CHAPTER 11

Economics and Societal Considerations of Drought

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Introduction

The economic and social effects of drought are diverse and related to physical characteristics of drought, including spatial extent, severity, duration, and frequency that combine to determine drought's overall effects on society. Most of the attention given to economic and social impacts of drought focuses on adverse consequences, but technology, public policies, economic activity, and social systems are largely adapted to the historical occurrence of drought—at least within the normal range. This chapter covers traditional impacts from drought, and also highlights possible adaptations, noting when adaptation may be difficult due to growing stresses on water resources in response to changes in global climate and regional demographics.

Droughts of particular combinations of severity, duration, and spatial extent occur at varying frequency—say, once in 50 years or once in 100 years. These dimensions can be relatively stationary in a location's climate, or they can change along with climate. The multiple dimensions of any given drought determine its effects on forest and rangeland systems, on society, and on the economy (Hornbeck 2012, McLeman and others 2014). Short, local, or mild droughts may have effects that are imperceptible in the larger forest and rangeland sector because of adaptation to these variations in water status and flows. The historical occurrence of these "average" droughts have created the conditions that determined forest and rangeland characteristics as well as the land use, technology, and production patterns of the associated human communities.

In contrast to the adaptations that society has made to more typical droughts, the United States has experienced droughts that were extreme in one or more of their characteristics, with significant consequences for technology, policies, economic activity in water-sensitive sectors, and social systems. Extreme droughts could occur more often or more widely in the United States in the future (Wuebbles and others 2014). Predictions from Wuebbles and others (2014) include significant drying in the winter and spring months in the North American monsoon region of the West (affecting mainly Arizona, New Mexico, and parts of Utah and Colorado). For the Southeastern United States, models project greater interannual variability in precipitation. Models project overall average drying of the continental United States throughout the 21st century, relative to 20th century conditions. Much of the projected drying in the Southeastern United States would occur through overall higher average temperatures, leading to increased evapotranspiration, compared to the average levels observed in recent history.

Wuebbles and others (2014) refer to shifts in distributions of precipitation and temperature—and hence drought—in ways that make droughts either longer in duration, more severe, more frequent, or, potentially, more widespread. The overall implication is that the likelihood of large magnitude droughts could be higher in the coming decades. As a result, we might expect society in general and local economies in particular to be challenged more regularly and more forcefully to adapt to these climate changes. Adaptation could entail the development of new and application of existing technologies, policies, and resource management approaches that can aid water-sensitive economic sectors—and society more broadly—to better withstand the negative consequences of drought.

In this chapter, we discuss how drought affects economic and social systems and then evaluate some specific effects of drought on forest and rangeland economies and societies. We describe a conceptual model of social and economic systems that defines where and how droughts are expected to influence these systems, and we examine social and economic resilience and the policies and programs that have been enacted to promote and maintain resilience. We address the direct effects of drought on the timber products sector, forest and rangeland water supplies, and the rangeland sector; and the indirect effects of drought on wildfire suppression expenditures. Finally, we examine nonmarket effects that include changes in recreation, effects on urban communities, and effects on tribal values and lifeways.

General Economic and Social Effects of Drought in Forests and Rangelands

An Economic and Social Conceptual Model of Drought

We begin by describing a conceptual model of drought impacts on the economy and society more broadly (fig. 11.1). The model shows how market and nonmarket goods and services are produced by an economy interacting with nature and how drought affects that production. Figure 11.1 shows that society has two broad classes of inputs that can be used to obtain desired goods and services: free inputs and purchased inputs. Free inputs are those that nature

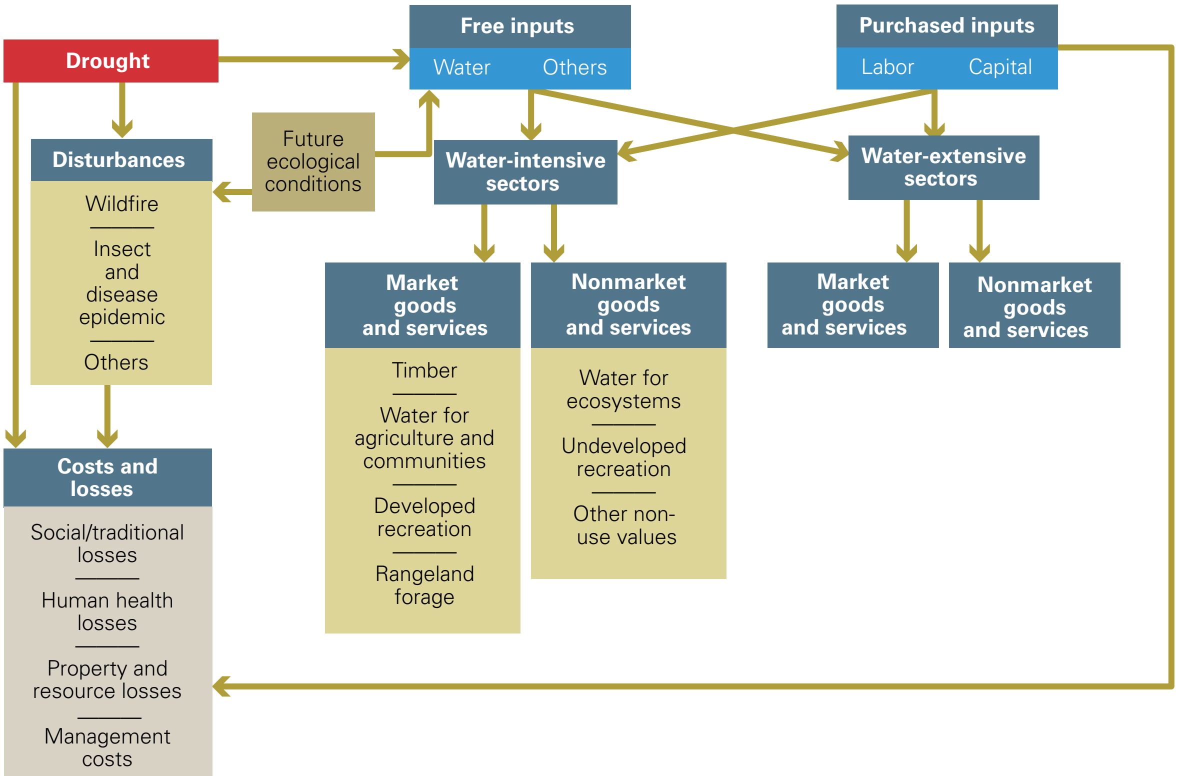

Figure 11.1—A conceptual model of an economy and society, which can produce and consume goods and services that are either water-intensive or water-extensive, and are affected by drought. (Colored boxes within encompassing squares are subcategories or examples).

provides (but humans can alter them subsequently and intervene to affect their distribution or character), such as water and sunshine and air. Purchased inputs, including capital and labor, are provisioned by society.[1] Two parts of society, described as sectors, are either water-intensive or water-extensive.[2] Each of these two sectors produces market and nonmarket goods and services. Drought alters the quantities (and qualities) of free inputs that are available to produce goods and services in both sectors, thus altering production possibilities and shifting supply curves in the markets for goods and services that depend on them. Drought also directly and indirectly results in costs and losses. Direct losses include the flows of timber, range forage, and water services. Direct costs include research (Miao and Popp 2014) and actions (e.g., construction) designed to reduce the extent of losses. Indirect losses derive from changes in ecological conditions, which means that drought changes the quantities of free inputs available to society for future production of goods and services. In terms of market goods and services that are water-intensive, possible categories of goods and services (there could be more) include timber (requiring water to grow), water for agriculture and communities (direct human consumption), developed recreation (e.g., downhill skiing, motorized water-based sports), and undeveloped recreation (e.g., cross-country skiing, nonmotorized water-based sports).[3] Nonmarket goods and services in forests and rangelands that are water-intensive include ecosystem health, plant and animal habitat, and the general quality of landscape esthetics.

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[1] Capital and labor, however, embody some water themselves, but this does not alter the general principles laid out in this conceptual model.

[2] A water-intensive sector is one for which some form of water is a major input to producing an output. A water-extensive sector is one for which water is a minor input, perhaps only embodied in the capital and labor used to produce the output.

[3] We note that the terms "water-intensive" and "water-extensive" are most often associated with agriculture and cropping systems, and thus entirely appropriate in most parts of the economy that we examine in this chapter. Recreation activities, on the other hand, might more accurately be classified as "water-dependent" or "nonwater-dependent."

Much of the research on the economic effects of drought on forests and rangelands has focused on quantifying how drought might affect the quantities and market values of the goods and services shown in the subcategories (mustard and gray boxes) in figure 11.1, as opposed to quantifying the effects on the economic value of market production and consumption (welfare). Our conceptual model attempts to address Logar and van den Bergh's (2013) criticism that while there have been many attempts to quantify the "costs" of drought, there is no comprehensive framework for understanding drought's effects on an entire economy or society in terms of overall economic welfare. Taking this broad perspective, Logar and van den Bergh (2013) delineate the societal effects of drought into three categories: (1) direct, focusing on costs and losses on primary producing sectors that consume and manage water; (2) indirect, by altering the amounts of inputs available for production in other sectors and by adding effects on disturbances such as wildfires and insect and disease epidemics, which themselves affect free inputs available to society and also induce allocation of purchased inputs for management; and (3) nonmarket, including effects on human and ecosystem health and social and cultural values.

Table 11.1 combines our conceptual model with the categorization advanced by Logar and van den Bergh (2013). As such, it lists several categories of goods and services production that could represent some of the subcategories (mustard and gray boxes) shown in figure 11.1. The forest and rangeland-related market goods and services that are water-intensive include timber production, forest and rangeland water supply sources, and rangeland production. The nonmarket effects coincide with those in the water-intensive nonmarket goods and services box shown in figure 11.1. Table 11.1 indicates whether the effect is direct, indirect, and/or nonmarket as well as the specific effects that occur and sometimes can be measured. In latter sections of this chapter, we provide some examples of effects found by researchers in most of these categories.

Figure 11.1 does not show many of the dynamics of society, specifically how drought that affects production of one category of good or service may change conditions faced in the production of another good or service. This chapter's appendix provides a graphical description of how drought can lead to shifts in supply and demand, affecting equilibrium market prices and quantities and economic welfare (Just and others 1982) in water-intensive and water-extensive parts of an economy. The appendix also describes how neoclassical economics would approach quantification of the effects of drought on markets for goods and services produced by forests and rangelands.

The economic effects of drought are complex because of the interplay among physical, social, and technological responses to drought. For example, drought lowers output in the water-intensive sectors of an economy, lowering wages, the price of capital (interest rates), and the prices of other inputs to production in the water-intensive sector, such as land. Drought also leads to lower income through its negative effects on the price of capital and labor (wage rates). Water-extensive sectors, however, can benefit from drought, as the costs of labor and capital decline; output increases while the prices of goods in those sectors decrease. Nevertheless, the overall effect on the economy, when both water-intensive and water-extensive sectors are combined, is to reduce wages, interest rates, and income. New technology introduced to the water-intensive sector can help to mitigate the negative effects of drought, allowing for more efficient use of water for each unit of water-intensive good output. Technology can be introduced through efforts of either the private sector or the public sector. It should be noted that capital markets are large and fluid, so technology investments would put only very slight upward pressure on interest rates.

There are a few notable studies on describing societies' responses to drought and their ability to mitigate negative impacts through new investments in technology. Banerjee and others (2013) describe the direct and indirect economic effects of drought from an ecosystems perspective, quantifying the "Millennium Drought" in Australia (1997–2010). The study focuses on quantifying impacts, not on measuring how economic welfare (see appendix) was affected by drought or how it would be in the future as a result of drought-related investments. It does, however, list the expenditures on mitigation and investments designed to help the region withstand future droughts with lower overall negative consequences for economic welfare. The study indicated that AU$810 million [US$745 million, at 2010 exchange rates (OZF-REX Foreign Exchange Services 2014)] was spent during the drought to mitigate the drought's effects and to better withstand future droughts. Expenditures included those by the national government to build a new system of integrated water pipelines to more efficiently allocate water among agricultural and potable water users.

Table 11.1—Economic and societal effects of drought in forests and rangelands

Type of effect	Economic subsector or aspect	Mechanism	Effects
Direct and indirect	Timber products sector	Reduced net volume growth	Lower income and employment, altered land use away from active forestry
Direct and indirect	Forest- and rangeland-based water	Reduced water quantity and quality	Lower consumption quantities, lower water quality, shifted water provision timing, higher water prices and treatment costs
Indirect	Wildfire management	Higher wildfire activity	Increased expenditures on suppression, fuels management, prevention, and post-fire mitigation by public and private landowners; greater losses of natural resources, reduced overall economic output in the economy due to wildfire-related evacuations, morbidity, and mortality
Indirect	Insect and disease management	Increased insect and disease activity	Increased expenditures on monitoring, suppression, and mitigation by public agencies and private individuals; higher prices and lower overall output and spatio-temporal shifts in production of valued ecosystem goods and services
Indirect	Rangeland sector	Reduced growth of vegetation needed by livestock and wildlife	Lower livestock production, higher livestock prices; lower wildlife populations and therefore fewer opportunities for hunting
Indirect	Urban and residential communities	Reduced growth to landscape plants, increased tree mortality, higher vulnerability to other disturbances	Lower property values, reduced shading resulting in higher energy costs, deterioration in human health and welfare
Nonmarket	Recreation sector	Altered ability of forests and rangelands to provide various types of recreation opportunities	Shifts in spending by recreationists across time, space, type, and to other sectors; lower fish populations and fewer fishing opportunities
Nonmarket	Human health	Increased air particulate matter	Increased rates of respiratory illness-related admissions to medical facilities due to wind-blown dust and wildfire smoke
Nonmarket	Indigenous cultures	Altered provision of water-affected ecosystem goods and services valued by indigenous cultures	Changes in the consumption and therefore the religious experiences available; altered rates of consumption of nontimber forest products
Nonmarket	Wildlife habitat	Reduced quantity and quality of habitat with potential endangerment or extinction of at-risk species	Increased management cost for species identified as threatened or endangered; potential cost of management restrictions on identified critical habitat; potential loss of genetic diversity

The South Australian government also bought water allocations from agricultural users and used this water to meet critical human needs and protect important drought-threatened riparian habitat. Mitigation costs also included expenditures by the South Australian government to repair levees damaged by floodplain subsidence; modify bridges, ferry landings, and pipelines to low-flow conditions; repair roads damaged by subsidence-related slumping and collapse; build new monitoring systems for threatened infrastructure; buy new and more efficient irrigation infrastructure; lime drought-exposed lakebeds to help reduce drought-related soil acidification; revegetate drought-exposed lakebeds; and buy water from the water market to create an environmental water reserve.

The Banerjee and others (2013) study described the extensive efforts of Australian government entities to mitigate and adapt to drought in anticipation that future droughts might be as severe. The study provides a specific example of how drought affected the production of goods and services and stimulated actions by government to help mitigate it. A study by Hornbeck (2012) details some of the economic and social effects of the American Dust Bowl of the 1930s, a drought that had large economic and social consequences, as well. This study is informative of how scientists can use historical data to analyze drought's economic effects. The study also highlights the consequences of an inability to anticipate or respond to severe drought: the region affected was not resilient enough to absorb its impacts without profound economic and social change. Hornbeck (2012) compares the long-run fates of low-, medium- and high-erosion counties in the affected region of the Great Plains. One effect was the reallocation of farmland from water-intensive to less water-intensive uses (especially from crops to pasture for livestock). However, the majority of the Dust Bowl's effects in the agricultural sector were manifested in significant net out-migration of people from affected regions and associated reductions in income, rather than through reallocations of resources to other sectors locally such as to industry or through investments into new technologies. As a result, agricultural sector impacts are quantified through changes in land values, which embody the long-run expected value of profits from these agricultural uses. In the affected region, land values declined by 30 percent in highly eroded counties and by 17 percent in medium-eroded counties, when compared to less-eroded counties. Further, losses in land values in most affected counties persisted at least into the 1990s—60 years. Hornbeck (2012) emphasizes that there were spatial effects tied to soil losses, creating shifts in production from more-eroded to less-eroded counties, coupled with an overall decline in output and hence higher prices, which resulted in land value increases in the latter that partially compensated for the land value losses in the former. Maladaptation by farmers to dustbowl conditions and the buildup of farm debt created additional vulnerability of the local population. In summary, drought (as with any natural disaster) can result in spatial as well as spatio-temporal reallocations of resources within affected sectors, which can mitigate overall losses to the sector. Moreover, drought can force reallocations across sectors, and these effects can be quantified by changes in incomes generated in each sector.

Societal and Economic Resilience

The experience of the 1930s Dust Bowl in America highlights the importance of societal and economic resilience in the face of large-scale and intense disturbances. In general, ecosystem stress due to drought increases societal and economic costs (such as those associated with emigration from drought-stricken areas) and losses (such as diminished land values resulting from reduced productivity) (Hornbeck 2012). The ability to withstand and recover from ecosystem stresses with minimal costs and losses reflects the degree of societal and economic resilience (Holmes and others 2014). For typical drought conditions, societal and economic resilience may be fairly high. For example, when confronted with normal dry spells, homeowners typically increase irrigation of their lawns and other landscaping to a degree sufficient to alleviate vegetative stress. Although simple actions such as these may entail costs and losses, they often are relatively modest. Further, resilience to typical drought conditions is high because a low-cost technology (irrigation) is usually accessible due to prevailing institutions (such as markets and public water supplies) and prior knowledge is adequate. However, as the severity, duration, and spatial extent of drought conditions increase, routine mitigation actions based on prior knowledge and accessible technology may not always produce the desired effect, and communities may incur substantial cost plus loss amounts. In particular, societal and economic cost plus loss amounts may increase at an increasing rate with greater ecosystem stress as the ability to mitigate damages is reduced and resilience is gradually exceeded. This dynamic process is shown graphically in figure 11.2, where the horizontal axis measures any or a combination of the three dimensions of ecosystem stress (severity, duration, spatial extent). Modest cost plus loss amounts associated with typical

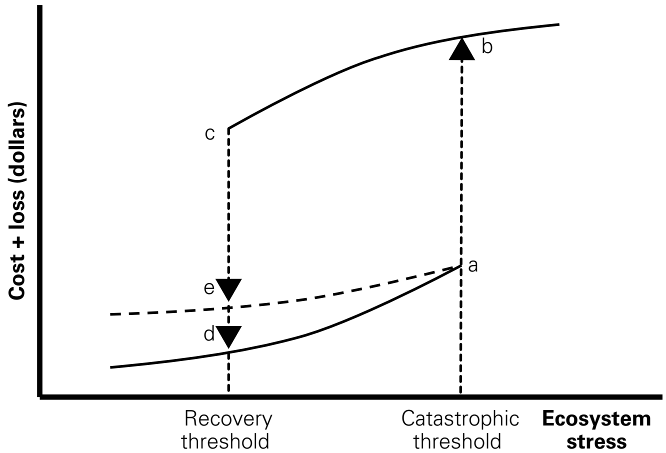

Figure 11.2—Economic impacts resulting from increasing levels of a disturbance may entail catastrophic surprises, and economic systems may fail to fully recover.

drought conditions are illustrated by points along the lower curve (moving along the curve from point d to a). The increasing slope indicates that as the capacity to manage greater ecosystem stress is diminishing, cost plus loss amounts are rapidly increasing.

Extreme levels of ecosystem stress may cause a dramatic upward shift in the cost-plus-loss function as the services provided by ecosystems degenerate and societal and economic resilience is exceeded (illustrated by the move from point a to point b on the upper curve in fig. 11.2). Even as the level of ecosystem stress subsides, communities may continue to invest in recovery efforts, keeping cost-plus-loss amounts on the upper curve in the figure (moving from point b to point c). However, over time, damage mitigation investments are diminished and communities recover, perhaps fully (illustrated by the recovery threshold and the move from c to d in the figure). When the damage to ecosystems is sufficiently severe, communities may fail to fully recover (moving from point c to point e).

Using the American Dust Bowl of the 1930s as an example, we see evidence of this dynamic process of ecological stress, catastrophic societal and economic loss, and (partial) recovery. Although the Great Plains historically experienced episodic periods of drought, an emerging cadre of "agricultural capitalists" willing to take entrepreneurial risks resulted in the Great Plow-up (Worster 1986), pushing much of the southern Great Plains beyond an unstable cropland-grassland equilibrium (McLeman and others 2014). Combined with the severe drought of the 1930s, enormous societal and economic costs and losses were exacted (e.g., associated with the costs of human migration, foreclosure of homes, and lost agricultural and other business income). Recent evidence shows that, despite the economic adjustments that occurred in the region since the 1930s, communities that experienced the worst drought conditions have not fully recovered (Hornbeck 2012).

People generally learn from their experience and make efforts to find ways to adapt to threatening environmental conditions, which increases societal and economic resilience. One strategy for increasing resilience is to create flexible institutions that can readily adapt to ecosystem stresses. For example, Welsh and others (2013) demonstrated how formal rules (water laws), in combination with informal rules governing local use of common-pool resources, have been effective in adapting to drought conditions by farmers in the Western United States. Another strategy for increasing social and economic resilience is to develop new technologies that are less vulnerable to ecosystem stresses. Using a statistical model linking historical droughts with patent applications for drought-resistant crops, Miao and Popp (2014) show how historical drought events have spurred innovation in agricultural biotechnology.

The societal and economic resilience in forest and rangelands to drought depends upon efforts to improve the adaptive capacity of communities across many spatial scales. Three adaptation strategies are suggested. First, increased knowledge of the impacts of drought on trees and forests and rangeland plants (including a better understanding of drought-fire-pest interactions) may help predict the timing, location, and severity of ecosystem stress so that pre-emptive mitigating actions can be taken. A second strategy would be the development of drought-resistant tree and rangeland plant species, but these investments will probably only occur if drought stress is anticipated to substantially reduce the productivity of important tree crops. Third, the development of institutions, such as local communication networks among forest and rangeland stakeholders, may facilitate more rapid and better informed responses to emerging ecosystem stressors such as drought.

Programs and Policies To Address Resilience

U.S. society has faced drought conditions throughout its history. As the United States grew economically and in population, local, State, and Federal governments created institutions that work to reduce the overall negative impacts from droughts and other natural phenomena—in short, to help to create a more economically and socially resilient society by building new economic policy infrastructure. The Federal Emergency Management Agency responds to large-scale disasters such as floods, hurricanes, and earthquakes to help victims. Firefighting agencies exist to mitigate the overall losses caused by wildfires on public and private lands. In the agricultural sector, programs have been developed—from price supports to crop insurance—to help farmers cope with natural disasters, from insect epidemics to hail storms to drought.

Although there are numerous programs and policies that address drought, drought impacts, and drought assistance, few of these are tailored for forest landowners. Livestock grazing is an exception where some forest and rangeland owners could receive assistance but only due to damage to the livestock—not forest products. The Agriculture Act of 2014[4] includes a provision that now allows orchardists (including Christmas tree farm operators) to qualify for drought assistance based on demonstrated damages.

Drought assistance programs are designed to relieve some of the financial burden to farmers, ranchers, and local governments that result from serious or severe droughts. Typically, a severe drought in a county will trigger an emergency notice, which will enable assistance to affected farmers [see USDA Farm Service Agency (2014) for a more complete description of the process]. Most of these programs are longstanding and have served farmers for decades (Western Drought Coordination Council, USDA Farm Service Agency, and Federal Emergency Management Agency 1999). No programs exist to specifically address issues of forest lands that are affected by drought.

Lessons from the Dust Bowl led to the creation of the Prairie States Forestry Project, in which the Forest Service, U.S. Department of Agriculture promoted the planting of trees along edges of croplands to shelter wheat fields from blowing winds and slow the displacement of soil. Between 1937 and 1942, when the project ended, the Forest Service planted nearly 220 million trees creating 18,600 miles of windbreaks that occupied 238,000 acres on 30,000 farms (Munns and Stoeckeler 1946). It also led to the purchase of lands for soil conservation, many of which form the heart of designated national grasslands, which are also managed by the Forest Service.

Continuing Federal interest in the impacts of drought on communities is demonstrated by the November 2013 Executive Order regarding preparedness for Climate Change (Office of the White House 2013a), which led to the introduction of the National Drought Resilience Partnership (Office of the White House 2013b). The primary focus of these actions is on streamlining the provision of Federal assistance (and the accompanying expenditures by the Federal Government) to private landowners (mostly farmers, some ranchers, and a few Christmas tree farmers) and on increasing the resiliency of local communities that face increasing stress from drought.

There is evidence that landowners who face higher drought risk are more likely to participate in Federal land management programs that help landowners drought-proof their farms and ranches (Wallander and others 2013). Measuring damage to a forest from drought, however, is problematic: there is no easily referenced counterfactual to show that it was actually the drought that reduced forest growth, and thus income, by a specific amount. Further, any program that reduces the losses experienced by individuals, through payments or other forms of assistance, carries with it issues of moral hazard (where covered individuals undertake greater risks as a consequence of having losses covered by others) and adverse selection (where individuals seeking coverage have above-average risk profiles).

Government programs in response to natural disturbances such as drought are one way in which resilience can be increased. Because such programs are not widely applied to the forest and rangeland sector, there is a paucity of research that elaborates drought's effects on the sector. The following part of this chapter provides some details on how drought does affect water-intensive parts of the sector.

Examples of Drought Effects on the Forest and Rangeland Sectors

The above discussion provides context for a description of the effects of drought on specific segments of the forest and rangeland dependent economy and its social systems. In the following sections, we provide a general summary of the effects of droughts on the forest and rangeland sectors. Detailed discussions of many of these

[4] Agriculture Act of 2014. P.L. 113-79 (February 7, 2014).

effects are provided in other chapters of this report. In this chapter, we discuss direct, indirect, and nonmarket effects, as suggested in Logar and van den Bergh (2013). Note, however, that adding up the costs and losses and other effects into an overall economic impact is not appropriate from an economics perspective. As noted above, "impact" depends on the many dimensions of drought. Moreover, there is much that is not understood about how drought affects the markets (and hence market prices or unit values) of the goods and services provided by forest and rangeland ecosystems.

Little is known about how drought redistributes wealth, and the production and consumption of goods and services across space, time, or economic sectors. For example, the costs incurred in firefighting are gains to the markets for firefighting inputs (e.g., fire engines, airplanes, firefighting labor). Likewise, the losses experienced in the market for one kind of recreation might reappear as gains in the market for another kind of recreation, due to substitutions across recreation types. Also, because humans are adaptable, societal changes induced by drought often have uncertain overall effects on the human condition, even if we can measure the effects on specific segments of society. Our examples, while classified according to direct, indirect, or nonmarket effects of drought (Logar and van den Bergh 2013), do not always fit neatly within this structure. For example, trees in forests can be killed by drought (a direct effect), but the effects of their loss is manifested in part in how their loss affects timber products supply and demand conditions, which translate into economic losses in that market. Moreover, not all effects are precisely quantified in these examples, nor are all even quantifiable given existing methods or data.

Direct Effects of Drought in Forest and Rangeland Sectors

The timber products industry—The timber products industry is directly responsible for close to 1.2 million U.S. jobs and over 72 billion dollars in labor income. Based on estimates from a contribution analysis of the U.S. forest sector using IMPLAN (IMpact analysis for PLANning) software and 2012 dataset (MIG 2012), economic activity associated with the forest sector generates an additional 4 million jobs with $210 billion of associated labor income, constituting 2 percent of the U.S. economy (MIG 2012). Droughts can affect the forest industry through their effect on forest inventories, which are assumed to affect the supply function for stumpage. Lower inventories lead to a contraction of supply and a corresponding increase in the market price and a decrease in the quantity of production. The magnitude of these effects on any particular forest parcel depends, in part, on the severity, duration, and frequency of drought events; the economy-wide effects depend on the spatial extent of the drought. Droughts can negatively impact forest inventories in two ways: (1) by increasing mortality, and (2) by reducing growth. Prolonged periods of dry conditions increase the likelihood of forest fires; increase tree vulnerability to pests and diseases; and, due to water stress, can lead to higher mortality of saplings and seedlings (Elliott and Swank 1994, Hanson and Weltzin 2000).

Although droughts occur periodically across the United States, an increase in frequency, severity, and duration could significantly affect forest species composition and live tree volumes. Prolonged periods of water stress not only increase the likelihood of tree mortality and pest outbreaks, but they can also lead to gradual changes in forest composition (chapters 3, 4, and 6) (Hanson and Weltzin 2000). During the drought experienced in South Carolina in 1998–2000, State foresters reported regeneration success that was 5 to 20 percent below the historical average (Knutson and Hayes 2001). Faced with higher rates of artificial regeneration failure, forest landowners can respond by introducing drought-resistant seedlings or by using natural regeneration methods. Although extreme, the possibility of landowners changing land use also exists. Lower success in tree establishment could lead to an age class gap over a prolonged drought, which could be a factor contributing to the current South Carolina shortage of small-diameter feedstock for pulp mills, oriented strand board mills, and other small-timber uses (Abt and others 2013). Pulp mills contribute a significant portion of the jobs in the primary wood processing industry; therefore, changes to the supply chain could trigger notable negative impacts.

The eventual decrease in forest inventories resulting from prolonged droughts could lead local industries to expand their procurement zones. However, transportation costs can limit a mill's ability to increase its procurement area. Given that product prices are set at the regional or national level, higher costs of roundwood inputs could make the affected mills less competitive, resulting in mill closures. Additionally, extended periods of water shortages could lead to higher electricity costs, affecting mill operating costs. Mills needing water in their production process, such as pulp and paper mills, could have their operations hampered and profits reduced (English 2007).

When viewed at a landscape scale, the effects of drought vary widely across stands because of the varying mix of species and site types. Several factors determine how drought affects tree growth, including tree species, forest composition, soil characteristics, and site hydrology. Studies show that pine species respond to water stress by reducing their growth rate, often by up to 30 percent (Amateis and others 2013, Vose and Swank 1994). For hardwood species, resilience to drought varies from high (e.g., oaks) to low (e.g., tulip poplar) (Elliott and Swank 1994, Klos and others 2009, Orwig and Abrams 1997). During a severe drought, trees on mesic sites likely experience higher competition than trees on xeric sites more adapted to drier conditions, leading to more severe impacts in the former sites than the latter (Orwig and Abrams 1997).

Ultimately, drought's tendency to reduce tree growth and increase tree mortality can potentially lead to job losses and income declines in rural, forest-dependent communities that are more acute than in more diversified, urban areas. For instance, Waters and others (1994) evaluation of a wood supply shock found a significant difference in job losses between a metropolitan area and the surrounding rural area, with the rural area experiencing the highest drop in employment and likely negative growth given higher difficulty for replacement of lost jobs.

Forest droughts that lead to large disturbance events, such as wildfire, can produce time-dependent impacts in the forest sector and the local economy. For example, wildfires can generate positive short-term impacts in local communities where external resources are brought in to fight the fires and where post-fire timber salvage and burn area rehabilitation activities generate economic activity (Nielsen-Pincus and others 2014). For instance, the salvage recovery plan for the 2006 fire affecting a section of the Malheur National Forest in Grant County, Oregon, estimated employment impacts ranging from 3 to 8 percent, depending on the volume or wood recovered (USDA Forest Service 2008).

Butry and others (2001) predicted that owners of salvaged timber would gain $33 to $61 million in salvage revenues following the drought-driven, half-million acres of wildfires in northeast Florida in May and June of 1998. Prestemon and others (2006) determined that post-wildfire salvage in the Bitterroot National Forest following the drought-enhanced 2000 Bitterroot Fire in western Montana would also generate more than $10 million of net benefits to the local economy, mainly through higher profits earned by wood processors that are partially offset by lower profits earned by owners of unburned timber in the region. Prestemon and Holmes (2008) estimated that post-wildfire salvage from the 2002 Biscuit Fire in southwest Oregon would generate from about $24 million at low salvage rates to $265 million in salvage sales at high salvage rate. In the long term, however, large wildfires can result in significant timber market losses (Prestemon and others 2006; Prestemon and Holmes 2008), with attendant employment declines (Nielsen-Pincus and others 2014).

Studies on the effects of policy-related harvest restrictions can inform the expected spatial effects of long-duration and large-scale droughts. Studies by Guan and Munn (2000) and Wear and Murray (2004) documented shifts in forest industry capital investment and production from the Pacific Northwest to the Southeastern United States as the result of efforts by Federal decisionmakers to protect spotted owl habitat and other ecosystem values. Waters and others (1994) analysis found that such restrictions resulted in an estimated 22-percent employment loss in the timber industry of western Oregon.

Forest and rangeland based water supplies—National forests are the single largest source of fresh water in the United States, accounting for 14 percent of all runoff. Over 900 cities rely on water originating from National Forest lands (Sedell and others 2000). These amounts vary widely by location across the United States. In the West, where most of the water originates in the mountains, half of all water originates in National forests. In Colorado, the percentage of water originating from National forests climbs to almost 70 percent. In the Mississippi River basin, by comparison, only 2–5 percent of water originates on National Forest land (Brown and others 2008). Weidner and Todd (2011) show how runoff from all forests affects communities by weighting water yield by the population served. They show a high dependence on forested watersheds throughout the Eastern United States, Rocky Mountains, Cascades, and Sierra Nevada (fig. 11.3).

Forests and rangelands are critical to water flow regulation and groundwater recharge (chapter 10). These ecosystems help regulate the supply of water by stabilizing surface flow (i.e., reducing streamflow flashiness) and allowing more subsurface recharge. When drought happens in forest or rangeland, vegetation will grow more slowly; in a severe drought, vegetation may die. Extensive mortality may increase

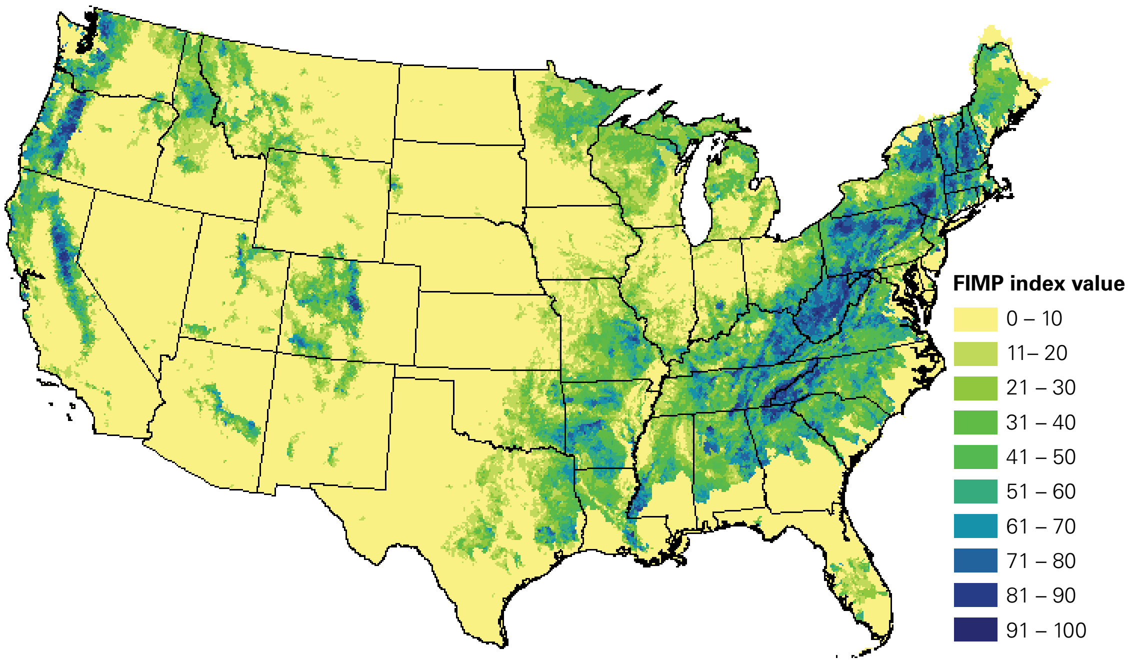

Figure 11.3—Index of forest importance (FIMP) to surface drinking water; higher values (shown in shades of blue) indicate greater importance (Source: Sedell and others 2000).

overall streamflow; however, flows will be likely more variable and groundwater recharge reduced (chapter 10). The end result is that the marginal cost of water (i.e., the cost of providing an additional unit of water) to downstream communities is higher when the forests and rangelands at the water supply source are under drought.

The increase in the marginal cost of water connects to three characteristics of U.S. drinking water markets. First, demand for water is inelastic—i.e., water consumers change their consumption little in response to water price changes, at least within the range of prices set by local water authorities (Dalhuisen and others 2003, Espey and others 1997). Research shows that a 10-percent increase in the marginal price (the price charged for an additional unit) of water is expected to reduce residential water demand by 3–4 percent in the short run and by 6 percent in the long run (Olmstead and Stavins 2009). Conversely, reducing water demand by 20 percent in the short run would require water prices to increase by 50 percent. Second, prices set by water authorities are typically below, and sometimes well below, the marginal costs of supplying water. This means that many water-providing agencies do not cover their production costs with the prices that are charged to consumers. Third, water is typically perceived to be a public good—it should be available to everyone and be clean and abundant—so efforts to recover costs through price increases are met with public and political opposition. Such price increases carry with them issues of legality, political constraints, and equity due to the larger-than-average impact to low-income households (Agthe and Billings 1987, Mansur and Olmstead 2012, Renwick and Archibald 1998).

The full economic cost of water includes costs of storage, transmission, and treatment, as well as opportunity costs associated with other uses and maintaining instream flows. Boland and Whittington (2000) note that significant efficiency and equity gains could be achieved by setting a single price that raises enough revenue to not only cover costs but provide enough funds to redistribute the extra revenues in the form of rebates back to low-income households. Alternatively, tier-based pricing schemes, called increasing block tariffs, could allow quantities deemed to be of subsistence value to be priced lower and larger quantities to be priced high enough to be responsive to price signals (Olmstead and others 2007). Such pricing policies, particularly if made flexible to respond to reduced water supplies, could therefore also help reduce consumption during times of drought. Further, pricing policies can provide the revenue for investments that are longer run solutions to drought-induced water shortages, including water reservoirs and tertiary water treatment facilities that produce water for reuse following initial consumption.

The net effect of these three market characteristics—inelastic water demand, water prices set below costs, and the public good view of water—is that water markets typically use quantity controls when shortages loom, despite evidence that quantity controls are economically inefficient compared to cost-based pricing policies (Brennan and others 2007, Collinge 1994, Krause and others 2003, Timmins 2003). Quantity controls can result in the amount of water demanded exceeding the amount of water available, especially in dry years when water is scarce. The larger the scarcity, the greater the divergence between marginal cost and price. For many communities, water shortages are already common. In 2015, for example, Governor Jerry Brown issued the first-ever executive order for mandatory water restrictions in California. The order requires a statewide 25-percent reduction in potable urban water use compared to 2013 usage. It also prohibits irrigation with potable water of ornamental turf on public street medians and outside of newly constructed homes and buildings without drip or microspray systems (Executive Department, State of California 2015). As long as municipal water prices lie below the true cost of supply, there will always be a perceived shortage among the 86 percent of U.S. households that get their water from municipal water companies.

Because of public and political opposition to higher water prices, and given that quantity controls create shortages, water authorities and communities gravitate toward measures that do not directly involve pricing policies or additional quantity controls. These measures are directed toward water conservation. Conservation policies focus on technologies to improve efficiency of water use and on rationing outdoor water use. Lawn-watering restrictions are commonplace in drought-stricken western communities. Governments have mandated the use of more water-efficient technologies, as well: Federal law requires new toilets, the largest user of in-home water, to use no more than 1.6 gallons per flush, a 73-percent decrease from the 6 gallons many older toilets use. Communities also subsidize adoption of water-efficient lawn irrigation systems (City of San Diego 2014, Kjelgren and others 2000) and the switch from older to new water-efficient toilets (Bennear and others 2013). While such policies are more palatable to the public, the fact that households achieve these water use reductions through regulations and incentives rather than through pricing policies implies that these measures are economically suboptimal, creating losses in consumer benefits (economic welfare) from water consumption (Brennan and others 2007, Collinge 1994, Krause and others 2003, Timmins 2003).

Insights into the underlying causes of water disputes and the reason for tight water regulation emerge by examining not just the marginal cost of water provision but also by examining the value that consumers place on the water that they consume. Values tend to be higher in places where water is scarcer. In particular, the differences in amounts of water provisioned by forests, along with the types of water uses in the basin, affect its marginal value (the value to the consumer of an additional unit of water consumed). This implies that the effects of drought are felt economically more acutely during times of water scarcity, including during droughts. Brown (2004) reports rough estimates of marginal values of instream flow for water resource regions throughout the country (table 11.2). Although users should consider that these values are rough approximations, the values are useful for comparing relative values among regions, and they illustrate how marginal values vary due to both the quantity of water in the region and how the community is using that water. Small changes in the quantity of water in New England or in the Mississippi River basin, where people and communities consider that water is abundant, are not likely to have a great concern because the value of a lost unit of water is small. Conversely, the quantity (and value) of water in relatively water-scarce regions such as the Lower Colorado River basin can have significant impacts, because the value of a lost unit of water is considered much larger.

Effects of drought on rangeland production—Drought in rangelands affects society and the economy by (1) reducing forage and water available for livestock grazing, and (2) by reducing overall vegetative land cover, which can lead to wind erosion and water erosion. In range management, drought is defined as the level of soil moisture that causes extreme plant stress and wilt (Carr 1966). Thus, the severity of drought in the rangeland sector is also a function of the timing of both water supply and plant demand. Drought also depends on temperature and wind through its effects on plant water demand and soil infiltration, soil texture, and soil depth. These variables are part of the Palmer (1968) Crop

Table 11.2—Marginal value of instream flow by water resource region (WRR) (year 2003 dollars per acre-foot per year)

Water resource region	Off-stream	Hydroelectric	Instream
New England	0.62	1.73	5.01
Mid-Atlantic	3.09	1.03	4.91
South-Atlantic-Gulf	1.87	1.56	5.03
Great Lakes	6.3	5.54	4.88
Ohio	3.17	0.71	4.96
Tennessee	3.18	7.02	5.16
Upper Mississippi	4.08	0.72	4.98
Lower Mississippi	0.4	0.35	4.75
Souris-Red-Rainy	0.29	0.26	6.45
Missouri	20.99	4.29	16.82
Arkansas-White-Red	4.08	2.05	7.7
Texas-Gulf	13.25	0.54	7.49
Rio Grande	16.54	1.42	28.26
Upper Colorado	13.32	17.79	26.32
Lower Colorado	25.56	16.19	42.46
Great Basin	36.08	1.31	16.52
Pacific Northwest	1.45	9.44	9.34
California	10.95	10.64	23.07

Source: Brown (2004).

Moisture Index, which reflects expected weekly evapotranspiration and plant specific needs (Meyer and others 1993).

A chief concern for long-term sustainability of rangeland is topsoil health and its ability to retain water (Mannering 1981, Marshall 1973). Semi-arid environments often have insufficient vegetative cover to protect the soil from wind and water erosion, whose effects are amplified by grazing (Dankwerts and King 1984, Robinson 1982). On western U.S. rangelands, typical erosion rates can be up to 1 mm/year (Mannering 1981), though topsoil only replenishes at a rate of less than 0.1 mm/year (Pimental and others 1976, 1995). Because animal stocking rates are generally determined by expected precipitation, degradation can occur quickly if drought occurs and grazing persists. Some of this erosion can be mitigated by vegetative buffers (Lee and others 2003, Osborne and Kovacic 1993).

The role of irrigation in rangeland and agriculture— Although soil conservation practices and modern irrigation have reduced the impact of episodic droughts, the effects of severe drought remain a prominent concern in rangeland-dependent communities. Nationally, irrigation accounts for 37 percent of total freshwater withdrawals (Barber and others 2009). In the West where water is scarce, 90 percent of water consumption is for irrigated agriculture. During the drought of 2002, direct Federal aid in South Dakota reached $100 million, and the total estimated impact was as high as $1.4 billion (Dierson and others 2002, Dierson and Taylor 2003). That same year, impacts to Missouri's agricultural sector were $251 million (Ding and others 2010).

Quantifying the economic effects of drought on crop and livestock production requires an accurate description of water markets. Water demand characterization requires measurement of the benefits of water used in the production of market goods and services, including for irrigation. Prices in the water sector are quantified by measuring the shadow price of water, that is, the change in net profits given a small change in water use by the water demanding goods and services market. Measuring the shadow price of water is done frequently in production economics with mathematical programming (Scheierling and others 2006), field experiments, and hedonic methods (Colby 1989, Young 2005).

Increasing water scarcity has led farmers to invest in water-saving techniques such as improved drip irrigation systems. In 1984, 71 percent of irrigation in the West was done with inefficient gravity-fed furrows. By 2008, that percentage had fallen to 48 percent; pressurized sprinkler systems represented 52 percent of irrigation water. This technology adoption in irrigation explains how, although total irrigated acres increased in the West by 2.1 million acres from 2004 to 2008, the water used in irrigation decreased by 100,000 acre-feet during that period (Schaible and Aillery 2012). Decreased use of water in agriculture, and the associated decrease in runoff of fertilizers and pesticides, has the added benefit of increasing downstream water quality (Warziniack 2014).

In spite of its widespread use in the water-scarce Western United States, most studies show that irrigation is an inefficient, low-value use of water, and the price of water charged to farmers is so low that it rarely factors into on-farm production decisions. The average price of an acre-foot of water in the West ($24 or $66 per acre of cropland) is lower than the cost of power to pump it out of the ground and distribute it through a sprinkler system ($76 for groundwater and $38 for surface water). Because of the low price charged for water for agriculture, water used for irrigation is often leased during wet years, when supply is plentiful and demand for other uses is low (Brown 2006).

Societal structural barriers exist to achieving more economically efficient water allocation in forest and rangeland systems in the United States. Economically efficient allocation of water would equate the value of a unit of water across uses, including instream uses for ecological sustainability. In reality, value between uses diverges substantially for two reasons. First, in the West, the doctrine of prior appropriation determines allocations, and while water rights are transferable, market transactions are limited by geographic structure of rivers and water pathways, costs of storing and transferring water, and impacts to other water users along the waterway. Second, most water use is highly subsidized, so when prices are charged, they rarely reflect the full cost of provision. Water rights that are leased or sold in markets are characterized by seniority and location, making each water right a unique good with high transaction costs.

Brown (2006) reviews 1,380 transactions in Western water markets between 1990 and 2003. He finds that water markets are far from competitive. Only three States (California, Colorado, and Texas) saw significant transactions during the period studied, representing two-thirds of all water transfers. Over half the sales were to municipal areas to satisfy the needs of fast growing cities, such as those along the Colorado Front Range, near Las Vegas, and near Reno. As well, over half of the sellers were irrigators. The median lease price for municipal uses was $56 per megaliter (ML, 1 million liters), or 4.6 times that paid for irrigation ($12/ML). The median sale prices were $2,120/ML for municipal uses and $1,917/ML for irrigation. Despite numerous studies suggesting agriculture-to-urban transfer of water rights would be welfare improving, few transfers have actually taken place (Brewer and others 2007, Brown 2006, Howe 1997). Reasons for the limited number of transfers include lack of markets, legal restrictions, and reluctance to further constrain local agriculture.

Research also indicates that government efforts to achieve ecological goals through water allocation and purchase decisions can have effects that create new conflicts while moving water allocations toward greater equity. Eleven percent of water rights purchases studied in Brown (2006) were for environmental purposes, sold for a median price of $706/ML. Most of these (105 of the 113) purchases were by government entities for the protection of aquatic species. And while regulations such as the Endangered Species Act[5] may require minimum flows for species preservation, instream water is also valued for its contribution to recreation and for riparian and wetland restoration. In a study of 67 river basins in the United States with significant irrigation, the marginal value of instream water for fishing exceeded that for irrigation in 51 basins (Hansen and Hallam 1991). Loomis and others (2000) found the benefits of purchasing water leases and farmland easements to restore a section of the Platte River near Denver outweighed the costs.

Indirect Effects of Drought in Forest and Rangeland Sectors: Federal Wildfire Expenditures

Forest and rangeland management is significantly affected by drought, and perhaps most acutely in its management of wildfires. Longstanding western drought is a likely cause of recent increased wildfire activity in forests and rangelands in much of the Western United States (Westerling and others 2003). Aside from sometimes justified increased investments to manage landscapes to be more resilient to wildfire (USDA Forest Service 2000), greater wildfire activity generally leads to increased expenditures needed for suppressing fires (Prestemon and others 2008).

To characterize the importance of the fire-suppression effect of drought in forests and rangelands, we compared Forest Service regional fire suppression average expenditures during drought years with average expenditures during nondrought years. The Palmer Hydrological Drought Index (PHDI) was selected as a "real time" measure of drought (Alley 1984) because it captures persistent, long-term effects that impact surface and subsurface water supply levels (Heim 2002). The index is available from the National Oceanic

[5] Endangered Species Act of 1973. P.L. 93-205. (December 28, 1973), as amended through P.L. 107–136 (January 24, 2002). 16 U.S.C. 1531.

and Atmospheric Administration (NOAA) (2014) and is created using temperature and precipitation data by climatic divisions; however, these exclude Hawaii and Alaska. The index is based on the identification of an existing water budget needed to maintain current production levels of ecosystem services in a place and time. The index represents the difference between the amount of water required to support the existing water requirement and the amount of actual water available. When the difference is negative, the location is considered to be experiencing drought while positive differences indicate the location is wet.

An average PHDI for each Forest Service region (fig. 11.4) for each month was created by overlaying the regions and the climate divisions and weighting the contribution of each climate division based on the proportion of Forest Service land area to obtain the agency's regional averages. Next, a fire season PHDI for each region was created by averaging the monthly regional PHDI averages over the months that are considered the fire season for each region (see Calkin and others 2005, table 11.3). Then, aggregate measures were created by averaging the regional fire season PHDIs for the western Regions (including Regions 1 through 6), the eastern Regions (including Regions 8 and 9), and in total [including all Regions 1 through 9, but excluding Region 10 (Alaska)]. The Forest Service regional suppression expenditure data were obtained by the authors from the Washington Office of Fire and Aviation Management and are calculated based on the Federal fiscal year (October 1 to September 30). All regions' fire seasons are within a single year, except for Region 5, which has a fire season that does not fall within the same fiscal year; to accommodate this fiscal year-spanning season for Region 5, we included the previous October PHDI in the average even though that October was technically in the previous fire season.

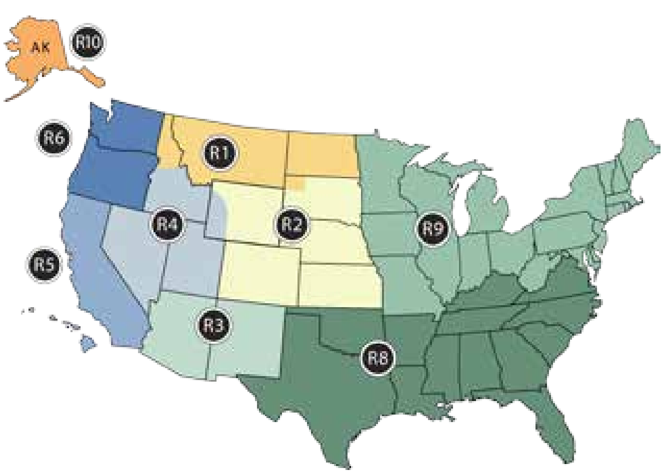

Figure 11.4—National Forest Service Regions. Note: there is no Region 7.

In table 11.3, we provide a comparison of Forest Service wildland suppression expenditures during drought conditions (where PHDI is negative) with those during nondrought conditions (where PHDI is positive) over the fiscal years 1995–2013 by Forest Service region, by West/East aggregates, and in total (millions of 2014 dollars). All regions and regional aggregates had statistically significantly higher wildland fire suppression expenditures in drought years than in nondrought years. Over the timeframe of this analysis, suppression expenditures during drought years were double those in nondrought years in total and across both the West and East aggregates, as well as in Regions 3, 5, 6, and 9. The factor column shows the multiple that drought expenditures were over nondrought expenditures (e.g., "2" means that expenditures in drought years were double the expenditures in nondrought years). Expenditures were triple in Regions 4 and 8, quadruple in Region 2, and quintuple in Region 1. Average expenditures from 1995 to 2013 are also reported in table 11.3, as well as average expenditures during years of drought and nondrought years, from which the factor of the relationship between average expenditures during drought versus nondrought years were calculated. All Forest Service regions had statistically different expenditures during drought versus nondrought years based on t-tests (p-values reported in table 11.3).

While decisions on fire suppression spending do not necessarily have to be based on damage mitigation alone, so that increased wildfire due to drought does not require greater suppression spending (Donovan and Brown 2005), they do demonstrate historical correlations with drought that are robust and informative. So while this analysis is not necessarily predictive of future experiences with suppression spending, evidence suggests that decisions by governments to invest more in protection as a result of greater drought-related wildfire disturbances are likely. The implications here are clear: markets for wildfire suppression services such as aerial fire suppression and the market for wildfire-related labor are benefited by increased severity, spatial extent, frequency, and duration of droughts. With increased drought resulting from climate change (Wuebbles and others 2014), these markets would therefore likely experience welfare gains (appendix), even while wildfires deliver

Table 11.3—Fiscal year suppression expenditures (2014 dollars in millions) on USDA Forest Service lands in the United States, by region, regional aggregate, and in total according to drought status (1995–2013)

Region	Factor[a]	Average expenditures	Average expenditures during drought	Average expenditures not during drought	t-test p-value	Fire season
R1	5	92	139	28	0.01	June, July, Aug.
R2	4	39	57	14	0.01	June, July, Aug., Sept.
R3	2	95	107	59	0.02	May, June, July
R4	3	85	127	38	0.01	June, July, Aug., Sept.
R5	2	272	340	178	0.02	Oct. (-1), July, Aug., Sept.
R6	2	136	181	95	0.02	June, July, Aug.
R8	3	41	57	22	0.01	March, April, May, June
R9	2	13	16	9	0.04	March, April, May
West (R1-6)	2	718	959	386	0.01	
East (R8-9)	2	53	63	26	0.01	
Total (R1-9)	2	771	831	450	0.04	

[a] Factor = Average expenditures during drought/average expenditures not during drought.
Note: there is no Region 7.

higher fire-related damages due to affected forests and rangelands and associated communities.

Nonmarket Effects of Drought in the Forest and Rangeland Sectors

Recreation impacts—Recreation services in forests and rangelands are provided by a combination of nature, labor, and capital. While service markets exist, such as the market for developed downhill skiing services (i.e., offering a place, the snow, the ski lifts, and associated built facilities), the majority of research in the economics of recreation has focused on recreation activities—specifically, valuing those activities and understanding what factors affect the benefits that the activities provide to those who participate in them. So discussion on recreation in this section is limited to describing how drought could affect recreation activities.

A limited amount of research has shown that drought conditions affect outdoor recreation activities in the United States, generally, and in forests and rangelands in particular. Notable studies include those by Creel and Loomis (1992), who quantified the overall recreational benefits of water; Ward and others (1996), who focused in particular on the connections between drought and water recreation, with evidence from California; and Thomas and Wilhelmi (2013), who examined all forms of recreation and tourism in southwestern Colorado. Drought can lower reservoir levels and therefore reduce the availability of water-based activities (such as fishing and recreational boating) and lakeside activities (such as swimming and camping). In the Ward and others (1996) study, the "use-value" marginal value estimates of water per acre-foot in reservoirs of California varied from $6 to $700/year. This range covers previous estimates for wetland areas in the San Joaquin Valley of California quantified by Creel and Loomis (1972), $348/acre-foot/year.

Thomas and Wilhelmi (2013), using a limited-resource survey and two focus groups, identified how drought in southwest Colorado affects the recreation sector. One finding was that drought affects winter recreation differently than summer recreation, due to dependence especially on snow in the winter (i.e., downhill and cross-country skiing, snowboarding, and snowmobiling) and on water and a wide variety of other resource values provided in the summer (i.e., boating/rafting/

canoeing, fishing, hiking, camping, horseback riding, wildlife viewing, off-road vehicle driving). In the winter, lower snowfall from drought generally reduces the economic net benefits in the recreation sector. In summer, drought can worsen water-based activities but conceivably can increase the provision of some dryland activities such as hiking and camping, owing to the greater number of rain-free days. In all times of the year, drought can alter animal migration patterns and thereby affect hunting and wildlife viewing. Drought may also have effects on insect and disease outbreaks in forests, affecting aesthetic values, and it can yield dry vegetation that is more prone to large and intense wildfires, which can force campground and forest closures, reducing summer recreational uses. Drought-induced reduction in tourism results in fewer jobs and lower economic output compared to nondrought periods.

While targeted studies have examined drought effects on recreation at fine spatial scales or for particular resources, recreation research from the most recent Resources Planning Act Assessment (Bowker and others 2012) indicates that prolonged drought in parts of the United States can have effects on a broad set of recreation activities. Bowker and others (2012) projected the probability of an individual's participation in various recreation activities as a function of socio-demographic and climate variables (including precipitation, potential evapotranspiration, and temperature). From their analysis, they concluded that: (1) in climate scenarios involving drier overall conditions in forests and rangelands, snow-dependent recreation activities are the most negatively affected of any category of recreation; and (2) there are some kinds of recreation activities that benefit from drier conditions, including nature center and historic site visitation, motorized off-road vehicle use, and adult equestrian participation.

Despite previous research efforts, a thorough understanding of the effects of a drought on recreation is lacking, which hampers our ability to fully characterize the overall effects of drought on this sector. Data are needed that can connect the levels of specific types of recreation at specific locations to the weather or climate conditions existing at the time and place of the specific activity. Although Bowker and others (2012) and other studies have advanced understanding of a few key relationships, a comprehensive understanding of drought effects across the entire spectrum of recreation activities would require additional recreation (panel) data. Panel data would quantify how drought in one time and place affects each specific type of recreation activity occurring in that same time and place, as well as how it affects participation in all activities in other locations and in future time periods. As Thomas and Wilhelmi (2013) and Thomas and others (2013) emphasize, estimates of recreation impacts from drought would be overestimated if these within- and across-activity spatio-temporal substitution opportunities available to recreationists are not accounted for.

Urban and residential communities—Most studies of the effects of water stress and high temperatures on tree and forest mortality have been designed to detect changes in background mortality and large scale die-off events in wildland forest areas (Allen and others 2010). Although drought-induced forest mortality in wildlands can alter the supply of ecosystem goods and services, large magnitude drought events can also alter the benefits experienced by people where most live and work—in cities. Evidence suggests that trees in cities are significantly affected by drought, and their responses lead to changes in the services that city trees provide. For example, the drought and heat event associated with the American Dust Bowl drought in 1934 killed approximately 20 percent of the trees in Manhattan, KS, and damaged another 30 percent (Stiles and Melchers 1935). Although the pre-drought tree density varied considerably across the urban forest, as many as 235 trees per city block were recorded in residential areas, so the overall number of affected trees was large. The city and property owners therefore incurred considerable expenses to remove and eventually replace many of the affected trees.

To our knowledge, the economic consequences of tree mortality due to drought and high temperatures have not been quantified. However, there is a growing body of research documenting how trees provide a variety of benefits to homeowners and residential and urban communities. Trees have been shown to enhance property values (Anderson and Cordell 1988; Donovan and Butry 2010, 2011) and lower crime rates in urban areas (Donovan and Prestemon 2012, Kuo and Sullivan 2001, Troy and others 2012). Tree shading has been found to reduce energy use in homes (Akbari and others 1997, Donovan and Butry 2009, McPherson and Simpson 2003), in this way mitigating some of the negative effects of the heat and sun associated with many droughts. Urban forests also have been shown to benefit stormwater management in built-up areas, reducing flooding and water-handling costs for cities and their residents (Sanders 1986, Wang and others 2008, Xiao and others 1998).

With respect to tree mortality, the loss of trees is connected to worsened human and urban environments and lowered house values. Recent research links tree mortality caused by pests to adverse public health outcomes (Donovan and others 2011, 2013; Lovasi and others 2008; Nowak and others 2014). Research also has documented how tree mortality resulting from other natural disturbances in residential forests is capitalized into property values. Losses in values are in the range of 1 to 10 percent of a home's value (Holmes and others 2010, Kovacs and others 2011). We anticipate that similar losses in value would result from drought-induced tree mortality.

Homeowners living within forests are often willing to incur expenses, such as irrigation, to help protect tree health, although such options may be limited when municipal water restrictions are enforced. Trees killed by drought conditions are generally removed when they threaten the safety of homeowners or other residents. Hazard trees that are removed may be replaced with different species that may be more drought resistant, although much remains to be learned about the selection of trees that improve the resilience of urban trees to drought conditions (Clark and Kjelgren 1990).

Although it is not currently known whether water deficits are more severe in urban trees than in trees growing in rural areas, there is growing concern that urban land uses create novel stresses on urban forests (Carreiro and Tripler 2005). Given the recognized high economic value of residential forests across the urban-rural gradient, greater attention to policies and potential technologies that improve urban forest resilience in the face of drought could yield positive net benefits.

Impacts of Drought on Tribal Values and Lifeways

There are 566 federally recognized tribes and more than 34 State-recognized tribes in the United States. These tribes, distributed across both drought-prone and mesic ecosystems throughout the country, are diverse in their cultural practices, the structure of their tribal economies, and their degree of dependence on forest and rangeland ecosystems. Hence, the effects of drought on tribal values and lifeways (defined here as the customs and practices of tribal societies) vary across all of these dimensions. In some places and for some peoples, the effects of drought are compounded and complicated by ongoing social, economic, and rapid ecosystem changes, making scientific attribution of the effects of drought alone difficult. Effects of drought, however, would likely be more acute for local populations whose livelihoods are most tightly connected to natural resources. For example, American Indians and Alaska Natives (AIAN) are particularly vulnerable because of their resource-based economic activities and spiritual and cultural values (Wildcat 2013).

General impacts of drought on tribes in the United States—As for all potentially drought-affected sectors or parts of an economy or community, it is important to identify risk, potential impacts, and vulnerabilities, especially related to water supply and water rights. Ongoing drought in the Western United States, where most tribal lands exist, is expected to continue to affect tribal health, culture, economies, and infrastructure. Competing demands for dwindling water resources challenge Federal trust responsibilities. Complicating factors, warming streams and hydrologic cycle changes affect fish populations important to tribal diets and ceremonies. Because of their natural resource dependence for income, employment, and cultural practices, many tribes are also vulnerable to higher rates of forest and rangeland disturbances, including invasive species spread, increased occurrences of epidemic pest populations and their associated damages, and wildfires. These disturbances increase forest mortality and reduce the quality and quantity of forest products valued by tribes (Voggesser and others 2013). Tribal elders have voiced concern for "bio-cultural" loss, defined as "the intimate innate connection that exists between tribal language, customs, and traditions and the biological health of their land, resources, and its inhabitants" (Collins and others 2010).

In order to successfully address environmental change, many scholars, tribal leaders, and agencies charged with consulting with tribes are calling for the incorporation of traditional ecological knowledge (TEK) in monitoring and assessing environmental change impacts, developing tribal community adaptation plans, and for "respectful partnering and collaboration of indigenous peoples and their communities with nonindigenous governments and organizations" (Wildcat 2013). Incorporating traditional values and TEK in these ways can support the perpetuation of traditional lifeways.

Relatedly, a workshop on climate change and drought on western native lands (Collins and others 2010) identified the ways that data and institutions could be marshalled to help mitigate overall impacts. The workshop participants concluded that inadequate communication of current conditions and potential impacts to tribes has resulted in a lack of attention to drought-related issues. Participants called for increasing documentation of impacts and data collection and monitoring in an effort to build awareness and bring attention to potential impacts and related needs. Participants also identified critical needs, such as for:

> "…reliable resources to support tribal drought planning and response; methods for integrating local and traditional knowledge into environmental monitoring and planning; education and outreach programs about drought, climate change, and water scarcity; and technical training opportunities related to climate monitoring for tribal resource managers…" (Ferguson and others 2011).

Finally, workshop participants identified four priorities for developing a regional drought early warning system: (1) integrate tribal observations and data into national and State monitoring efforts; (2) ensure maintenance and sustainability of existing observation networks; (3) facilitate data sharing and access; and (4) explore ways to use existing data and provide technical training for tribal staff (Ferguson and others 2011).

The Forest Service notes that this call for collaboration is now a catalyst to developing tools and sponsoring webinars and face-to-face training in climate adaptation planning and strategies, which make partnerships through the Tribal Climate Change Project (University of Oregon 2015) mutually beneficial to all involved. Partners include the Institute for Tribal Environmental Professionals at Northern Arizona University, the Pacific Northwest Tribal Climate Change Network at the University of Oregon, and the Forest Service Pacific Northwest Research Station.

The National Wildlife Federation suggests that drought may result in the most pervasive climate-related changes to impact tribes (Curry and others 2011). It could be the most pervasive because water is the foundation for tribal lifeways, economies, subsistence, and treaty rights (Curry and others 2011). In addition, water is considered by many as a traditional food (Lynn and others 2012). Cozzetto and others (2013) synthesize this argument (italics in original):

> *"Water is sacred. This is tradition. In contrast to the non-tribal utilitarian view of water, Native Americans revere water and water is life. It is integral to many Native American practices such as purification and blessing rituals and is used to acknowledge all relations and to establish connection to Mother Earth and Father Sky. Water is a holistic and integrating component connecting continents, humans, animals, and plants through a continuous cycle of liquid, solid, and vapor states. Without water, life would not exist as we know it. Water is the one thing we all need, all of us, all of life. As Native Americans, we honor and respect the tradition of water and must protect it always."*

Indigenous peoples depend on a wide variety of native species for food, medicine, ceremonies, community, and economic health. "The indigenous relationship between food and people is intimately tied to the cultural, physical, emotional, psychological, and spiritual health of tribal communities" (Lynn and others 2013). Drought tends to reduce the production of traditional foods, and this reduction is compounded by ongoing background effects of disease, pollution, invasive species, and unsustainable resource management activities. Declining ability to access and harvest traditional foods is leading to increasing health problems including obesity, diabetes, heart disease, and cancer (Lynn and others 2013). Disruption in resource availability and drought-associated changes in species composition could therefore negatively impact tribal subsistence-food production, health, culture, economic activities, and lifeways.

Specific impacts of drought on tribes in the United States—Drought has varying effects according to the location of the tribe, which is connected to biophysical, cultural, and economic contexts. Drought in the Southwestern United States has effects on livestock, agriculture, water supply, water rights, soil quality, and aquatic species (Cozzetto and others 2013), requiring tribal peoples to use marginal resources and travel farther to haul water. Cozzetto and others (2013) identified five categories of tribal water resources impacts; these include impacts on: (1) water supply and management (including water sources and infrastructure); (2) aquatic species important for culture and subsistence; (3) ranching and agriculture, particularly from climate extremes (e.g., droughts, floods); (4) tribal sovereignty and rights associated with water resources, fishing, hunting, and gathering; and (5) soil quality (e.g., from coastal and riverine erosion prompting tribal relocation or from drought-related land degradation).

In a drought preparedness workshop in Flagstaff, AZ, in 2010 for tribes in the Four Corners Region, current drought effects and vulnerabilities were catalogued:

multiple impacts from seasonal dust storms; shifting plant ranges and absence of or reduction in ceremonial and medicinal plants; drying of springs and declines in surface water supplies; livestock reductions tied to poor range conditions; inadequate water infrastructure for the growing water demand in the region; bureaucratic and institutional conflict; and a rising degree of economic, social, and cultural vulnerability due to changing society and climate (Ferguson and others 2011). Workshop participants acknowledged impacts from complacency and a lack of respect for the precious nature of water and the threat of drought.

Many of the listed impacts of droughts on tribes in the United States are illustrated by specific experiences. For example, a multiyear drought in the early 2000s forced the Hualapai Tribe in Arizona to sell cattle because of high water and feed costs, resulting in increased wildfires, road closures associated with wildfires, increased invasive species and wildlife diseases, lost wetlands, wind erosion, and visibility problems (Cozzetto and others 2013). In the Pacific West, drought has reduced forage quantity (Bender and others 2011). Changes in ecosystem water status in the Midwest, Northeast, and South have reduced forest nut crop abundance and have stressed ecosystems used by tribes (McKenney-Easterling and others 2000, Speer and others 2009, Voggesser and others 2013).

The effects of drought are recognized to be greatest in locations of the United States where water is both scarce and key to tribal livelihoods. Reservoirs, hydropower facilities, irrigated agriculture, municipal water systems, tribal water rights, freshwater aquatic systems, and water-intensive recreation are all impacted by drought conditions (Dalton and others 2013). Solar and wind facilities, more common in the water-scarce Western United States, also require water for periodic cleaning of solar-collection and reflection surfaces and, for thermal power plants, turning steam turbines (Solar Energy Industries Association 2014); the water necessary to successfully support these alternative energy facilities may be lacking, especially during drought (Collins and others 2010).

But drought's effects, perhaps manageable for short-duration, low-severity, or moderate spatial-scale droughts, require addressing multiple trade-offs and longstanding water use allocation disputes when droughts increase in magnitude along these dimensions. Competition for limited water resources pits the interests and needs of hydropower, solar power, irrigation, drinking water, aquatic systems, and water-intensive recreation. In the Northwest, for example, many water supplies are overallocated (more demand than water available), leading to conflicts among potential users and uses (Curry and others 2011). And in spite of the tribes' historical, treaty-based senior water-rights status, which gives them priority under normal (nondrought) conditions, when water is scarce, existing laws often mean that nontribe water consumers are given water allocation priority in order to provide water to livestock and for household (domestic) uses. Moreover, tribes' treaty-based seniority is often in legal dispute. Competition for water, the issue of treaty water rights, and how to interpret those rights in light of changing conditions, will become increasingly important and contentious (Lynn and others 2013).

Also, in the case of large-magnitude and persistent drought, fisheries disputes emerge between recreational fishers and native subsistence fishers. In the midst of drought and ongoing climate change, changes in streamflow and temperature threaten aquatic ecosystems, especially the spawning and migration of salmon and trout species. Cascading effects of limited water will impact recreational, commercial, and tribal fisherman. In Alaska, Alaska Natives and rural residents participate in a subsistence fishery that may experience catch limits and season reductions.

Just as for nontribal communities, indirect and direct effects of drought can result in health and economic losses. Because droughts increase wildfire activity, tribes in fire-prone landscapes may experience economic effects when wildfires force the closure of roads and recreation areas that they are dependent upon for their livelihood (Dalton and others 2013). Wildfire smoke and particulate matter is also a health concern in many tribal areas. In addition, drought is associated with food insecurity, especially for the poor and those living in rural communities, due to drought's direct effects on agricultural production. In some parts of the country, particularly the Colorado Plateau, drought impacts are compounded by warming temperatures that increase evapotranspiration rates, reduce soil moisture, and increase stress on vegetation and water resources, creating circumstances for increased soil erosion (Ferguson and others 2011). And, as highlighted in another section of this chapter, drought affects forest- and rangeland-based water production, which in extreme cases can limit access to clean and affordable drinking water (Ferguson and others 2011).

Conclusions

The U.S. economy and society more broadly is adapted to the rhythm of drought, in terms of its severity, duration, spatial extent, frequency, and seasonality. The effects of moderate, short-duration, and spatially limited droughts are easily handled by our economy through adjustments in inputs and outputs without altering our technologies, local economies, locations of human populations, or traditions. Intense, long-duration, and spatially expansive droughts that America has experienced, on the other hand, affect all of these components of society in sometimes profound ways, with impacts that can span decades.

While economists have a basic understanding of how drought affects forest and rangeland systems, we still know very little about how drought affects the economic and social systems of the United States (table 11.4). For example, although we have fairly precise measures of droughts' effects on Federal wildfire management expenditures, we know little about the scale of these impacts on State and local firefighting expenditures. Long-term or persistent droughts or indeed climate change related dryness, would further affect the required size of the overall firefighting capacity of all agencies of governments, for which we know very little.

Likewise, although we understand some of the benefits of trees in urban settings, we know less about how drought affects the production of those benefits in these same urban settings because effects are transmitted through loss of trees, and there is much to be learned about how drought affects mortality of the urban trees. Water effects of drought seem clearly quantified, yet less is understood about the long-term economic effects of water mining (the permanent draw-down of water supplies residing underground). While researchers have quantified some effects of drought on recreation-based goods and services, very little is known about how the various types of recreation activities substitute and complement each other across space and time, or how other modes of consumption outside of the recreation sector can mitigate some of the losses experienced by specific types of recreation.

In the timber products sector, silviculturists have a general understanding of the effects of drought on growth and yield. However, while the effects of drought on growth and yield in particular forest types in particular places might be acute, economies are global: substitution possibilities for consumers of forest products and across producing regions reduce some of the negative impacts felt in the specific location of the drought, reducing net overall economic losses.

Finally, when describing the economic and social impacts of drought, all such effects need to be scaled by the size of the forest and rangeland based economy, the national economy, and the sizes of local and national human populations. Although smaller economies may be more greatly affected in terms of impacts on sectors, larger economies and more numerous populations are likely to experience greater overall impacts of drought due to potentially larger spatial coverage and because these economies are often less diverse economically (have fewer sectors), limiting substitution opportunities among labor, capital, and goods markets that can mitigate its most acute impacts.

Although this chapter describes some of the economic and social effects of drought in forest and rangelands (table 11.4), our examples did not address how a greater amount of sun (lower cloud cover), which is correlated with drought, can itself have separate effects on economies and societies and alter the suitability of habitats directly affected by sunshine. We also have sidestepped discussion of how forests and rangelands themselves might help to mitigate some of the negative effects of drought: trees provide shade that reduces energy use and water demands in urban settings; they provide shade for precipitation that is stored in the form of snow in high elevations; and they provide a refuge for hikers and campers seeking to escape high heat and sun associated with drought. With further study, these mitigating effects could be better quantified, and the missing pieces can be filled in. This additional study could help wildland managers and policymakers design new and adapt existing approaches to reducing the overall negative impacts of drought. The urgency of such policy and managerial responses could become greater as climate change alters the severity, duration, spatial extents, and frequencies of droughts in forests and rangelands, and as economies grow and populations grow into the future.

The research cited in this chapter also outlines many ways that the private sector, Government, and tribes can work to mitigate the overall effects of drought in society. Private-sector actors can respond to drought by pursuing innovative research and deploying new technology meant to improve water use efficiency; and governments can help by funding similar research and

Table 11.4—Measured effects of drought on the forest and rangeland sector, as reported in this chapter

Economic subsector or aspect	Mechanism	Ownership, spatial and temporal scope	Some effects identified
Timber products sector	Reduced net volume growth, leading to lower overall inventory quantities	National	Lower success in post-harvest and new planted forest seedling establishment success, reduced harvest volumes, lowered overall employment, increased fire-related timber salvage, timber production shifts to less drought-prone locations, altered timber procurement zones, changed locations of pulp and paper manufacturing facilities
Forest- and rangeland-based water	Reduced water quantity and quality	National Forests and Rangelands of the United States	*Home Use:* Drought encourages adoption of new municipal ordinances or graduated pricing that changes water-use by appliances in homes and outdoors on properties *Commercial*: lost output due to transfers of water use priorities away from agriculture and water-using manufacturing toward municipal users, to protect water-dependent wildlife and meet inelastic final consumer demand *Rangeland and Agriculture*: higher soil erosion rates and therefore long-run effects on productivity, planting of more drought-tolerant grasses, increased rates of tree-planting (including shelter belts), increased use of water-efficient irrigation technologies and techniques
Wildfire management	Higher wildfire activity	National Forests and Rangelands of the United States	Higher wildfire suppression and post-fire mitigation expenditures, 65 percent higher during drought compared to nondrought conditions
Recreation	Altered precipitation patterns, temperatures, and precipitation seasonality	National	Reduced snow-based recreation opportunities, reduced water-based recreation opportunities, enhanced equestrian and off-road vehicle activities, perhaps higher rates of visitation to nature interpretive centers
Urban and residential communities	Killing of valuable residential and street trees, due in particular to additional stresses from physical structures and infrastructure, higher vulnerability to other disturbances	Urban/residential areas; national	In the American Dust Bowl, 235 trees/block killed in Manhattan, KS; tree mortality reduced home values 1-10 percent; higher home energy costs due to lower shading, greater flooding risks and increased storm water management costs, deterioration in human health and welfare (including higher incidences of asthma, worsened human birth outcomes, higher human mortality)
Tribal values and lifeways	Altered provision of water-affected ecosystem goods and services valued by indigenous cultures, through effects on wildfire, insects, diseases, invasive species, altered production of nontimber forest and rangeland products	National	Increased epidemics of native and exotic pests, which reduces the supply of forest and rangeland-based ecosystem goods and services; bio-cultural losses due to worsened ecosystem health status; lost goods and services provided directly by water, including the spiritual value of water as a traditional "food," water as a symbol for life, water as vehicle and instrument of purification and blessing rituals, water as a connection to wildlife; reduced availability of medicinal plants and traditional foods, adversely affecting human health; reduced productivity of, and income from, rangeland livestock managed by tribal peoples; increased marginalization of tribal peoples in the competition with the wider society for water supplies, fishing; reduced income and electricity provided by tribally owned hydroelectric facilities and other energy resources; lost income from recreation on tribal lands due to higher wildfire activity; increased use of local and traditional knowledge as a means of mitigating drought's impacts

development (Miao and Popp 2014). Decisionmakers in the private and public sectors can act to reduce the negative effects of drought on wages, the cost of capital, income earned, and prices paid to consume water-intensive goods by investing in new technology that can reduce water input per unit of output. By investing in new water-storage technologies, for example, public and private organizations can reduce evaporation and water waste. Governments can also more directly collaborate with tribes to better monitor drought conditions and design interventions that can alleviate the special vulnerabilities that tribal societies face. This collaboration could include joint efforts to diversify tribal energy portfolios, protect traditional fishing and hunting rights when drought reduces animal populations, and create more effective mechanisms to respond to drought-related natural disturbances.

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APPENDIX: Graphical Description of the Economic Effects of Drought on Production of a Good

Depending on its severity and persistence, one can view drought either as a transitory state or as a new "permanent" state, both of which have the potential to alter the distribution of inputs to productive economic activity. Figure 11.A1 describes how water scarcity (drought) would lead to a shift in resources used. It is a stylized model of one produced good (B) and two inputs, water (W) and another input (X) in the production of B. The vertical axis identifies the quantity of water used and the horizontal axis identifies the quantity of the other input in production in this two-input production technology. Two curves, labeled B_1 and B_2, are shown. All along B_1 the output quantity is the same, but different quantities of W and X can be used to produce B_1. The same is true for B_2: output is constant along the entire curve, and the quantities of W and X can be varied to produce that output quantity. Assume that B_1 is the range of output quantities of B—a water-intensive good—that can be produced in normal (nondrought) conditions, while B_2 is the (lower) quantity produced under drought conditions. The angled straight lines identify the relative prices of the two inputs: the flatter the slope of these lines, the more expensive is water relative to the other input. Optimal production, in terms of minimizing costs of inputs, is defined where the straight lines are tangent to the curved lines of B. Assume that the two parallel-angled straight lines represent the relative price of W to X. Without a drought, the production is at point *a*, using the quantity W_a of water X_a of the other input. Without a change in the relative prices of the inputs during drought, production would shift to the curve B_2, implying lower levels of both inputs to production level defined at point *b*, with W_b units of water and X_b units of the other input. During a drought, however, water can become more expensive, flattening the sloped line to the single-angled one shown in figure 11.A1. In that case, the optimal combination of inputs would favor production at point *c*, implying a still lower quantity, W_c, of water but a higher quantity, X_c, of the other input. In this way, with higher relative prices for water, drought would increase demand for the other input and reduce the demand for water.

B_1 and B_2 in this example are produced by the same technology. In the face of persistent drought or changes in drought severity or frequencies or spatial extents, producers might invest in a technology that is more water efficient at producing the same good, to avoid persistently higher prices paid for the water as an input in production. New technology conceivably would use water less intensively and other inputs more intensively, yielding a comparable quantity of good produced but at lower cost.

Another way to view the effects of drought on an economy is to consider its effects on the supply and demand of goods and services that depend on water in their production and thereby affect the overall welfare or value produced by the production and consumption of goods whose production depends on water. [See Just and others (1982) for details of welfare analytical techniques.] Figure 11.A2 is an abstract expression of

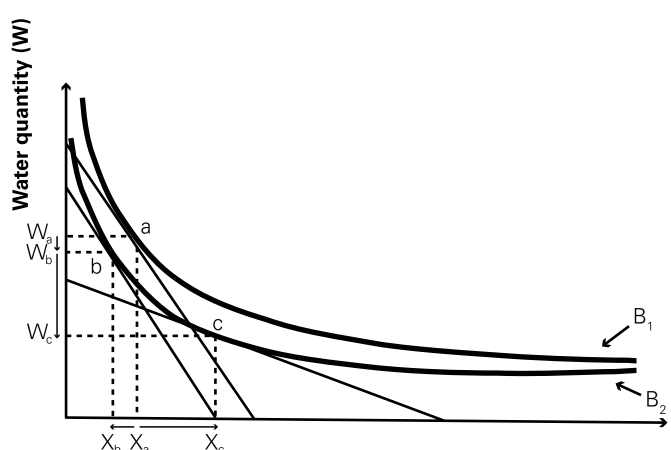

Figure 11.A1—Optimal quantities of water and other inputs in the production of a good, B.

the supply and demand for a good that depends on water for some of its production. The supply of this good is a function of the price per unit of capital (r), price per unit of labor (w), and the initial quantity of water provided by nature (N_0) available. The position of the supply function in price-quantity space is also a function of technology for producing the water-intensive good (z) (discussed later). Supply increases with the price of the good: a higher price of the good encourages more production as a rational response to greater potential profits earned by producers. Water provided by nature (N) affects the position of the supply curve (S_0) in price-quantity space; higher N would move supply outward (to the right). The prices of capital and labor also shift supply; if the price of either capital or labor is higher, then supply shifts back (to the left). Demand, D, is a function of total income of potential consumers (higher income shifts demand outward) and the quantity-demanded decreases with the price of the good. One way that income can change is if the prices of either capital or labor change. For example, if either the price of capital (also known as the return to capital or the interest rate) or the price of labor (the wage rate) decreases, then income would decrease. The area bounded by the vertical axis on the left, the supply curve on the bottom, and demand curve on the top is economic surplus, the sum of consumer surplus and producer surplus, commonly referred to welfare ($Welfare_0$)—the blue shaded portion in figure 11.A2. Consumer surplus is defined as the sum of what all demanders (consumers) of the good would be willing to pay minus what they would actually pay (the area above price and below the demand curve). Producer surplus is defined as the costs incurred in producing each good minus the prices received for those goods in the market, defined by the area above the supply curve and below the equilibrium market price. The price in equilibrium is P_0 and the quantity supplied is Q_0.

Now, imagine a situation that reduces the provision of water, altering N_1, as in the case of drought (figure 11.A3). This acts to shift supply back to S_1. With demand fixed, welfare is reduced to a smaller area, to $Welfare_1$. The welfare lost is shaded in orange. Price increases to P_1 and quantity supplied decreases to Q_1.

We note here that lower output would eventually lead to the freeing up of capital and labor from the water-intensive sector due to lower overall output, and this labor and capital would be available to the water-extensive sector of the economy. The price of capital and labor would decline as a result. The water-extensive sector, therefore, can gain as a result of the drought, mitigating some of the overall losses in the

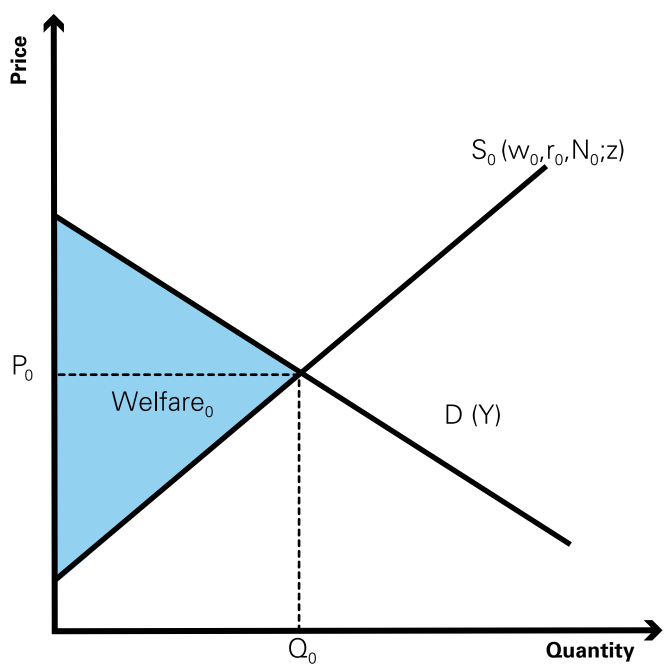

Figure 11.A2—A water-intensive goods market.

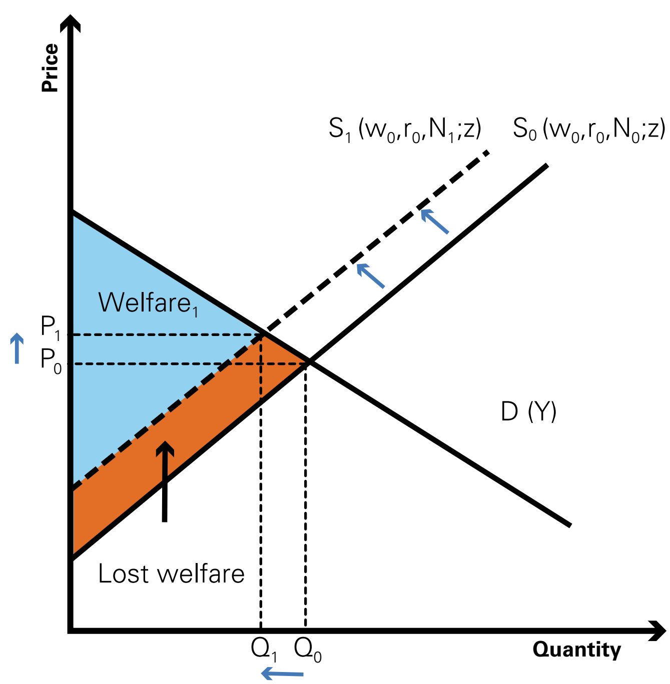

Figure 11.A3—A reduction in the quantity of water available in a water-intensive goods sector.

economy. Figure 11.A4 illustrates this scenario. For a good produced in the water-extensive economic sector, initial supply is SO_0, expressed as a function of the initial price of capital (r_0) and labor (w_0). Demand for the good in that sector is DO, a function of total income (Y), as before. For the good in this water-extensive sector, PO_0 is the initial market price and QO_0 is the initial production quantity. Initial welfare in the market for this good is represented by the blue triangle and labeled $Welfare_0$. With drought, the prices of labor and capital drop to r_1 (and $r_1 < r_0$) and w_1 (and $w_1 < w_0$). Supply therefore shifts out to SO_1, with a new and lower equilibrium price, PO_1, and a higher equilibrium quantity, QO_1. The effect for the market for this good is a gain in overall market welfare, adding the shaded tan area to the blue area. The above discussion is focused on particular goods, but it could apply to a whole basket (aggregate) of goods that are either water intensive (figs. 11.A1–11.A3) or not (fig. 11.A4) in their production.

The graphical representations in figures 11.A2–11.A4 ignore shifts in demand that would occur because of the lower prices of capital and labor, meaning overall lower income in the economy (Y). Losses in the water-intensive sector would tend to outweigh the gains in the water-extensive sector of the economy. In other words, the demand curves in figures 11.A3–11.A4 would also shift back slightly, causing further adjustments in prices, quantities, and overall welfare in all markets. Other inputs to production could also be described beyond just labor, capital, and water. For example, land is an input common in the water-intensive sector—especially in agriculture. So if a drought affects the agricultural sector, just as for capital and labor, the market price of land would also drop.

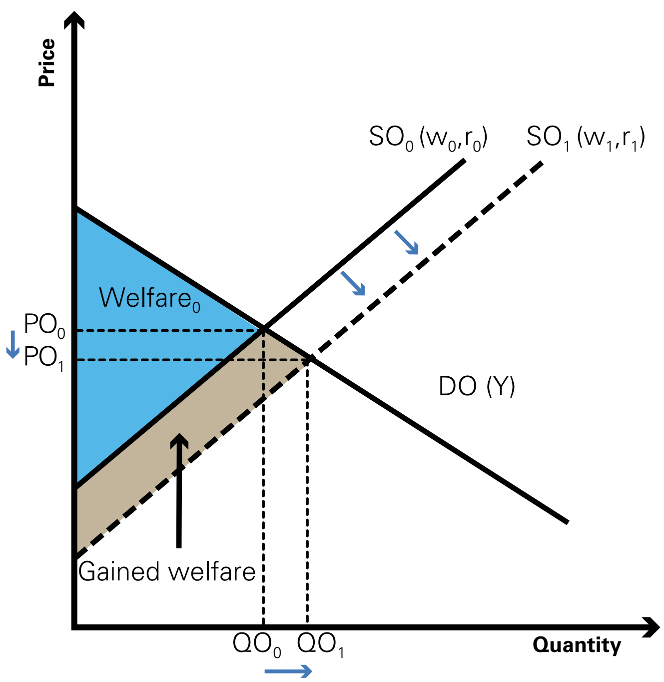

Figure 11.A4—Goods production in other sectors not directly affected by drought (water-extensive sectors).

One could also conceive of two kinds of labor: labor in the water-intensive sector and labor in the nonwater-intensive sector of the economy; in this case, the two kinds of labor might not be perfect substitutes for each other, due to specialized skills. If demand for labor in the water-intensive sector drops due to lower overall production possibilities, then some—but not all—labor could migrate to the nonwater-intensive sector of the economy; some labor, however, might remain idle until water returns (the drought ends) or the labor acquires new skills (e.g., through training) that makes it equivalent to the specialized labor of the nonwater-intensive sector.

Finally, not described in the figures, is a role for technology (z in figures 11.A2 and 11.A3) used in the water-intensive sector. New technology could be developed and used in the water-intensive sector that allows for more efficient use of water (smaller quantities used for each unit of output). This would cause the supply curve to shift outward, allowing for greater overall production levels at each price received for the water-intensive good in the market. This would serve to mitigate the overall negative consequences for the water-intensive sector, helping to support prices and keep wages and interest rates (and hence incomes) higher than they would be without the new technology. Producers of the water-intensive good could invest in research and development (Miao and Popp 2014) of new water-efficient technology, or governments can provide it or do research that makes its use feasible. An example of a water-efficient technology is a drip irrigation system, which uses less water than a sprinkler system in the agricultural sector.