38

39 Soil respiration includes the flux of CO₂ from the soil to the atmosphere from the
40 combined activities of plant roots and their associated mycorrhizal fungi and
41 heterotrophic bacteria and fungi in the soil. It is typically measured by placing small
42 chambers over replicated plots of soil or estimated using eddy-covariance measurements
43 of changes in atmospheric properties, particularly at night. Soil respiration is the
44 dominant mechanism that returns plant carbon dioxide to Earth's atmosphere, and it is

1 normally seen to increase with increasing temperature. Mean soil respiration in arid and
2 semi-arid ecosystems is 224 g C/m²/yr (Raich and Schlesinger 1992; Conant et al. 1998),
3 though in individual sites, it can be expected to vary with soil moisture content during
4 and between years.

5 **3.11.3 Net Carbon Balance**

6
7 The net storage or loss of carbon in any ecosystem is the balance between carbon uptake
8 by plants (autotrophic) and the carbon released by plant respiration and heterotrophic
9 processes. Although elegant experiments have attempted to measure these components
10 independently, the difference between input and output is always small and thus
11 measurement errors can be proportionately large. It is usually easier to estimate the
12 accumulation of carbon in vegetation and soils on landscapes of known age. This value,
13 NEP, typically averages about 10 percent of NPP in forested ecosystems. Arid soils
14 contain relatively little soil organic matter, and collectively make only a small
15 contribution to the global pool of carbon in soils (Schlesinger 1977; Jobbagy and Jackson
16 2002). Given the low NPP of arid lands, they are likely to result in only small amounts of
17 carbon sequestration. Since soil organic matter is inversely related to mean annual
18 temperature in many arid regions (Schlesinger 1982; Nettleton and Mays 2007),
19 anticipated increases in regional temperature will lead to a loss of soil carbon to the
20 atmosphere, exacerbating increases in atmospheric carbon dioxide. Recent measurements
21 of NEP by micrometeorological techniques, such as eddy covariance, across relatively
22 large spatial scales confirm these relatively low carbon uptake for arid lands (Grunzweig
23 et al. 2003), but point to the role of life-form (Unland et al. 1996), seasonal rainfall
24 characteristics (Hastings et al. 2005, Ivans et al. 2006), and potential access to
25 groundwater as important modulators of the process (Scott et al. 2006).

26
27 In many areas of desert, the amount of carbon stored in inorganic soil carbonates greatly
28 exceeds the amount of carbon in vegetation and soil organic matter, but the formation of
29 such carbonates is slow and not a significant sink for carbon in its global cycle
30 (Schlesinger 1982, Monger and Martinez-Rios 2000). Some groundwater contains high
31 (supersaturated) concentrations of carbon dioxide, which is released to the atmosphere
32 when this water is brought to the Earth's surface for irrigation, especially when
33 carbonates and other salts precipitate (Schlesinger 2000). Thus, soil carbonates are
34 unlikely to offer significant potential to sequester atmospheric carbon dioxide in future
35 warmer climates.

36 **3.11.4 Biogeochemistry**

37
38 Arid-land soils often have limited supplies of nitrogen, such that nitrogen and water can
39 "co-limit" the growth of vegetation (Hooper and Johnson 1999). These nitrogen
40 limitations normally appear immediately after the receipt of seasonal rainfall. The
41 nitrogen limitations of arid lands stem from small amounts of N received by atmospheric
42 deposition and nitrogen fixation and rather large losses of N to wind erosion and during
43 microbial transformations of soil N that result in the losses of ammonia (NH₃), nitric
44 oxide (NO), nitrous oxide (N₂O), and nitrogen gas (N₂) to the atmosphere (Schlesinger et

1 al. 2006). These microbial processes are all stimulated by seasonal rainfall, suggesting
2 that changes in the rainfall regime as a result of climate change will alter N availability
3 and plant growth. N deposition is spatially variable, being greater in areas downwind
4 from major urban centers such as Los Angeles, increasing the abundance of herbaceous
5 vegetation and potentially increasing the natural fire regime in the Mojave Desert
6 (Brooks 2003).

7
8 In arid lands dominated by shrub vegetation, the plant cycling of N and other nutrients in
9 arid lands is often heterogeneous, with most of the activity focused in the soils beneath
10 shrubs (Schlesinger et al. 1996). The dynamics of these “islands of fertility” will
11 determine much of the response of desert vegetation to changes in climate. For instance,
12 so long as there are localized patches of high soil nutrient availability, shrub-dominated
13 vegetation may persist long after changes in climate might be expected to lead to the
14 invasion of non-native grasses.

15 **3.11.5 Trace-gases**

16
17 In addition to significant losses of N trace gases, some of which confer radiative forcing
18 on the atmosphere (e.g., N₂O), deserts are also a minor source of methane, largely
19 resulting from activities of some species of termites, and VOC gases from vegetation and
20 soils (Geron et al. 2006). VOCs can serve as precursors to the formation of tropospheric
21 ozone and organic aerosols, thus influencing air pollution. Emissions of such gases have
22 increased as a result of the invasion of grasslands by desert shrubs during the past 100
23 years (Guenther et al. 1999), and emissions of isoprene are well known to increase with
24 temperature. The flux of these gases from arid lands is not well studied, but is known to
25 be sensitive to temperature, precipitation, and drought stress. For example, total annual
26 VOC emissions in deserts may vary three-fold between dry and wet years; and slight
27 increases in daily leaf temperatures can increase annual desert isoprene and monoterpene
28 fluxes by 18 percent and seven percent, respectively (Geron et al. 2006). Thus, changes in
29 VOC emissions from arid lands can be expected to accompany changes in regional and
30 global climate.

31 **3.12 *Arid Land Rivers and Riparian Zones***

32
33 River and floodplain (riparian) ecosystems commonly make up less than one percent of
34 the landscape in arid regions of the world. Their importance, however, belies their small
35 areal extent (Fleischner 1994). They are highly productive ecosystems embedded within
36 much lower productivity upland ecosystems. They provide essential wildlife habitat for
37 migration and breeding, and these environments are critical for breeding birds, threatened
38 and endangered species, and arid-land vertebrate species. Riparian vegetation in arid
39 lands can occur at scales from isolated springs to ephemeral and intermittent
40 watercourses, to perennial rivers (Webb and Leake 2006). The rivers and riparian zones
41 of arid lands are dynamic ecosystems that are highly responsive to changing hydrology,
42 geomorphology, human utilization, and climate change. As such, river and riparian
43 ecosystems will likely prove to be responsive components of arid landscapes to future
44 climate change.

1
2 Global climate change can potentially impact river and riparian ecosystems in arid
3 regions through a wide variety of mechanisms and pathways (Regab and Prudhomme
4 2002). Three pathways in which riverine corridors in arid lands are highly likely to be
5 affected are particularly important. The first is the impact of climate change on water
6 budgets. Both sources of water and major depletions will be considered. The second is
7 competition between native and non-native species in a changing climate. The potential
8 importance of thresholds in these interactions will be explicitly considered. The third
9 mechanism pertains to the role of extreme climate events (e.g., flood and droughts) in a
10 changing climate. Extreme events have always shaped ecosystems, but the interactions of
11 a warmer climate with a strengthened hydrologic cycle are likely to be significant
12 structuring agents for riverine corridors in arid lands.

13 **3.12.1 Water Budgets**

14

15 Analysis of water budgets under a changing climate is one tool for assessing the impact
16 of climate change on arid-land rivers and riparian zones. Christiansen et al. (2004) have
17 produced a detailed assessment of the effects of climate change on the hydrology and
18 water resources of the Colorado River basin. Hydrologic and water resources scenarios
19 were evaluated through coupling of climate models, hydrologic models, and projected
20 greenhouse gas scenarios for time periods from 2010-2039, 2040-2069, and 2070-2099.
21 Average annual temperature changes for the three periods were 1.0, 1.7, and 2.4°C,
22 respectively, and basin-average annual precipitation was projected to decrease by three,
23 six, and three percent for the three periods, respectively. These scenarios produced annual
24 runoff decreases of 14, 18, and 17 percent from historical conditions for the three
25 designated time periods. Such decreases in runoff will have substantial effects on human
26 populations and river and riparian ecosystems, particularly in the lower elevation arid
27 land compartments of this heavily appropriated catchment (e.g., Las Vegas and Southern
28 California).
29

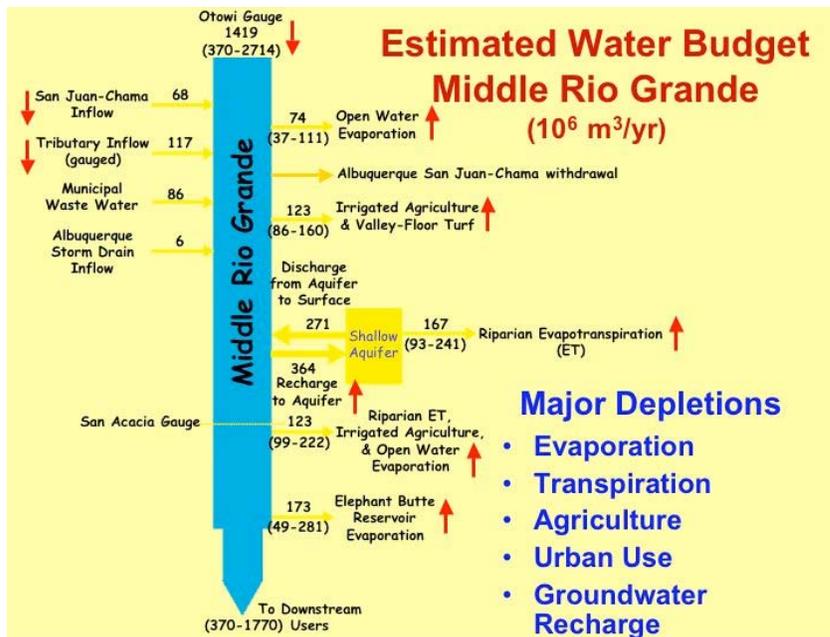


Figure 3.15 A water budget for a 320 km segment of the Middle Rio Grande of New Mexico, USA, with water sources on the left and top, depletions on the right, and downstream output on the bottom (Dahm et al. 2002). The red arrows indicate the direction of change for various water sources and depletions predicted with a warmer climate.

Changing climate also can have a significant effect on major depletions of surface waters in arid regions. Dahm et al. (2002) examined major depletions along a 320-km reach of the Rio Grande in central New Mexico. Major depletions were reservoir evaporation, riparian zone evapotranspiration, agriculture, groundwater recharge, and urban/suburban use. All of these depletions are sensitive to climate warming. Reservoir evaporation is a function of temperature, wind speed, and atmospheric humidity. Riparian zone evapotranspiration is sensitive to the length of the growing season, and climate warming will lengthen the period of time that riparian plants will be actively respiring (Goodrich et al. 2000; Cleverly et al. 2006), and also increase the growing season for agricultural crops dependent on riparian water. Temperature increases positively affect groundwater recharge rates from surface waters through changes in viscosity (Constantz and Thomas 1997, Costanz et al. 2002). The net result of climate warming is greater depletion of water along the riverine corridor (Figure 3.15). Global warming will place additional pressure on the major depletions of surface water in arid regions, in addition to likely effects on the supply side of the equation.

3.12.2 Native and Non-Native Plant Interactions

Competition between native and non-native species in a changing climate is a second area where climate change is predicted to have a substantial effect on riparian zones of arid lands. Riparian zones of arid lands worldwide are heavily invaded by non-native species of plants and animals (Prieur-Richard and Lavorel 2000; Tickner et al. 2001). Salt

1 cedar (*Tamarix spp.*) and Russian olive (*Elaeagnus angustifolia*) are particularly effective
2 invaders of the arid land riparian zones of the western United States (Brock 1994, Katz
3 and Shafroth 2003). Shallow ground water plays an important role in structuring riparian
4 plant communities (Stromberg et al. 1996) and groundwater level decline, whether by
5 human depletions or intensified drought in a changing climate, will alter riparian flora.
6 Stromberg et al. (1996) describe riparian zone “desertification” from a lowered water
7 table whereby herbaceous species and native willows and cottonwoods are negatively
8 impacted. Horton et al. (2001a, b) describe a threshold effect where native canopy
9 dieback occurs when depth to ground water exceeds 2.5-3.0 meters. Non-native salt cedar
10 (*Tamarix chinensis*), however, are more drought tolerant when water tables drop, and
11 readily return to high rates of growth when water availability again increases. Plant
12 responses like these are predicted to shift the competitive balance in favor non-native
13 plants and promote displacement of native plants in riparian zones under a warmer and
14 changing climate.

15
16 Another example of a threshold effect on river and riparian ecosystems in arid lands is
17 the persistence of aquatic refugia in a variable or changing climate. Hamilton et al. (2005)
18 and Bunn et al. (2006) have shown the critical importance of waterhole refugia in the
19 sustenance of biological diversity and ecosystem productivity in arid-land rivers. Arid
20 regions worldwide, including this example from inland Australia, are dependent on the
21 persistence of these waterholes during drought. Human appropriation of these waters or
22 an increase in the duration and intensity of drought due to climate change would
23 dramatically affect aquatic biodiversity and the ability of these ecosystems to respond to
24 periods of enhanced water availability. For example, most waterhole refugia throughout
25 the entire basin would be lost if drought persisted for more than two years in the Cooper
26 Creek basin of Australia, or if surface diversions of flood waters reduced the available
27 water within refugia in the basin (Hamilton et al. 2005; Bunn et al. 2006). Desiccation of
28 waterholes could become more common if climate change increases annual
29 evapotranspiration rates of if future water withdrawals reduce the frequency and intensity
30 of river flows to waterholes. Roshier et al. (2001) pointed out that temporary wetland
31 habitats throughout arid-lands in Australia are dependent upon infrequent, heavy rainfalls
32 and are extremely vulnerable to any change in frequency or magnitude. Climate change
33 that induces drying or reduced frequency of large floods would deleteriously impact
34 biota, particularly water birds that use these temporary arid-land habitats at broad spatial
35 scales.

36 **3.12.3 Extreme Events**

37
38 The role of extreme events (e.g., flood and droughts) in a changing climate is predicted to
39 increase with a warmer climate (IPCC 2007). Extreme climatic events are thought to
40 strongly shape arid and semi-arid ecosystems worldwide (Holmgren et al. 2006). Climate
41 variability, such as associated with the El Niño Southern Oscillation (ENSO)
42 phenomenon, strongly reverberates through food webs in many arid lands worldwide.
43 Riparian vegetation is especially sensitive to the timing and magnitude of extreme events,
44 particularly the timing and magnitude of minimum and maximum flows (Auble et al.
45 1994). GCMs do not yet resolve likely future regional precipitation regimes or future

1 temperature regimes. A stronger overall global hydrologic cycle, however, argues for
2 more extreme events in the future (IPCC 2007). The ecohydrology of arid-land rivers and
3 riparian zones will certainly respond to altered precipitation patterns (Newman et al.
4 2006) and the highly variable climate that characterizes arid-lands is likely to become
5 increasingly variable in the future.

6 *3.13 Wind and Water Erosion*

7
8 Due to low and discontinuous cover, there is a strong coupling between vegetation in arid
9 lands and geomorphic processes such as wind and water erosion (Wondzell et al. 1996).
10 Erosion by wind and water has a strong impact on ecosystem processes in arid regions
11 (Valentin et al. 2005, Okin et al. 2006). Erosion impacts the ability of soils to support
12 plants and erosion can deplete nutrient-rich surface soils, thus reducing the probability of
13 plant establishment and recruitment. Although erosion by water has received by far the
14 most attention in the scientific literature, the few studies that have investigated both wind
15 and water erosion have shown that they can be of similar magnitude under some
16 conditions (Breshears et al. 2003).

17 **3.13.1 Water Erosion**

18
19 Water erosion primarily depends on the erosivity of precipitation events (rainfall rate, and
20 drop size) and the erodibility of the surface (infiltration rate, slope, soil, and vegetation
21 cover). Climate change may impact all of these except slope. For instance, it is well
22 established that the amount of soil that is detached (and hence eroded) by a particular
23 depth of rain is related to the intensity at which this rain falls. Early studies suggest soil
24 splash rate is related to rainfall intensity and raindrop fall velocity (Ellison 1944; Bisal
25 1960). It is also well established that the rate of runoff depends on soil infiltration rate
26 and rainfall intensity. When rainfall intensity exceeds rates of infiltration, water can
27 runoff as inter-rill flow, or be channeled into rills, gullies, arroyos, and streams. The
28 intensity of rainfall is a function of climate, and therefore may be strongly impacted by
29 climate change. The frequency of heavy precipitation events has increased over most land
30 areas, including the United States, which is consistent with warming and observed
31 increases in atmospheric water vapor (IPCC 2007). Climate models predict additional
32 increases in the frequency of heavy precipitation, and thus highly erosive events.
33 Warming climates may also be responsible for changes in surface soils themselves, with
34 important implications for the erodibility of soils by water. In particular, higher
35 temperatures and decreased in soil moisture, such as those predicted in many climate
36 change scenarios, have been shown to decrease the size and stability of soil aggregates,
37 thus increasing their susceptibility to erosion (Lavee et al. 1998).

38
39 By far the most significant impact of climate change on water erosion is via its effects on
40 vegetation cover. The widespread conversion of grasslands to shrublands throughout the
41 desert Southwest (Van Auken 2000) has resulted in significantly greater erosion. Flow
42 and erosion plots in the Walnut Gulch Experimental Watershed in Arizona and the
43 Jornada LTER site in New Mexico have demonstrated significant differences in water
44 erosion between grasslands and shrublands (Wainwright et al. 2000). For instance,

1 greater splash detachment rates (Parsons et al. 1991, 1994, 1996), and inter-rill erosion
2 rates (Abrahams et al. 1988) are observed in shrublands compared to grasslands; and
3 shrubland areas are more prone to develop rills, which are responsible for significant
4 increases in overall erosion rates (Luk et al. 1993). Episodes of water erosion are often
5 associated with decadal drought-interdrought cycles because depressed vegetation cover
6 at the end of the drought makes the ecosystem vulnerable to increased erosion when rains
7 return (McAuliffe et al. 2006).

8
9 The arid regions of the United States have already experienced dramatic increases in
10 erosion rates due to widespread losses of vegetation cover. These changes have created
11 conditions where anticipated increases in precipitation intensity, coupled with reductions
12 in soil aggregate stability due to net warming and drying, will increase potential erosion
13 rates dramatically in the coming decades.

14 **3.13.2 Wind Erosion**

15
16 As with water erosion, the magnitude of wind erosion is related to both the erosivity of
17 the wind and the erodibility of the surface. However, the impact of increased wind
18 erosion in deserts can have continental-scale impacts because the resulting dust can travel
19 long distances with significant impacts to downwind ecosystems, air quality, and
20 populations. Both hemispheres have experienced strengthening of mid-latitude westerly
21 winds since the 1960s (IPCC 2007). This trend is likely to continue into the near future.
22 Thus, desert regions of the United States are likely to experience more erosive conditions
23 in the near future.

24
25 The susceptibility of soil to erosion by wind is determined by both the erodibility of the
26 surface soil and the amount of vegetation present to disrupt wind flows and shelter the
27 surface from erosion. As discussed above, anticipated net aridification in the desert
28 Southwest is likely to lead to a decrease in soil aggregate size and stability. Increased
29 temperatures and drought occurrence will result in lower relative humidity in arid lands.
30 Because the top few millimeters of soil are in equilibrium with soil moisture in the
31 overlying air, the decrease in relative humidity may result in soils that require less wind
32 power to initiate erosion (Ravi et al. 2006). Increased drought occurrence throughout the
33 western United States can further lead to lower soil moisture content, which can also
34 increase the erodibility of the soil (Bisal 1960; Cornelis et al. 2004).

35
36 Short- term changes in vegetation cause significant changes in the wind erodibility of the
37 surface. For instance Okin and Reheis (2002) and Reheis (2006) have shown that annual
38 variation in wind erosion on a regional scale is related to variation in precipitation. There
39 appears to be a one-year lag in this effect, with low precipitation one year resulting in
40 significant wind erosion and dust emission the following year. This lag is hypothesized to
41 be due to the fact that the effect of low precipitation must propagate through the system
42 by first affecting vegetation cover. This one-year lag effect has been observed in other
43 arid systems (Zender and Kwon 2005). In addition, dust emission from playas in the
44 desert Southwest also appears to occur after years of particularly intense rainfall. This
45 phenomenon seems to result from the increased delivery of fine-grained sediment to these

1 playas during especially wet years or years with intense rainfall events. Anticipated
2 climatic changes in the coming decades include both increase drought frequency and also
3 increased precipitation intensity during rain events (IPCC 2007). Both of these effects are
4 likely to increase wind erosion and dust emission in arid regions due to, in the first case,
5 suppression of vegetation and, in the second case, greater water erosion resulting in
6 increased delivery of fines to dry lakes.

7
8 Long-term and ongoing vegetation changes in arid regions, namely the conversion of
9 grasslands to shrublands, have dramatically increased wind erosion and dust production
10 due to increased bare areas in shrublands compared to the grasslands they replaced.
11 Measurements of aeolian sediment flux in the Chihuahuan Desert have shown nearly ten-
12 fold-greater rates of wind erosion and dust emission in mesquite-dominated shrublands
13 compared to grasslands on similar soils (Gillette and Pitchford 2004). Large-scale
14 conversion of grasslands to shrublands, coupled with anticipated changes in climate in
15 the coming decades, increases in wind speed, temperature, drought frequency, and
16 precipitation intensity, contribute to greater wind erosion in and dust emission from arid
17 lands.

18 **3.13.3 Impacts of Water and Wind Erosion**

19
20 Dust can potentially influence global and regional climate by scattering and absorbing
21 sunlight (Sokolik and Toon 1996) and affecting cloud properties (Wurzler et al. 2000),
22 but the overall effect of mineral dusts in the atmosphere is likely to be small compared to
23 other human impacts on the Earth's climate system (IPCC 2007). Desert dust is thought
24 to play a major role in ocean fertilization and CO₂ uptake (Duce and Tindale 1991; Piketh
25 et al. 2000; Jickells et al. 2005), terrestrial soil formation, and nutrient cycling (Swap et
26 al. 1992; Wells et al. 1995; Chadwick et al. 1999), and public health (Leathers 1981;
27 Griffin et al. 2001). In addition, desert dust deposited on downwind mountain snowpack
28 has been shown to decrease the albedo of the snowpack, thus accelerating melt by as
29 much as 20 days (Painter et al. 2007).

30
31 In arid regions, erosion has been shown to increase sediment delivery to large rivers (e.g.,
32 the Rio Grande), and can change the flow conditions of those rivers (Jepsen et al. 2003).
33 Transport of eroded sediment to streams can change conditions in waterways, impacting
34 water quality, riparian vegetation and water fauna (Cowley 2006).

35 **3.14 Indicators and Observing Systems – Arid Lands**

36 **3.14.1 Existing Systems**

37 38 **Long-Term Ecological Research (LTER) Sites**

39 Jornada Basin [Las Cruces, NM – <http://jornada-www.nmsu.edu/>]

40 Sevilleta [Albuquerque, NM – <http://sev.lternet.edu/>]

41 42 **National Ecological Observatory Network (NEON)**

1 Santa Rita Experimental Range [Tucson, AZ –
2 <http://www.sahra.arizona.edu/santarita/>]
3 Onaqui-Benmore [Salt Lake City, UT – <http://www.neoninc.org>]
4

5 **International Biome Project (IBP) Sites**

6 Rock Valley [Nevada Test Site, NV – archived at University of California, Los
7 Angeles, CA]

8 Silverbell [Arva Valley, AZ – archived at University of Arizona, Tucson, AZ]
9

10 **Free-Air CO₂ Enrichment (FACE) Site**

11 Nevada Desert FACE [Nevada Test Site, NV –
12 http://www.unlv.edu/Climate_Change_Research/]
13

14 **Land-Surface Flux Assessment Sites**

15 Audobon Ranch, Ameriflux Sites [<http://public.ornl.gov/ameriflux/>]

16 Semi-arid Ecohydrology Array (SECA)
17 [<http://eebweb.arizona.edu/faculty/huxman/seca/>]

18 ARS Flux Tower Network
19 [http://edcintl.cr.usgs.gov/carbon_cycle/FluxesResearchActivities.html]
20

21 **Rainfall Manipulations**

22 ARS Rainout Shelter [Burns, OR] (Svejcar et al. 2003)

23 Nevada Global Change Experiment
24 [http://www.unlv.edu/Climate_Change_Research/]
25

26 **Long-Term Ecological Data**

27 National Phenology Network [<http://www.uwm.edu/Dept/Geography/npn/>]

28 TRENDS Project [<http://fire.lternet.edu/Trends/>]

29 UA Desert Laboratory at Tumamoc Hill Permanent Plots [Tucson, AZ –
30 <http://www.paztcn.wr.usgs.gov/home.html>]

31 The Portal Project [Portal, AZ – [http://biology.unm.edu/jhbrown/Portal-](http://biology.unm.edu/jhbrown/Portal-LTREB/PortalFront.htm)
32 [LTREB/PortalFront.htm](http://biology.unm.edu/jhbrown/Portal-LTREB/PortalFront.htm)]
33

34 **National Park Service Inventory & Monitoring Program**

35 The NPS has recently initiated I&M program as many of its Parks and Monuments in
36 arid lands (<http://science.nature.nps.gov/im/>)
37

38 **Repeat Photography**

39 Repeat photography is a valuable tool for documenting changes in vegetation and
40 erosion. Hart and Laycock (1996) present a bibliography listing 175 publications using
41 repeat photography and information on the ecosystems photographed, where they are
42 located, number of photographs, and dates when the photographs were taken. More
43 recent publications have added to this list (e.g., Webb 1996; McClaran 2003; Webb et
44 al. 2007), and Hall (2002) has published a handbook of procedures. Time-series aerial
45 photographs dating back to the 1930s and 1940s are also a useful source for

1 quantifying landscape-scale changes in land cover (e.g., Archer 1996; Asner et al.
2 2003).

3 **3.15 Needs**

4
5 While the deserts of North America have been the site of many important ecological
6 studies, there have been relatively few long-term monitoring sites at an appropriate
7 spatial representation that allow us the means to access changes in ecosystem structure
8 and function in response to global change. Coordinated measurements of plant
9 community composition in plots across the North American deserts would enhance our
10 ability to detect change and relate that to aspects of climate. Several important data sets
11 stand as benchmarks – the long-term photographic record at the Santa Rita Experimental
12 Range, the long-term perennial plant and winter annual plant studies at Tumamoc Hill,
13 the long-term data collected from large-scale ecosystem manipulations at Portal Arizona,
14 and the new Mojave Desert Climate Change Program. Greater spatial representation of
15 such efforts is important in future assessment of change in these biomes.

16
17 Soil moisture is a key indicator and integrator of ecological and hydrological processes.
18 However, as noted in the Water Resources chapter (Chapter 4), there is a dearth of
19 information on the long-term patterns and trends in this important variable. Even on well-
20 instrumented watersheds in arid lands (e.g., Lane and Kidwell 2003; NWRC 2007;
21 SWRC 2007) soil moisture records are only erratically collected over time and are
22 limited in their spatial coverage and depth. Thus, there is a pressing need for a distributed
23 network of soil moisture sensors in arid lands. Ideally, such a network would also include
24 collection of plant, soil and precipitation samples for determination of the stable isotope
25 composition of C, O, and H. Such isotope data would provide important clues regarding
26 when and where plants were obtaining soil moisture and how primary production and
27 WUE are being affected by environmental conditions (e.g., Boutton et al. 1999; Roden et
28 al. 2000; Williams and Ehleringer 2000).

29
30 Most land-surface exchange research has focused on forested systems. There is, however,
31 a need for understanding the seasonal carbon dynamics, biomass, annual productivity,
32 canopy structure, and water use in deserts (Asner et al. 2003; Farid et al. 2006; Sims et
33 al. 2006). Part of this derives from our relatively poor understanding of non-equilibrium
34 processes in ecological systems - desert ecosystem function is driven by highly episodic
35 inputs of precipitation (Huxman et al. 2004). Part derives from the importance of the
36 strong, two-way coupling between vegetation phenology and the water cycle, which is
37 critical for predicting how climate variability influences surface hydrology, water
38 resources, and ecological processes in water-limited landscapes (e.g., Scanlon et al. 2005).
39 Shifts in phenology represent an integrated vegetation response to multiple environmental
40 factors, and understanding of vegetation phenology is prerequisite to inter-annual studies
41 and predictive modeling of land surface responses to climate change (White et al.
42 2005). Along these lines, the ability to detect ecosystem stress and impacts on vegetation
43 structure will be requisite to understanding regional aspects of drought (Breshears et al.
44 2005) that result in substantial land use and land cover changes.

1
2 In regions where the eroded surfaces are connected to the regional hydraulic systems
3 (e.g., not in closed basins), sediment delivery to streams and streambeds is an excellent
4 indicator of integrated erosion in the catchment. There is currently no integrated
5 monitoring system in place for the measurement of bedload, but the USGS National
6 Water Information System (<http://waterdata.usgs.gov/nwis>) does collect water quality
7 data that could inform sediment loads. Unfortunately, there are very few sites in the arid
8 U.S. that are monitored continuously. Additional arid region rivers could be instrumented
9 and sampled to provide further monitoring of water erosion. In closed basins, or the
10 upland portion of open basins, the development and expansion of rills and gullies is the
11 clearest indicator of water erosion. There is no system in place for the monitoring of these
12 features (Ries and Marzloff 2003), but high resolution remote sensing (~1-meter
13 resolution) might be used to monitor the largest of these features.

14
15 The most important indicator of wind erosion is the dust that it produces. Because dust is
16 transported long distances, even a sparse network of monitoring sites can identify dust
17 outbreaks. For instance, Okin and Reheis (2002) have used meteorological data collected
18 as part of the COOP network to identify dust events and to correlate them to other
19 meteorological variables. The expansion of this network to include observations in more
20 locations, and especially at locations downwind of areas of concern, would be a
21 significant improvement to monitoring wind in the arid portions of the United States.
22 This existing observation network might also be integrated with the Aeronet aerosol
23 monitoring network and radar or lidar systems deployed throughout the region, but
24 particularly near urban centers and airports. In addition, there are several remote sensing
25 techniques that can be used to identify the spatial extent and timing of dust outbreaks
26 (Chomette et al. 1999; Chavez et al. 2002; Miller 2003), though there is no system in
27 place to integrate or track the evolution of dust sources through time.

28 *3.16 Findings and Conclusions – Arid Lands*

29 **Species Distributions and Community Dynamics**

- 30
31
- 32 ■ Responses to climate trends in the Sonoran Desert (decrease in the frequency of
33 freezing temperatures, lengthening of the freeze-free season, and increased
34 minimum temperatures (Weiss and Overpeck 2005)) may include contraction of
35 the overall boundary of the Sonoran Desert in the southeast, and expansion
36 northward, eastward, and upward in elevation, and changes to plant species
37 ranges. Realization of these changes will be co-dependent on what happens with
38 precipitation and disturbance regimes (e.g., fire). Similar scenarios can be
39 expected for other deserts.
 - 40 ■ Experimental data suggest that shrub recruitment at woodland-grassland ecotones
41 along elevation gradients will be favored by increases in summer precipitation,
42 but will be unaffected by increases in winter precipitation (Weltzin and
43 McPherson 2000). This suggests increases in summer precipitation, should they
44 occur, would favor down-slope migration of woodland boundaries.

- 1 ▪ “Global warming type” droughts, such as those early in the 21st Century, will
2 increase rates of perennial plant mortality in arid lands, accelerate rates of erosion,
3 and create opportunities for exotic plant invasions.
- 4 ▪ Proliferation of non-native annual and perennial grass will predispose sites to fire
5 resulting in a loss of native woody plants and charismatic mega flora. Low
6 elevation arid ecosystems will henceforth experience climate-fire synchronization
7 where none previously existed (Figure 3.16).
- 8 ▪ By virtue of their profound impact on the fire regime and hydrology, invasive
9 plants in arid lands will trump direct climate impacts on native vegetation where
10 they gain dominance. The climate-driven dynamics of the fire cycle is likely to
11 become the single most important feature controlling future plant distributions in
12 U.S. arid lands.
- 13 ▪ Greater temperatures predicted to co-occur with drought portend increased
14 mortality for the dominant woody vegetation typical of North American Deserts;
15 and open the door for establishment of exotic annual grasses
- 16 ▪ Due to climate-fire interactions, wide-spread conversion of shrubland to degraded
17 non-native grasslands is anticipated for the hot deserts of North America
- 18 ▪ The main invasion of exotic buffelgrass in southern Arizona happened with
19 warmer winters beginning in the 1980s, and its range will extend further north and
20 upslope as minimum temperatures continue to increase (Arriaga et al. 2004). This
21 upslope and northward extension will be promoted by the introduction of cold-
22 resistant cultivars
- 23 ▪ Exurban development will be a major source for exotic species introductions by
24 escape from horticulture

26 **Ecosystem Processes**

- 28 ▪ Plant productivity is strongly water limited, and is thus vulnerable to changes with
29 changes in regional precipitation.
- 30 ▪ Arid soils contain relatively little soil organic matter, and collectively make only a
31 small contribution to the global pool of carbon in soils (Schlesinger 1977;
32 Jobbagy and Jackson 2002).
- 33 ▪ Low plant productivity limits the amount of carbon sequestration that can be
34 expected per unit area; but given the large geographic extent of drylands, their
35 contribution to carbon storage is potentially significant.
- 36 ▪ The risk of loss of ecosystem carbon pools is high; greatest losses will be
37 associated with desertification processes and annual plant invasions.
- 38 ▪ Arid land soils are often deficient in nitrogen, so (1) erosional losses of soil
39 nitrogen will further restrict regional productivity; and (2) vegetation, especially
40 exotic grasses, will be very responsive to N-deposition.
- 41 ▪ N deposition is spatially variable, being greater in areas downwind from major
42 urban centers,
- 43 ▪ Emissions of volatile organic carbon gases have increased as a result of the
44 displacement of grasslands by desert shrubs during the past 100 years

46 **Riparian Systems**

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- Climate change will place increasing pressure on montane water sources to arid land rivers and increase the magnitude of all major water depletions in arid land river and riparian ecosystems.
- The net result of climate warming will be greater depletion of water along riverine corridors
- The balance of competition between native and non-native species in riparian zones will continue to shift towards favoring exotics as temperatures increase, as the timing and amount of water shifts, and as the intensity of disturbances are magnified (Figure 3.17).
- Major disturbances that structure arid-land riverine corridors (e.g., floods, droughts) are likely to increase in number and intensity.
- Land use change, increased nutrient availability, increasing human water demand, and the continued pressure from non-native species will act synergistically with climate warming to restructure the rivers and riparian zones of arid lands.

Erosion

- Climate change directly impacts the erosivity of precipitation and winds.
- Increases in precipitation intensity and the proportion of precipitation that comes in high-intensity storms will increase water erosion from uplands and delivery of nutrient-rich sediment to riparian areas (Figure 3.18).
- Increases in wind speed and gustiness will increase wind erosion, dust emission, and transport of nutrient-rich dust to downwind ecosystems, causing more rapid spring melt and shorter availability of snowmelt for human use.
- Climate change indirectly influences erodibility of the surface via effects on vegetation cover.
- Higher temperatures and decreased soil moisture will reduce the stability of surface soil aggregates, making the surface more erodible.



Figure 3.16 Mojave Desert scrub near Las Vegas, NV (foreground); and area invaded by the exotic annual grass (*Bromus madritensis*) background following a fire that carried from desert floor upslope into pinyon-juniper woodlands (photo: T.E. Huxman).

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Figure 3.17 Non-native salt cedar (right) has invaded and displaced native cottonwood and poplar forests (left) in many southwestern riparian corridors.



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Figure 3.18 Dust storm in Arizona.

