

2
CHAPTER

Agriculture

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2.1 INTRODUCTION

This synthesis and assessment report builds on an extensive scientific literature and series of recent assessments of the historical and potential impacts of climate change and climate variability on managed and unmanaged ecosystems and their constituent biota and processes. It identifies changes in resource conditions that are now being observed, and examines whether these changes can be attributed in whole or part to climate change. It also highlights changes in resource conditions that recent scientific studies suggest are most likely to occur in response to climate change, and when and where to look for these changes. As outlined in the Climate Change Science Program (CCSP) Synthesis and Assessment Product 4.3 (SAP 4.3) prospectus, this chapter will specifically address climate-related issues in cropping systems, pasture and grazing lands, and animal management.

In this chapter the focus is on the near-term future. In some cases, key results are reported out to 100 years to provide a larger context but the emphasis is on the next 25-50 years. This nearer term focus is chosen for two reasons. First, for many natural resources, planning and management activities already address these time scales through the development of long-lived infrastructure, plant species rotation, and other significant investments. Second, climate projections are relatively certain over the next few decades. Emission scenarios for the next

few decades do not diverge from each other significantly because of the “inertia” of the energy system. Most projections of greenhouse gas emissions assume that it will take decades to make major changes in the energy infrastructure, and only begin to diverge rapidly after several decades have passed (30-50 years).

To average consumers, U.S. agricultural production seems uncomplicated – they see only the staples that end up on grocery store shelves. The reality, however, is far from simple. Valued at \$200 billion in 2002, agriculture includes a wide range of plant and animal production systems (Figure 2.1).

The United States Department of Agriculture (USDA) classifies 116 plant commodity groups as agricultural products, as well as four livestock groupings (beef cattle, dairy, poultry, swine) and products derived from animal production, e.g., cheese or eggs. Of these commodities, 52 percent of the total sales value is generated from livestock, 21 percent from fruit and nuts, 20 percent from grain and oilseed, two percent from cotton, and five percent from other commodity production, not including pastureland or rangeland production (Figure 2.2).

The many U.S. crops and livestock varieties are grown in diverse climates, regions, and soils. No matter the region, however, weather and climate



characteristics such as temperature, precipitation, carbon dioxide (CO₂), and water availability directly impact the health and well-being of plants and livestock, as well as pasture and rangeland production. The distribution of crops and livestock is also determined by the climatic resources for a given region and U.S. agriculture

has benefited from optimizing the adaptive areas of crops and livestock. For any commodity, variation in yield between years is related to growing-season weather effects. These effects also influence how insects, disease, and weeds affect agricultural production.

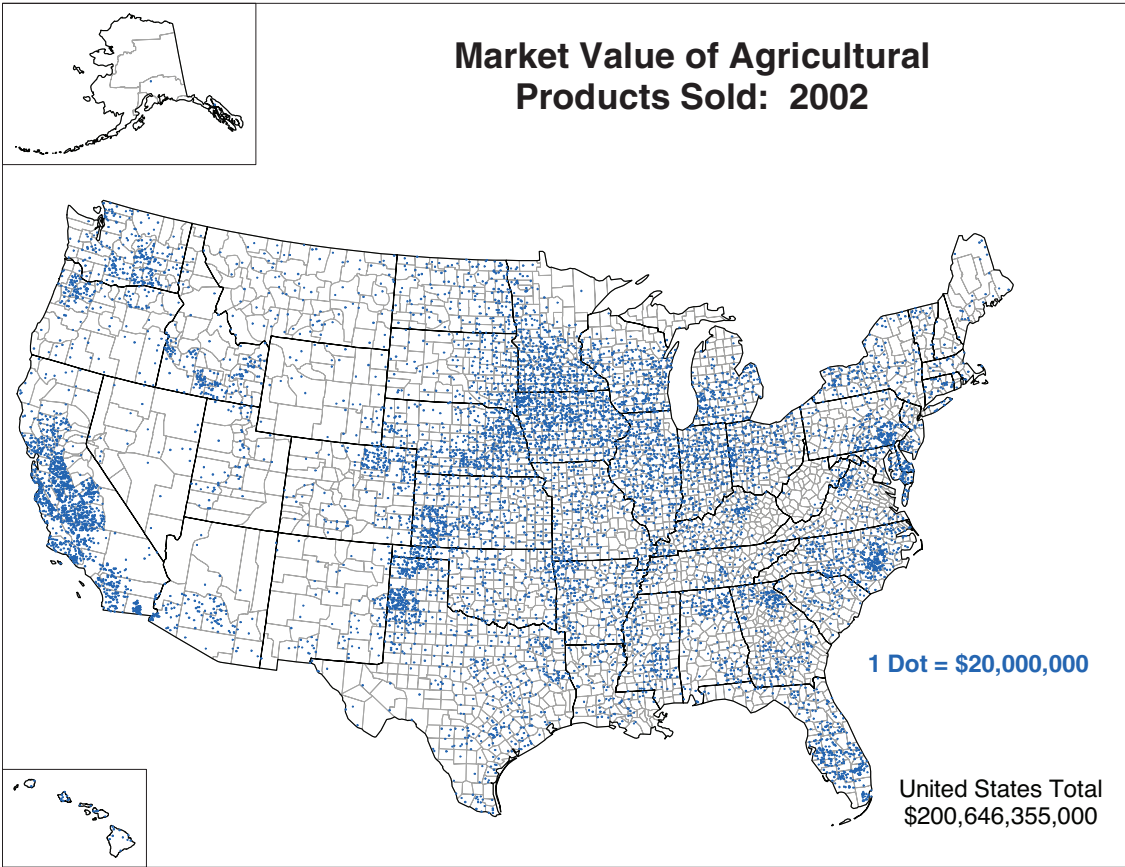
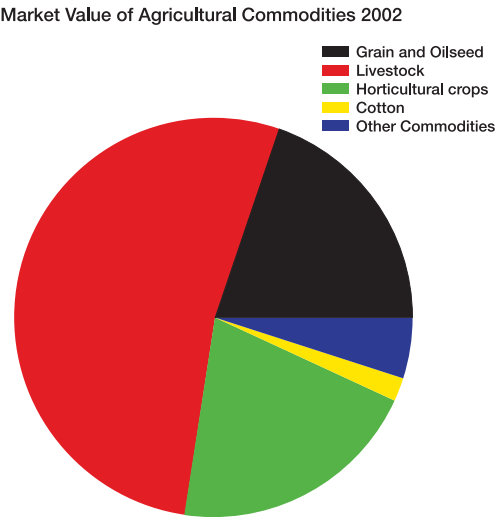


Figure 2.1 The extensive and intensive nature of U.S. agriculture is best represented in the context of the value of the production of crops and livestock. The map above presents the market value of all agricultural products sold in 2002 and their distribution. (USDA National Agricultural Statistics Service.)

Figure 2.2 The sales value of individual crops and livestock is represented at right. As the chart indicates, crops and livestock represent approximately equal portions of the commodity value. (USDA National Agricultural Statistics Service.)



The goal in this chapter is to provide a synthesis of the potential impacts of climate on agriculture that can be used as a baseline to understand the consequences of climate variability. A variety of agricultural crops will be considered in this report. Among them is corn (*Zea mays*), the most widely distributed U.S. crop after pastureland and rangeland; wheat, which is grown in most states, but has a concentration in the upper Great Plains and northwest United States; and orchard crops, which are restricted to regions with moderate winter temperatures. For any of these crops, shifts in climate can affect production through, for instance, variance in temperature during spring (flowering) and fall (fruit maturity).

Additionally, this chapter will look at beef cow production, which is ubiquitous across the United States (Figure 2.3). Because of the regular presence of beef cows across the nation, beef cow vitality provides an effective indicator of the regional impact of climate change. While beef cows are found in every state, the greatest numbers are raised in regions that have an abundance of native or planted pastures (Figure 2.4), which provide easy access to accessible feed supplies for the grazing animals.

Over the past 25 years, there has been a decline in land classified as rangeland, pastureland, or grazed forest. Many of these shifts relate to changing land use characteristics, such as population growth (Table 2.1); the growing eastern U.S. has experienced the greatest reduction in such land resources (Table 2.2). This chapter will provide an overview of the state of pasturelands and rangelands as defined by the USDA. Pastureland is a land cover/use category of land managed primarily for the production of introduced forage plants for livestock grazing. Pastureland cover may consist of a single species in a pure stand, a grass mixture, or a grass-legume mixture. Management usually consists of cultural treatments: fertilization, weed control, reseeding or renovation, and control of grazing. Rangeland is a land cover/use category on which the climax or potential plant cover is

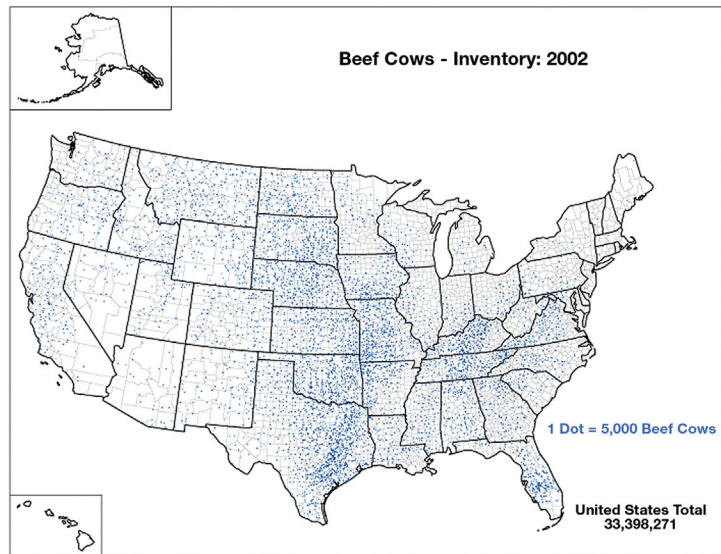
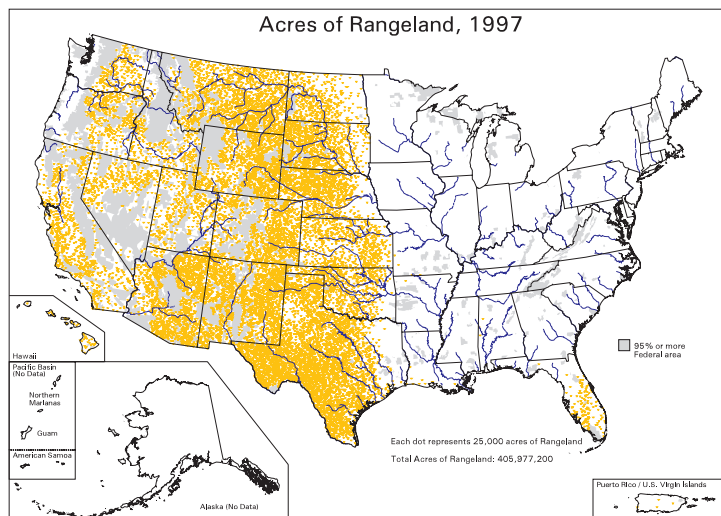
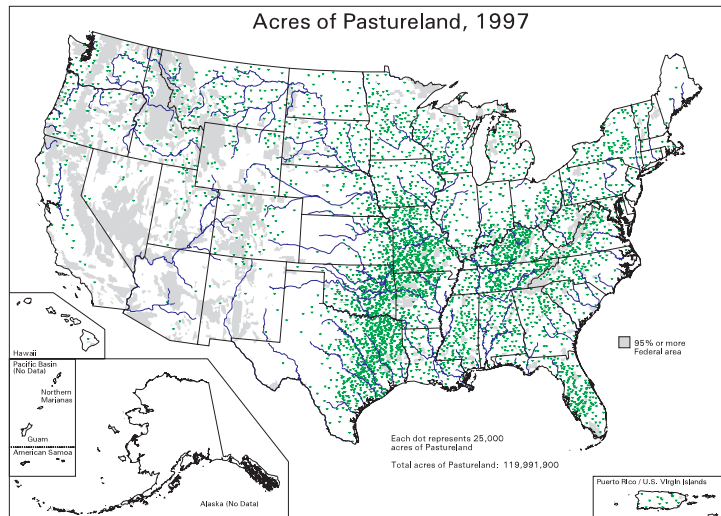


Figure 2.3 Distribution of beef cow inventory across the United States in 2002. (USDA National Agricultural Statistics Service.)



Figures 2.4a and 2.4b Distribution of pastureland and rangeland across the United States in 1997.



composed principally of native grasses, grass-like plants, forbs, or shrubs suitable for grazing and browsing, and introduced forage species that are managed like rangeland. This would include areas where introduced hardy and persistent grasses, such as crested wheatgrass, are planted and such practices as deferred grazing, burning, chaining, and rotational grazing are used, with little or no chemicals or fertilizer applied. This chapter will also consider the effects of climate on these areas.

2.2 OBSERVED CHANGES AND RESPONSES

2.2.1 Crops

2.2.1.1 SCOPE OF THE AGRICULTURAL SYSTEMS

As noted earlier, agriculture is a diverse system that covers a wide range of species and production systems across the United States. However, this chapter's scope includes species covered in the available scientific literature that evaluates observed responses to changing climate

Table 2.1 Non-federal grazing land (in millions of acres). Source: Natural Resources Conservation Service (NRCS).

| Year | Rangeland | Pastureland (millions of acres) | Grazed Forest land (millions of acres) | Total (millions of acres) |
|------|-----------|------------------------------------|--|------------------------------|
| 1982 | 415.5 | 131.1 | 64.3 | 610.9 |
| 1992 | 406.7 | 125.2 | 61.0 | 592.9 |
| 1997 | 404.9 | 119.5 | 58.0 | 582.4 |
| 2001 | 404.9 | 119.2 | 55.2 | 579.3 |
| 2003 | 405.1 | 117.0 | 54.3 | 576.4 |

Table 2.2 Changes in pasturelands by major water resource areas (in millions of acres). Source: www.nrcs.usda.gov/technical/land/nri03/national_landuse.html

| | 1982 | 1992 | 2003 |
|---------------------------------------|--------------|--------------|--------------|
| Arkansas-White-Red | 18.6 | 19.0 | 19.8 |
| California / Great Basin | 2.3 | 2.2 | 2.3 |
| Great Lakes | 5.8 | 4.7 | 4.4 |
| Lower Colorado / Upper Colorado | 0.8 | 0.9 | 0.9 |
| Lower Mississippi | 5.6 | 5.4 | 5.0 |
| Missouri | 20.4 | 19.2 | 18.0 |
| New England / Mid Atlantic | 7.4 | 6.3 | 5.6 |
| Ohio / Tennessee River | 20.9 | 19.8 | 17.7 |
| Pacific Northwest | 4.6 | 4.7 | 4.3 |
| Souris- Red-Rainy / Upper Mississippi | 14.5 | 12.7 | 11.7 |
| South Atlantic-Gulf | 15.5 | 15.9 | 13.9 |
| Texas-Gulf / Rio Grande | 14.7 | 14.4 | 13.4 |
| Totals | 131.1 | 125.2 | 117.0 |

characteristics. In the crops section, the focus is on maize (corn), soybean (*Glycine max*), wheat (*Triticum aestivum*), rice (*Oryza sativa*), sorghum (*Sorghum bicolor*), cotton (*Gossypium hirsutum*), peanut (*Arachis hypogea*), dry kidney bean (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*), and tomato (*Lycopersicon esculentum*).

Animal production systems cover beef cattle, dairy, swine, and poultry as the primary classes of animals. While climate changes affect all of these animals, the literature predominantly addresses beef, dairy, and swine. Poultry are primarily grown in housed operations, so the effect of climate change more directly affects the energy requirements for building operations compared to a direct effect on the animal. Similar statements can be made for swine production since the vast majority of the animals are housed. Temperature affects animals being moved from buildings to processing plants, but because these animals are moved quickly from production to processing, this is a problem only in extreme conditions.

Both pasture and rangeland are reviewed in this chapter. In the pastureland section, 13 species are considered in the analysis; for rangeland, species include a complex mixture of grasses and forbs, depending on the location.

As much as possible, the conclusions about the effects of global change on agriculture and other ecosystems are based on observed trends as much as possible. However, an immediate obstacle to using this observational approach is that the productivity of most agricultural enterprises has increased dramatically over the past decades due to improvements in technology, and the responses to these changes in technology overwhelm responses to global change that almost certainly are present but are statistically undetectable against the background of large technological improvements. Fortunately, numerous manipulative experiments have been conducted on these managed agricultural systems wherein temperature, CO₂, ozone (O₃), and/or other factors have been varied. From such experiments, the relative responses to the changing climate variables can be deduced. A second challenge, however, is that the details of each experiment have been different

— different temperature changes have been explored, different concentrations of CO₂, different crop varieties and so forth. The problem remains as to how to represent such experimental variability in methods in a way that provides a consistent baseline for comparison.

As noted in the Introduction, in about 30 years, CO₂ concentrations are expected to have increased about 60 ppm (from today's 380 ppm to about 440 ppm), and temperatures over the contiguous United States are expected to have increased by an average of about 1.2°C. We have therefore used these increments as baseline comparison points compared to current CO₂ and temperatures to estimate the likely responses of crops to global change for the 30-year time horizon of this report. We have done this by constructing mathematical response functions for crops and experiments that use the experimental data available.

2.2.1.2 PLANT RESPONSE TO TEMPERATURE

2.2.1.2.1 General Response

Crop species differ in their cardinal temperatures (critical temperature range) for life cycle development. There is a base temperature for vegetative development, at which growth commences, and an optimum temperature, at which the plant develops as fast as possible. Increasing temperature generally accelerates progression of a crop through its life cycle (phenological) phases, up to a species-dependent optimum temperature. Beyond this optimum temperature, development (node and leaf appearance rate) slows. Cardinal temperature values are presented below, in Tables 2.3 and 2.4, for selected annual (non-perennial) crops under conditions in which temperature is the only limiting variable.

One caveat is that the various scenarios for global change predict increasing air temperatures, but plants often are not growing at air temperature. For example, under arid conditions, amply irrigated crops can easily be 10°C cooler than air temperature due to transpirational cooling. Solar and sky radiation, wind speed, air humidity, and plant stomatal conductance are all variables that affect the difference in temperature between plants and air. While recognizing this problem, it is important to understand that published cardinal temperatures such as those in Tables

The goal in this chapter is to provide a synthesis of the potential impacts of climate on agriculture that can be used as a baseline to understand the consequences of climate variability.



2.3 and 2.4 are based on air temperature, rather than vegetation temperature. That is because air temperatures are much easier to measure than plant temperatures, and usually only air temperatures are reported from experiments; also many crop growth models assume that plants are growing at air temperature rather than at their own vegetation temperature. Nevertheless, crop canopy temperatures are sufficiently coupled to air temperatures that for a first approximation, we expect future crop canopy temperatures to increase by about the same amount as air temperatures with global warming.

Faster development of non-perennial crops is not necessarily ideal. A shorter life cycle results in smaller plants, shorter reproductive phase duration, and lower yield potential. Because of this, the optimum temperature for yield is nearly always lower than the optimum temperature for leaf appearance rate, vegetative growth, or reproductive progression. In addition, temperatures that fall below or above specific thresholds

at critical times during development can also have significant impact on yield. Temperature affects crop life cycle duration and the fit of given cultivars to production zones. Day-length sensitivity also plays a major role in life cycle progression in many crops, but especially for soybean. Higher temperatures during the reproductive stage of development affect pollen viability, fertilization, and grain or fruit formation. Chronic as well as short-term exposure to high temperatures during the pollination stage of initial grain or fruit set will reduce yield potential. This phase of development is one of the most critical stages of growth in response to temperatures extremes. Each crop has a specific temperature range at which vegetative and reproductive growth will proceed at the optimal rate and exposures to extremely high temperatures during these phases can impact growth and yield; however, acute exposure from extreme events may be most detrimental during the reproductive stages of development.

Table 2.3. For several economically significant crops, information is provided regarding cardinal, base, and optimum temperatures (°C) for vegetative development and reproductive development, optimum temperature for vegetative biomass, optimum temperature for maximum grain yield, and failure (ceiling) temperature at which grain yield fails to zero yield. The optimum temperatures for vegetative production, reproductive (grain) yield, and failure point temperatures represent means from studies where diurnal temperature range was up to 10°C.

| Crop | Base Temp Veg | Opt Temp Veg | Base Temp Repro | Opt Temp Repro | Opt Temp Range Veg Prod | Opt Temp Range Reprod Yield | Failure Temp Reprod Yield |
|---------|------------------|-------------------|------------------|---------------------|-------------------------|-----------------------------|---------------------------|
| Maize | 8 ¹ | 34 ¹ | 8 ¹ | 34 ¹ | | 18-22 ² | 35 ³ |
| Soybean | 7 ⁴ | 30 ⁴ | 6 ⁵ | 26 ⁵ | 25-37 ⁶ | 22-24 ⁶ | 39 ⁷ |
| Wheat | 0 ⁸ | 26 ⁸ | 1 ⁸ | 26 ⁸ | 20-30 ⁹ | 15 ¹⁰ | 34 ¹¹ |
| Rice | 8 ¹² | 36 ¹³ | 8 ¹² | 33 ¹² | 33 ¹⁴ | 23-26 ^{13,15} | 35-36 ¹³ |
| Sorghum | 8 ¹⁶ | 34 ¹⁶ | 8 ¹⁶ | 31 ¹⁷ | 26-34 ¹⁸ | 25 ^{17,19} | 35 ¹⁷ |
| Cotton | 14 ²⁰ | 37 ²⁰ | 14 ²⁰ | 28-30 ²⁰ | 34 ²¹ | 25-26 ²² | 35 ²³ |
| Peanut | 10 ²⁴ | >30 ²⁴ | 11 ²⁴ | 29-33 ²⁵ | 31-35 ²⁶ | 20-26 ^{26,27} | 39 ²⁶ |
| Bean | | | | | 23 ²⁸ | 23-24 ^{28,29} | 32 ²⁸ |
| Tomato | 7 ³⁰ | 22 ³⁰ | 7 ³⁰ | 22 ³⁰ | | 22-25 ³⁰ | 30 ³¹ |

¹Kiniry and Bonhomme (1991); ²Muchow et al. (1990); ³Herrero and Johnson (1980); ⁴Hesketh et al. (1973); ⁵Boote et al. (1998); ⁶Boote et al. (1997); ⁷Boote et al. (2005); ⁸Hodges and Ritchie (1991); ⁹Kobza and Edwards (1987); ¹⁰Chowdury and Wardlaw (1978); ¹¹Tashiro and Wardlaw (1990); ¹²Allocijja and Ritchie (1991); ¹³Baker et al. (1995); ¹⁴Matsushima et al. (1964); ¹⁵Horie et al. (2000); ¹⁶Alagarwamy and Ritchie (1991); ¹⁷Prasad et al. (2006a); ¹⁸Maiti (1996); ¹⁹Downs (1972); ²⁰K.R. Reddy et al. (1999, 2005); ²¹V.R. Reddy et al. (1995); ²²K.R. Reddy et al. (2005); ²³K.R. Reddy et al. (1992a, 1992b); ²⁴Ong (1986); ²⁵Bolhuis and deGroot (1959); ²⁶Prasad et al. (2003); ²⁷Williams et al. (1975); ²⁸Prasad et al. (2002); ²⁹Laing et al. (1984); ³⁰Adams et al. (2001); ³¹Peat et al. (1998).

For most perennial, temperate fruit and nut crops, winter temperatures play a significant role in productivity (Westwood 1993). There is considerable genotypic variation among fruit and nut crops in their winter hardiness (that is, the ability to survive specific low temperature extremes), and variation in their “winter chilling” requirement for optimum flowering and fruit set in the spring and summer (Table 2.5). Placement of fruit and nut crops within specific areas are related to the synchrony of phenological stages to the climate and the climatic resources of the region. Marketable yield of horticultural crops is highly sensitive to minor environmental stresses related to temperatures outside the optimal range, which negatively affect visual and flavor quality (Peet and Wolfe 2000).

2.2.1.2.2 Temperature effects on crop yield

Yield responses to temperature vary among species based on the crop’s cardinal temperature requirements. Plants that have an optimum range at cooler temperatures will exhibit significant decreases in yield as temperature increases above this range. However, reductions in yield with increasing temperature in field conditions may not be due to temperature alone, as high temperatures are often associated with lack of rainfall in many climates. The changes in temperature do not produce linear responses with increasing temperature because the biological response to temperature is nonlinear, therefore, as the temperature increases these effects will be larger. The interactions of temperature and water deficits negatively affect crop yield.

Table 2.4 Temperature thresholds for selected vegetable crops. Values are approximate, and for relative comparisons among groups only. For frost sensitivity: “+” = sensitive to weak frost; “-” = relatively insensitive; “()” = uncertain or dependent on variety or growth stage. Adapted from Krug (1997) and Rubatzky and Yamaguchi (1997).

| Climatic Classification | Crop | Acceptable Temp (C) For Germination | Opt Temp (C) For Yield | Acceptable Temp (C) Growth Range | Frost Sensitivity |
|-------------------------|--------------|-------------------------------------|------------------------|----------------------------------|-------------------|
| Hot | Watermelon | 21-35 | 25-27 | 18-35 | + |
| | Okra | 21-35 | 25-27 | 18-35 | + |
| | Melon | 21-32 | 25-27 | 18-35 | + |
| | Sweet Potato | 21-32 | 25-27 | 18-35 | + |
| Warm | Cucumber | 16-35 | 20-25 | 12-30(35) | + |
| | Pepper | 16-35 | 20-25 | 12-30(35) | + |
| | Sweet corn | 16-35 | 20-25 | 12-30(35) | + |
| | Snap bean | 16-30 | 20-25 | 12-30(35) | + |
| | Tomato | 16-30 | 20-25 | 12-30(35) | + |
| Cool-Warm | Onion | 10-30 | 20-25 | 7-30 | - |
| | Garlic | 7-25 | 20-25 | 7-30 | - |
| | Turnip | 10-35 | 18-25 | 5-25 | - |
| | Pea | 10-30 | 18-25 | 5-25 | () |
| Cool | Potato | 7-26 | 16-25 | 5-25(30) | + |
| | Lettuce | 5-26 | 16-25 | 5-25(30) | (+) |
| | Cabbage | 10-30 | 16-18(25) | 5-25 | - |
| | Broccoli | 10-30 | 16-18(25) | 5-25 | - |
| | Spinach | 4-16 | 16-18(25) | 5-25 | - |



Marketable yield of horticultural crops is highly sensitive to minor environmental stresses related to temperatures outside the optimal range, which negatively affect visual and flavor quality.



2.2.1.2.2.1 Maize

Increasing temperature causes the maize life cycle and duration of the reproductive phase to be shortened, resulting in decreased grain yield (Badu-Apraku et al. 1983; Muchow et al. 1990). In the analyses of Muchow et al. (1990), the highest observed (and simulated) grain yields occurred at locations with relatively cool temperatures (growing season mean of 18.0 to 19.8°C in Grand Junction, Colo.), which allowed long maize life cycles, compared to warmer sites (e.g., 21.5 to 24.0°C in Champaign, Ill.), or compared to warm tropical sites (26.3 to 28.9°C). For

the Illinois location, simulated yield decreased 5 to 8 percent per 2°C temperature increase. Using this relationship, a temperature rise of 1.2°C over the next 30 years in the Midwest may decrease yield by about 4 percent (Table 2.6) under irrigated or water-sufficient management.

Lobell and Asner (2003) evaluated maize and soybean production relative to climatic variation in the United States, reporting a 17 percent reduction in yield for every 1°C rise in temperature, but this response is unlikely because the confounding effect of rainfall was

Table 2.5 Winter chill requirement, winter hardiness (minimum winter temperature), and minimum frost-free period (growing season requirements) for selected woody perennial fruit and nut crops. Not shown in this table is the fact that flowers and developing fruit of all crops are sensitive to damage from mild to moderate frosts (e.g., 0 to -5°C), and high temperature stress (e.g., >35°C), specific damaging temperatures varying with crop and variety. Values are approximate and for relative comparisons only. Adapted from Westwood (1993).

Winter Chill Requirement (hours)¹

| Crop | Common Varieties | Other | Minimum Winter Temp (C) | Minimum Frost-Free Period (days) |
|------------------|------------------------------|--------------------|-------------------------|----------------------------------|
| Almond | 100-500 | | -10 | >180 |
| Apple | 1000-1600 | 400-1800 | -46 to -4 | <100 (+) |
| Blueberry | 400-1200 (northern highbush) | 0-200 | -35 to -12 | <100 (+) |
| Cherry | 900-1200 | 600-1400 | -29 to -1 | <100 (+) |
| Citrus | 0 | | -7 to 4 | >280 |
| Grape (European) | 100-500 | | -25 to 4 | >120 |
| Grape (American) | 400-2000 (+) | | -46 to -12 | <100 (+) |
| Peach | 400-800 | 200-1200 | -29 to 4 | >120 |
| Pear | 500-1500 | | -35 to -1 | >100 |
| Pecan | 600-1400 | | -10 | >180 |
| Pistachio | 600-1500 | 400-600 (Asian) | -10 | >180 |
| Plum | 800-1200 | 500-600 (Japanese) | -29 to 4 | >140 |
| Raspberry | 800-1700 | 100-1800 | -46 (+) | <100 (+) |
| Strawberry | 300-400 | | -12 | <100 (+) |
| Walnut | 400-1500 | | -29 | >100 |

¹Winter chilling for most fruit and nut crops occurs within a narrow temperature range of 0 to 15°C, with maximum chill-hour accumulation at about 7.2°C. Temperatures below or above this range do not contribute to the chilling requirement, and temperatures above 15°C may even negate previously accumulated chill.

not considered. In a recent evaluation of global maize production response to both temperature and rainfall over the period 1961-2002, Lobell and Field (2007) reported an 8.3 percent yield reduction per 1°C rise in temperature. Runge (1968) documented maize yield responses to the interaction of daily maximum temperature and rainfall during the period 25 days prior to, and 15 days after, anthesis of maize. If rainfall was low (0-44 mm per 8 days), yield was reduced by 1.2 to 3.2 percent per 1°C rise. Alternately, if temperature was warm (maximum temperature (Tmax) of 35°C), yield was reduced 9 percent per 25.4 mm rainfall decline. The Muchow et al. (1990) model, also used to project temperature effects on crops, may underestimate yield reduction with rising temperature because it had no temperature modification on assimilation or respiration, and did not provide for any failures in grain-set with rising temperature. Given the disagreement in literature estimates and lack of real manipulative temperature experiments on maize, the certainty of the estimate in Table 2.6 is only possible to likely.

Yield decreases caused by elevated temperatures are related to temperature effects on pollination and kernel set. Temperatures above 35°C are lethal to pollen viability (Herrero and Johnson 1980; Schoper et al. 1987; Dupuis and Dumas 1990). In addition, the critical duration of pollen viability (prior to silk reception) is a function of pollen moisture content, which is strongly dependent on vapor pressure deficit (Fonseca and Westgate 2005). There is limited data on sensitivity of kernel set in maize to elevated temperature, although in-vitro evidence suggests that the thermal environment during endosperm cell division phase (eight to 10 days post-anthesis) is critical (Jones et al. 1984). A temperature of 35°C, compared to 30°C during the endosperm division phase, dramatically reduced subsequent kernel growth rate (potential) and final kernel size, even if ambient temperature returns to 30°C (Jones et al. 1984). Temperatures above 30°C increasingly impaired cell division and amyloplast replication in maize kernels, and thus reduced grain sink strength and yield (Commuri and Jones 2001). Leaf photosynthesis rate of maize has a high temperature optimum of 33°C to 38°C. There is a minimal sensitivity of light use (quantum) efficiency to these elevated temperatures (Oberhuber and Edwards 1993; Edwards

and Baker 1993); however, photosynthesis rate is reduced above 38°C (Crafts-Brandner and Salvucci 2002).

2.2.1.2.2.2 Soybean

Reproductive development (time to anthesis) in soybean has cardinal temperatures that are somewhat lower than those of maize. A base temperature of 6°C and optimum temperature of 26°C are commonly used (Boote et al. 1998), having been derived, in part, from values of 2.5°C and 25.3°C developed from field data by Grimm et al. (1993). The post-anthesis phase for soybean has a surprisingly low optimum temperature of about 23°C, and life cycle is slower and longer if mean daily temperature is above 23°C (Pan 1996; Grimm et al. 1994). This 23°C optimum cardinal temperature for post-anthesis period closely matches the optimum temperature for single seed growth rate (23.5°C), as reported by Egli and Wardlaw (1980), and the 23°C optimum temperature for seed size (Egli and Wardlaw 1980; Baker et al. 1989; Pan 1996; Thomas 2001; Boote et al. 2005). As mean temperature increases above 23°C, seed growth rate, seed size, and intensity of partitioning to grain (seed harvest index) in soybean decrease until reaching zero at 39°C mean (Pan 1996; Thomas 2001).

The CROPGRO-soybean model, parameterized with the Egli and Wardlaw (1980) temperature effect on seed growth sink strength, and the Grimm et al. (1993, 1994) temperature effect on reproductive development, predicts highest grain yield of soybean at 23-24°C, with progressive decline in yield, seed size, and harvest index as temperature further increases, reaching zero yield at 39°C (Boote et al. 1997, 1998). Soybean yield produced per day of season, when plotted against the mean air temperature at 829 sites of the soybean regional trials over the United States, showed highest productivity at 22°C (Piper et al. 1998).

Pollen viability of soybean is reduced if temperatures exceed 30°C (optimum temperature), but has a long decline slope to failure at 47°C (Salem et al. 2007). Averaged over many cultivars, the cardinal temperatures (base temperature (Tb), optimum temperature (Topt), and Tmax) were 13.2°C, 30.2°C, and 47.2°C, respectively, for pollen germination, and 12.1°C, 36.1°C, and



47.0°C, respectively, for pollen tube growth. Minor cultivar differences in cardinal temperatures and tolerance of elevated temperature were present, but differences were not very large or meaningful. Salem et al. (2007) evaluated soybean grown at 38/30°C versus 30/22°C (day/night) temperatures. The elevated temperature reduced pollen production by 34 percent, pollen germination by 56 percent, and pollen tube elongation by 33 percent. The progressive reduction in seed size (single seed growth rate) above 23°C, along with reduction in fertility (i.e., percent seed set) above 30°C, results in reduction in seed harvest index at temperatures above 23-27°C (Baker et al. 1989; Boote et al. 2005). Zero seed harvest index occurs at 39°C (Pan 1996; Thomas 2001; Boote et al. 2005).

The implication of a temperature change on soybean yield is thus strongly dependent on the prevailing mean temperature during the post-anthesis phase of soybean in different regions. For the upper Midwest, where mean soybean growing season temperatures are about 22.5°C, soybean yield may actually increase 2.5 percent with a 1.2°C rise (Table 2.6). By contrast, soybean production in the southern United States, where mean growing season temperatures are 25°C to 27°C, soybean yield would be progressively reduced – 3.5 percent for 1.2°C increase from the current 26.7°C mean (Table 2.7) (Boote et al. 1996, 1997). Lobell and Field (2007) reported a 1.3 percent decline in soybean yield per 1°C increase in temperature, taken from global production against global average

Table 2.6 Percent grain yield and evapotranspiration responses to increased temperature (1.2°C), increased CO₂ (380 to 440 ppm), and the net effects of temperature plus increased CO₂ assuming additivity. Current mean air temperature during reproductive growth is shown in parentheses for each crop/region to give starting references, although yield of all the cereal crops declines with a temperature slope that originates below current mean air temperatures during grain filling.

| Crop | Grain Yield | | | Evapotranspiration | |
|----------------------------|----------------------------------|---|---|---------------------------|---|
| | Temperature (1.2°C) ¹ | CO ₂ (380 to 440 ppm) ² | Temp/CO ₂ Combined Irrigated | Temp (1.2°C) ³ | CO ₂ (380 to 440 ppm) ⁴ |
| % change | | | | | |
| Corn – Midwest (22.5°C) | -4.0 | +1.0 | -3.0 | +1.8 | |
| Corn – South (26.7°C) | -4.0 | +1.0 | -3.0 | +1.8 | |
| Soybean – Midwest (22.5°C) | +2.5 | +7.4 | +9.9 | +1.8 | -2.1 |
| Soybean – South (26.7°C) | -3.5 | +7.4 | +3.9 | +1.8 | -2.1 |
| Wheat – Plains (19.5°C) | -6.7 | +6.8 | +0.1 | +1.8 | -1.4 |
| Rice – South (26.7°C) | -12.0 | +6.4 | -5.6 | +1.8 | -1.7 |
| Sorghum (full range) | -9.4 | +1.0 | -8.4 | +1.8 | -3.9 |
| Cotton – South (26.7°C) | -5.7 | +9.2 | +3.5 | +1.8 | -1.4 |
| Peanut – South (26.7°C) | -5.4 | +6.7 | +1.3 | +1.8 | |
| Bean – relative to 23°C | -8.6 | +6.1 | -2.5 | +1.8 | |

¹Response to temperature summarized from literature cited in the text. ²Response to CO₂ with Michaelis-Menten rectangular hyperbola interpolation of literature values shown in Table 2.7. ³From Table 2.8 the sensitivity of a standard alfalfa crop to warming at constant relative humidity on clear summer day would be 1.489% per °C, so assuming the crop ET will respond similarly with warming by 1.2°C, the expected change in ET would be 1.8%. ⁴From Table 2.7 assuming linear ET response to 60 ppm increase in CO₂ interpolated from the range, 350 to 700 ppm or 370 to 570 ppm for sorghum.

temperature during July-August, weighted by production area. These two estimates are in agreement and likely, considering that Lobell and Field (2007) averaged over cool and warm production areas.

2.2.1.2.2.3 *Wheat*

Grain-filling period of wheat and other small grains shortens dramatically with rising temperature (Sofield et al. 1974, 1977; Chowdhury and Wardlaw 1978; Goudrian and Unsworth 1990). Assuming no difference in daily photosynthesis, which can be inferred from the sink removal studies of Sofield et al. (1974, 1977), yield will decrease in direct proportion to the shortening of grain filling period as temperature increases. This temperature effect is already a major reason for the much lower wheat yield potential in the Midwest than in northern Europe, even with the water limitation removed.

The optimum temperature for photosynthesis in wheat is 20-30°C (Kobza and Edwards 1987). This is 10°C higher than the optimum (15°C) for grain yield and single grain growth rate (Chowdhury and Wardlaw 1978). Any increase in temperature beyond the 25-35°C range that is common during grain filling of wheat will reduce the grain filling period and, ultimately, yields. Applying the nonlinear slope of reduction in grain filling period from Chowdhury and Wardlaw (1978), relative to the mean temperatures during grain fill in the wheat growing regions of the Great Plains, reduction in yield is about 7 percent per 1°C increase in air temperature between 18 and 21°C, and about 4 percent per 1°C increase in air temperature above 21°C, not considering any reduction in photosynthesis or grain-set. Similarly, Lawlor and Mitchell (2000) stated that a 1°C rise would shorten the reproductive phase by 6 percent, grain filling duration by 5 percent, and would reduce grain yield and harvest index proportionately. Bender et al. (1999) analyzed spring wheat grown at nine sites in Europe and found a 6 percent decrease in yield per 1°C temperature rise. Lobell and Field (2007) reported a 5.4 percent decrease in global mean wheat yield per 1°C increase in temperature. Grain size will also be reduced slightly. These four references are very much in agreement, so the projected temperature effect on yield in Table 2.6 is considered very likely. Effects of rising temperature on photosynthesis

should be viewed as an additional reduction factor on wheat yield, primarily influenced via water deficit effects (Paulsen 1994). Temperatures of 36/31°C (maximum/minimum) for two to three days prior to anthesis causes small unfertilized kernels with symptoms of parthenocarpy – that is, small shrunken kernels with notching and chalking of kernels (Tashiro and Wardlaw 1990). Increased temperature also reduces starch synthesis in wheat endosperm (Caley et al. 1990).

2.2.1.2.2.4 *Rice*

The response of rice to temperature has been well studied (Baker and Allen 1993a, 1993b; Baker et al. 1995; Horie et al. 2000). Leaf-appearance rate of rice increases with temperature from a base of 8°C, until reaching 36-40°C, the thermal threshold of survival (Alocilja and Ritchie 1991; Baker et al. 1995), with biomass increasing up to 33°C (Matsushima et al. 1964); however, the optimum temperature for grain formation and yield of rice is lower (25°C) (Baker et al. 1995). Baker et al. (1995) summarized many of their experiments from sunlit controlled-environment chambers and concluded that the optimum mean temperature for grain formation and grain yield of rice is 25°C. They found that grain yield is reduced about 10 percent per 1°C temperature increase above 25°C, until reaching zero yield at 35-36°C mean temperature, using a 7°C day/night temperature differential (Baker and Allen 1993a; Peng et al. 2004).

Grain number, percent filled grains, and grain harvest index followed nearly the same optimum and failure curve points. Declining yield above 25°C is initially attributed to shorter grain filling duration (Chowdhury and Wardlaw 1978; Snyder 2000), and then to progressive failure to produce filled grains – the latter is caused by reduced pollen viability and reduced production of pollen (Kim et al. 1996; Matsui et al. 1997; Prasad et al. 2006b). Pollen viability and production begins to decline as daytime maximum temperature exceeds 33°C, and reaches zero at Tmax of 40°C (Kim et al. 1996). Because flowering occurs at mid-day in rice, Tmax is the best indicator of heat stress on spikelet sterility. Grain size of rice tends to hold mostly constant, declining only slowly across increasing temperature, until the pollination failure point (Baker and Allen 1993a). Rice ecotypes,



japonica and *indica*, mostly do not differ in the upper temperature threshold (Snyder 2000; Prasad et al. 2006b), although the *indica* types are more sensitive to cool temperature (night temperature less than 19°C) (Snyder 2000).

Screening of rice genotypes and ecotypes for heat tolerance (33.1/27.3°C versus 28.3/21.3°C mean day/night temperatures) by Prasad et al. (2006b) demonstrated significant genotypic variation in heat tolerance for percent filled grains, pollen production, pollen shed, and pollen viability. The most tolerant cultivar had the smallest decreases in spikelet fertility, grain yield and harvest index at elevated temperature. This increment of temperature caused, for the range of 14 cultivars, 9-86 percent reduction in spikelet fertility, 0-93 percent reduction in grain weight per panicle, and 16-86 percent reduction in harvest index. Mean air temperature during the rice grain filling phase in summer in the southern United States and many tropical regions is about 26-27°C. These are above the 25°C optimum, which illustrates that elevated temperature above current will likely reduce U.S. and tropical region rice yield by about 10 percent per 1°C rise, or about 12 percent for a 1.2°C rise.

2.2.1.2.2.5 Sorghum

In general, the base and optimum temperatures for vegetative development are 8°C and 34°C, respectively (Alagarwamy and Ritchie 1991), while the optimum temperature for reproductive development is 31°C (Prasad et al. 2006a). Optimum temperature for sorghum vegetative growth is between 26°C and 34°C, and for reproductive growth 25°C and 28°C (Maiti 1996). Maximum dry matter production and grain yield occur at 27/22°C (Downs 1972). Grain filling duration is reduced as temperature increases over a wide range (Chowdury and Wardlaw 1978; Prasad et al. 2006a). Nevertheless, as temperature increased above 36/26°C to 40/30°C (diurnal maximum/minimum), panicle emergence was delayed by 20 days, and no panicles were formed at 44/34°C (Prasad et al. 2006a). Prasad et al. (2006a) found that grain yield, harvest index, pollen viability, and percent seed-set were highest at 32/22°C, and progressively reduced as temperature increased, falling to zero at 40/30°C. Vegetative biomass was highest at 40/30°C and photosynthesis was

high up to 44/34°C. Seed size was reduced above 36/26°C. Rice and sorghum have exactly the same sensitivity of grain yield, seed harvest index, pollen viability, and success in grain formation (Prasad et al. 2006a). In addition, maize, a related warm-season cereal, may have the same temperature sensitivity. Basing the yield response of sorghum only on shortening of filling period (Chowdury and Wardlaw 1978), yield would decline 7.8 percent per 1°C temperature rise from 18.5-27.5°C (a 9.4 percent yield reduction for a 1.2°C increase). However, if site temperature is cooler than optimum for biomass/photosynthesis (27/22°C), then yield loss from shorter filling period would be offset by photosynthesis increase. The response from Chowdury and Wardlaw (1978) is supported by the 8.4 percent decrease in global mean sorghum yield per 1°C increase in temperature reported for sorghum by Lobell and Field (2007); therefore, the reported responses are likely.

2.2.1.2.2.6 Cotton

Cotton is an important crop in the southern United States, and is considered to have adapted to high-temperature environments. Despite this perception, reproductive processes of cotton have been shown to be adversely affected by elevated temperature (Reddy et al. 2000, 2005). Being a tropical crop, cotton's rate of leaf appearance has a relatively high base temperature of 14°C, and a relatively high optimum temperature of 37°C, thus leaf and vegetative growth appear to tolerate elevated temperature (Reddy et al. 1999, 2005). On the other hand, reproductive progression (emergence to first flower) has a temperature optimum of 28-30°C, along with a high base temperature of about 14°C (Reddy et al. 1997, 1999). Maximum growth rate per boll occurred at 25-26°C, declining at higher temperatures, while boll harvest index was highest at 28°C, declining at higher temperatures, reaching zero boll harvest index at 33-34°C (Reddy et al. 2005).

Boll size was largest at temperatures less than 20°C, declining progressively as temperature increased. Initially there was compensation with increased boll number set as temperature increased up to 35/27°C day/night temperature, but above 30°C mean temperature, percent boll set, boll number, boll filling period, rate of boll growth, boll size, and yield all decreased (Reddy



et al. 2005). Instantaneous air temperature above 32°C reduces pollen viability, and temperature above 29°C reduces pollen tube elongation (Kakani et al. 2005), thus acting to progressively reduce successful boll formation to the point of zero boll yield at 40/32°C day/night (35°C mean) temperature (Reddy et al. 1992a, 1992b). Pettigrew (2008) evaluated two cotton genotypes under a temperature regime 1°C warmer than current temperatures and found lint yield was 10 percent lower in the warm regime. The reduced yields were caused by a 6 percent reduction in boll mass and 7 percent less seed in the bolls.

These failure point temperatures show that cotton is more sensitive to elevated temperature than soybean and peanut, but similar in sensitivity to rice and sorghum. There is no well-defined cotton-yield response to temperature in the literature, but if cotton yield is projected with a quadratic equation from its optimum at 25°C to its failure temperature of 35°C, then a 1.2°C increase from 26.7°C to 27.9°C would give a possible yield decrease of 5.7 percent.

2.2.1.2.2.7 *Peanut*

Peanut is another important crop in the southern United States. The base temperature for peanut-leaf-appearance rate and onset of anthesis are 10°C and 11°C, respectively (Ong 1986). The optimum temperature for leaf appearance rate is above 30°C, while the optimum for rate of vegetative development to anthesis is 29-33°C (Bolhuis and deGroot 1959). Leaf photosynthesis has a fairly high optimum temperature of about 36°C. Cox (1979) observed that 24°C was the optimum temperature for single pod growth rate and pod size, with slower growth rate and smaller pod size occurring at higher temperatures. Williams et al. (1975) evaluated temperature effects on peanut by varying elevation, and found that peanut yield was highest at a mean temperature of 20°C (27/15°C max/min), a temperature that contributed to a long life cycle and long reproductive period. Prasad et al. (2003) conducted studies in sunlit controlled environment chambers, and reported that the optimum mean temperature for pod yield, seed yield, pod harvest index, and seed size occurred at a temperature lower than 26°C; quadratic projections to peak and minimum suggest that the optimum temperature was 23-24°C, with a failure point temperature of 40°C for zero yield and zero harvest index.

Pollen viability and percent seed-set in that study began to fail at about 31°C, reaching zero at about 39-40°C (44/34°C treatment) (Prasad et al. 2003). For each individual flower, the period sensitive to elevated temperature starts six days prior to opening of a given flower and ends one day after, with greatest sensitivity on the day of flower opening (Prasad et al. 1999; Prasad et al. 2001). Percent fruit-set is first reduced at bud temperature of 33°C, declining linearly to zero fruit-set at 43°C bud temperature (Prasad et al. 2001).

Genotypic differences in heat-tolerance of peanut (pollen viability) have been reported (Craufurd et al. 2003). As air temperature in the southern United States already averages 26.7°C during the peanut growing season, any temperature increase will reduce seed yields (4.5 percent per 1°C, or 5.4 percent for a 1.2°C rise in range of 26-28°C) using the relationship of Prasad et al. (2003). At higher temperatures, 27.5-31°C, peanut yield declines more rapidly (6.9 percent per 1°C) based on unpublished data of Boote. A recent trend in peanut production has been the move of production from south Texas to west Texas, a cooler location with higher yield potential.

2.2.1.2.2.8 *Dry Bean and Cowpea*

Dry bean is typical of many vegetable crops and is grown in relatively cool regions of the United States. Prasad et al. (2002) found that red kidney bean, a large-seeded ecotype of dry bean, is quite sensitive to elevated temperature, having highest seed yield at 28/18°C (23°C mean) or lower (lower temperatures were not tested), with linear decline to zero yield as temperature increased to 37/27°C (32°C mean). In that study, pollen production per flower was reduced above 31/21°C, pollen viability was dramatically reduced above 34/24°C, and seed size was decreased above 31/21°C. Laing et al. (1984) found highest bean yield at 24°C, with a steep decline at higher temperatures. Gross and Kigel (1994) reported reduced fruit-set when flower buds were exposed to 32/27°C during the six to 12 days prior to anthesis and at anthesis, caused by non-viable pollen, failure of anther dehiscence, and reduced pollen tube growth. Heat-induced decreases in seed and fruit set in cowpea have been associated with formation of non-viable pollen (Hall 1992). Hall (1992) also



reported genetic differences in heat tolerance of cowpea lines. Screening for temperature-tolerance within bean cultivars has not been done explicitly, but the Mesoamerican lines are more tolerant of warm tropical locations than are the Andean lines, which include the red kidney bean type (Sexton et al. 1994). Taking the initial slope of decline from data of Prasad et al. (2002), bean yield will likely decrease 7.2 percent per 1°C temperature rise, or 8.6 percent for 1.2°C above 23°C (Table 2.6).

2.2.1.2.2.9 Tomato

Tomato is an important vegetable crop known to suffer heat stress in mid-summer in southern U.S. locations. The base and optimum temperature is 7° and 22°C for rate of leaf appearance, rate of truss appearance, and rate of progress to anthesis (Adams et al. 2001). Leaf photosynthesis of tomato has a base at 6-8°C (Duchowski and Brazaityte 2001), while its optimum is about 30°C (Bunce 2000). The rate of fruit development and maturation has a base temperature of 5.7°C and optimum of 26°C, and rate of individual fruit growth has its optimum at 22-25°C (Adams et al. 2001). Largest fruit size occurs at 17-18°C, and declines at progressively higher temperature (Adams et al. 2001; De Koning 1996). Rate of fruit addition (fruit-set, from pollination) has an optimum at or lower than 26°C and progressively fails as temperature reaches 32°C (Adams et al. 2001). Peat et al. (1998) observed that the number of fruits per plant (or percent fruit-set) at 32/26°C day/night (29°C mean) was only 10 percent of that at 28/22°C (25°C mean). The projected failure temperature was about 30°C. Sato et al. (2000) found that only one of five cultivars of tomato successfully set any fruit at chronic exposures to 32/26°C, although fruit-set recovered if the stressful temperature was relieved.

Sato et al. (2000) also noted that pollen release and pollen germination were critical factors affected by heat stress. The anticipated temperature effect on tomato production will depend on the region of production and time of sowing (in the southern United States); however, at optima of 22°C for leaf/truss development, 22-26°C for fruit addition, 22-25°C for fruit growth, and fruit-set failures above 26°C, temperatures exceeding 25°C will likely reduce tomato production. Depending on region of production, tomato

yield is projected to decrease 12.6 percent for 1.2°C rise above 25°C, assuming a non-linear yield response and assuming optimum temperature and failure temperatures for yield of 23.5°C and 30°C, respectively.

2.2.1.3 CROP RESPONSES TO CO₂

2.2.1.3.1 Overview of Individual Crop Responses to CO₂

Reviews of the early enclosure CO₂ studies indicate a 33 percent increase in average yield for many C₃ crops under a doubling CO₂ scenario (Kimball 1983) at a time when doubling meant increase from 330 to 660 parts per million (ppm) CO₂. The general phenomenon was expressed as increased numbers of tillers-branches, panicles-pods, and numbers of seeds, with minimal effect on seed size. The C₄ species response to doubling of CO₂ was reported by Kimball (1983) to be 10 percent. High temperature stress during reproductive development can negate CO₂'s beneficial effects on yield, even though total biomass accumulation maintains a CO₂ benefit (e.g., for *Phaseolus* bean, Jifon and Wolfe 2000). Unrestricted root growth, optimum fertility, and excellent control of weeds, insects, and disease are also required to maximize CO₂ benefits (Wolfe 1994). Most C₃ weeds benefit more than C₃ crop species from elevated CO₂ (Ziska 2003).

In recent years, new field “free-air CO₂ enrichment” (FACE) technology has allowed evaluation of a few select crops to better understand their response under field conditions without enclosure-confounding effects. Generally, the FACE results corroborate previous enclosure studies (Ziska and Bunce 2007), although some FACE results suggest yield responses are less than previously reported (Long et al. 2006). Although the continuously increasing “ambient” reference concentration is a cause for lesser response, the smaller increment of CO₂ enrichment requires even better replication and sampling in FACE to evaluate the response. Enclosures are not the only concern; single-spaced plants, or unbordered plants may respond too much, and potted plants that are root bound may not respond well. Additional research, data analysis, and evaluation of a broader range of crops using FACE techniques will be required to sort discrepancies where they exist.



Table 2.7 Percent response of leaf photosynthesis, total biomass, grain yield, stomatal conductance, and canopy temperature or evapotranspiration, to a doubling in CO₂ concentration (usually 350 to 700 ppm, but sometimes 330 to 660 ppm). *Responses to increase from ambient to 550 or 570 ppm (FACE) are separately noted.

| Crop | Leaf Photosynthesis | Total Biomass | Grain Yield | Stomatal Conductance | Canopy T, ET |
|----------|----------------------|---------------------|------------------------------------|---------------------------|---|
| % change | | | | | |
| Corn | 31 [*] | 41, 2, 3, 4 | 41, 2 | -34 ⁵ | |
| Soybean | 39 ⁶ | 37 ⁶ | 38 ⁶ , 34 ⁷ | -40 ⁶ | -9 ⁸ , -12 ^{9, 10*} |
| Wheat | 35 ¹¹ | 15-27 ¹² | 31 ¹³ | -33 to -43 ^{14*} | -8 ^{15, 16*} |
| Rice | 36 ¹⁷ | 30 ¹⁷ | 30 ^{17, 18} | | -10 ^{19, 27} |
| Sorghum | 9 ^{20, 21*} | 32 ^{2*} | 8 ²⁰ , 0 ^{22*} | -37 ^{21*} | -13 ^{23*} |
| Cotton | 33 ²⁴ | 36 ²⁴ | 44 ²⁴ | -36 ²⁴ | -8 ²⁵ |
| Peanut | 27 ²⁶ | 36 ²⁶ | 30 ²⁶ | | |
| Bean | 50 ²⁶ | 30 ²⁶ | 27 ²⁶ | | |

References: ¹Leakey et al. (2006)*; ²King and Greer (1986); ³Ziska and Bunce (1997); ⁴Maroco et al. (1999); ⁵Leakey et al. (2006)*; ⁶Ainsworth et al. (2002); ⁷Allen and Boote (2000); ⁸Allen et al. (2003); ⁹Jones et al. (1985); ¹⁰Bernacchi et al. (2007)*; ¹¹Long (1991); ¹²Lawlor and Mitchell (2000); ¹³Amthor (2001); ¹⁴Wall et al. (2006)*; ¹⁵Andre and duCloux (1993); ¹⁶Kimball et al. (1999)*; ¹⁷Horie et al. (2000); ¹⁸Baker and Allen (1993a); ¹⁹Baker et al. (1997a); ²⁰Prasad et al. (2006a); ²¹Wall et al. (2001); ²²Ottman et al. (2001)*; ²³Triggs et al. (2004)*; ²⁴K.R. Reddy et al. (1995, 1997); ²⁵Reddy et al. (2000); ²⁶Prasad et al. (2003); ²⁷Yoshimoto et al. (2005).

Effects of doubling of CO₂ on leaf photosynthesis, total biomass, grain or fruit yield, conductance, and canopy temperature or evapotranspiration (ET) of important non-water-stressed crops are shown in Table 2.7. (In addition to the specific references cited below, Kimball et al. (2002) provide CO₂ responses of several more crop and soil parameters for a variety of species.)

Maize, being a C₄ species, is less responsive to increased atmospheric CO₂. Single leaf photosynthesis of maize shows no effect of CO₂ on quantum efficiency, but there is a minor increase in leaf rate at light saturation (3 percent for 376 to 542 ppm; Leakey et al. 2006). There is a paucity of data for maize grown to maturity under elevated CO₂ conditions. Until 2006, there was only one data set for maize grown to maturity under CO₂ treatments: King and Greer (1986) observed 6.2 percent and 2.6 percent responses to increasing CO₂ from 355 to 625 and 875 ppm, respectively, in a 111-day study. The mean of the two levels gives about 4.4 percent increase to doubling or more of CO₂.

Leakey et al. (2006) conducted a full-season FACE study of maize grown to maturity, and

reported no significant response of maize to a 50 percent increase in CO₂ (376 to 542 ppm (target: 370 to 550 ppm)). However, they used a very small biomass sample size in their FACE study (four random plant samples per replicate). This small sample size coupled with the small increment of CO₂ increase raises concern about whether these experimental measurements were sufficient to detect a statistically significant response. Ziska and Bunce (1997) reported a 2.9 percent increase in biomass when CO₂ was increased from 371 to 674 ppm during a 33-day, glasshouse study. Maroco et al. (1999) reported a 19.4 percent biomass increase when CO₂ was increased from 350 to 1,100 ppm during a 30-day growth period at very high light (supplemented above outdoor ambient) for a short duration on young plants. Thus, 4 percent increases in both biomass and grain yield of maize are possible, with increase in CO₂ from 350 to 700 ppm. This is less than the simulated 10 percent increase for C₄ species to incremental CO₂ increases (330 to 660 ppm) as parameterized in the CERES-Maize (Crop Environment Resource Synthesis) or EPIC (Environmental Policy Integrated Climate) models based on sparse data (Tubiello et al. 2007).



In summary, the evidence for maize response to CO₂ is sparse and questionable, resulting in only a possible degree of certainty. The expected increment of CO₂ increase over the next 30 years is anticipated to have a negligible effect (i.e., 1 percent) on maize production, unless there is a water-savings effect in drought years (Table 2.6). Sorghum, another important C₄ crop, gave 9, 34, and 8 percent increases in leaf photosynthesis, biomass, and grain yield, respectively, with doubling of CO₂ when grown in 1-by-2-meter, sunlit controlled-environment chambers (Prasad et al. 2005a). Over an entire season, with a CO₂ increase from 368 to 561 ppm, sorghum grown as part of a FACE study in Arizona gave 3 and 15 percent increases in biomass, and -4 percent and +20 percent change in grain yield, under irrigated versus water-limited conditions, respectively (Ottman et al. 2001).

Soybean is a C₃ legume that is quite responsive to CO₂. Based on the metadata summarized by Ainsworth et al. (2002), soybean response to a doubling of CO₂ is about 39 percent for light-saturated leaf photosynthesis, 37 percent for biomass accumulation, and 38 percent for grain yield. (These values are only from soybean raised in large, ≥1-square-meter crop stands grown in soil because yield response to CO₂ potted plants was shown to be affected by pot size). Allen and Boote (2000) reported a response of 34 percent in sunlit controlled-environment chambers to increases in CO₂ from 330 to 660 ppm. Ainsworth et al. (2002) found that under similar conditions, leaf conductance was reduced by 40 percent, which is consistent with other C₃ and C₄ species (Morison 1987), and seed harvest index was reduced by 9 percent. The C₃ photo-

synthetic response to CO₂ enrichment is well documented, and generally easy to predict using either the Farquhar and von Cammerer (1982) equations, or simplifications based on those equations. The CROP-GRO-soybean model (Boote et al. 1998), parameterized with Farquhar kinetics equations (Boote and Pickering 1994; Alagarswamy et al. 2006), was used to simulate soybean yield to CO₂ rises from 350 to 700 ppm. The CROPGRO-soybean model predicted 29-41 percent increase in biomass, and 29 to 34 percent increase in grain yield (Boote et al. 1997), values that are comparable to metadata summarized by Ainsworth et al. (2002) and Allen and Boote (2000). Crop models can be used to project yield responses to CO₂ increase from past to present and future levels. Simulations by Boote et al. (2003) suggested that soybean yield in Iowa would have increased 9.1 percent between 1958 and 2000, during which time the CO₂ increased from 315 to 370

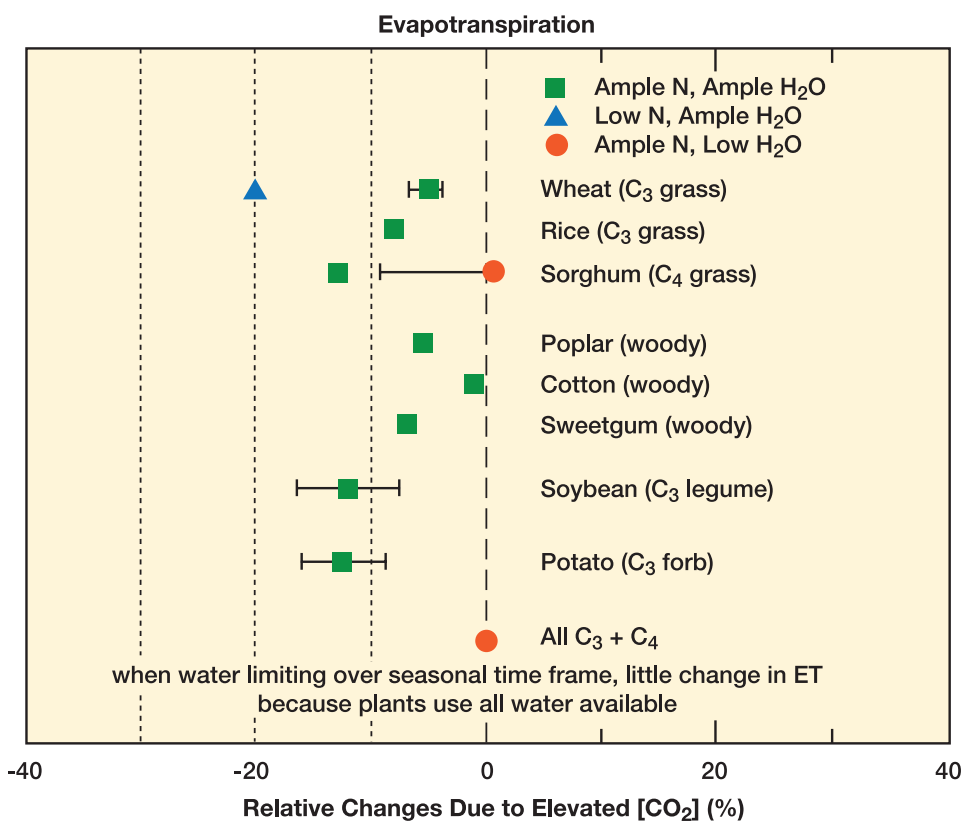


Figure 2.5 Relative changes in evapotranspiration due to elevated CO₂ concentrations in FACE experiments at about 550 ppm. [Wheat and cotton data from Table 2 of Kimball et al. (2002); rice datum from Yoshimoto et al. (2005); sorghum datum from Triggs et al. (2004); poplar datum from Tommasi et al. (2002); sweetgum from Wullschleger and Norby (2001); soybean datum from Bernacchi et al. (2007); and potato datum from Magliulo et al. (2003)].

ppm; thus some of the past yield trend of soybean was associated with global change rather than technological innovation.

Using the same type of Michaelis-Menten rectangular hyperbola projection for soybean as used for all other crops, a CO₂ increase from 380 to 440 ppm is projected to increase yield by 7.4 percent (Table 2.7) in the dominant soybean-growing regions in the Midwest. For this region, expected temperatures are so close to the optimum for soybean yield, and the temperature increment so small (1.2°C) that the net effect of climate change on soybean yield is dominated by the CO₂ increment. To the extent that water-use efficiency increases with CO₂ enrichment and conserves soil water, yield response for rainfed regions will be enhanced by a net 0.9 percent increase in ET.

Other C₃ field crop species exhibit similar responses to increasing CO₂. For wheat, a cool-season cereal, doubling of CO₂ (350 to 700 ppm) increased light-saturated leaf photosynthesis by 30–40 percent (Long 1991), and grain yield by about 31 percent, averaged over many data sets (Amthor 2001). For rice, doubling CO₂ (330 to 660 ppm) increased canopy assimilation, biomass, and grain yield by about 36, 30, and 30 percent, respectively (Horie et al. 2000). Baker and Allen (1993a) reported a 31 percent increase in grain yield, averaged over five experiments, with increase of CO₂ from 330 to 660 ppm. Rice shows photosynthetic acclimation associated with decline in leaf nitrogen (N) concentration, and a 6–22 percent reduction in leaf rubisco content per unit leaf area (Vu et al. 1998).

For peanut, a warm-season grain legume, doubling CO₂ increased light-saturated leaf photosynthesis, total biomass and pod yield of peanut by 27, 36, and 30 percent, respectively (Prasad et al. 2003). Doubling CO₂ (350 to 700 ppm) increased light-saturated leaf photosynthesis, biomass, and seed yield of dry bean by 50, 30, and 27 percent (Prasad et al. 2002).

For cotton, a warm-season non-legume, doubling CO₂ (350 to 700 ppm) increased light-saturated leaf photosynthesis, total biomass, and boll yield by 33 percent, 36 percent, and 44 percent (K. R. Reddy et al. 1995, 1997), respectively, and decreased stomatal conductance by 36 percent

(V. R. Reddy et al. 1995). Under well-watered conditions, leaf and canopy photosynthesis of cotton increased about 27 percent with CO₂ enrichment, to 550 ppm CO₂ in a FACE experiment in Arizona (Hileman et al. 1994). Mauney et al. (1994) reported 37 percent and 40 percent increases in biomass and boll yield of cotton with CO₂ enrichment to 550 ppm. Even larger increases in yield and biomass of cotton were obtained under the same enrichment for cotton under water-deficit situations (Kimball and Mauney 1993). An important consideration relative to cotton responses in Arizona is that the large vapor pressure deficit may have given more benefit to elevated CO₂ via water conservation effects. So, the degree of responsiveness in arid region studies may differ from that in humid regions. There were no reported effects of doubled CO₂ on vegetative or reproductive growth stage progression in cotton (Reddy et al. 2005), soybean (Allen and Boote 2000; Pan 1996), dry bean (Prasad et al. 2002), and peanut (Prasad et al. 2003).

The certainty level of biomass and yield response of these C₃ crops to CO₂ is likely to very likely, given the large number of experiments and the general agreement in response across the different C₃ crops.

2.2.1.3.2 Effects of CO₂ Increase in Combination with Temperature Increase

There could be beneficial interaction of CO₂ enrichment and temperature on dry matter production (greater response to CO₂ as temperature rises) for the vegetative phase of non-competitive plants, as highlighted by Idso et al. (1987). This effect may be beneficial to production of radish (*Raphanus sativus*), lettuce (*Lactuca sativa*), or spinach (*Spinacea oleracea*), mainly because any factor that speeds leaf area growth (whether CO₂ or temperature) speeds the exponential phase of early growth. However, this “beta” factor effect does not appear to apply to closed canopies or to reproductive grain yield processes.

There are no reported beneficial interactions in grain yield caused by the combined effects of CO₂ and temperature increase for rice (Baker and Allen 1993a, 1993b; Baker et al. 1995; Snyder 2000), wheat (Mitchell et al. 1993), soybean (Baker et al. 1989; Pan 1994), dry bean (Prasad

In recent years, new field “free-air CO₂ enrichment” (FACE) technology has allowed evaluation of a few select crops to better understand their response under field conditions without enclosure-confounding effects.



et al. 2002), peanut (Prasad et al. 2003), or sorghum (Prasad et al. 2005a). In other words, the separate main effects of CO₂ and temperature were present, but yield response to CO₂ was not enhanced as temperature increased. By contrast, there are three reported negative effects caused by elevated CO₂ and temperature in terms of fertility. Elevated CO₂ causes greater sensitivity of fertility to temperature in rice (Kim et al. 1996; Matsui et al. 1997), sorghum (Prasad et al. 2006a), and dry bean (Prasad et al. 2002). For rice, the relative enhancement in grain yield with doubled CO₂ decreases, and actually goes negative as T_{max} increases in the range 32–40°C (Kim et al. 1996). Likewise, the relative CO₂ enhancement of grain yield of soybean (Baker et al. 1989) lessened as temperature increased from optimum to super-optimum. In the case of rice, sorghum, and dry bean, failure point temperature (i.e., the point at which reproduction fails) is about 1–2°C lower at elevated CO₂ than at ambient CO₂. This likely occurs because elevated CO₂ causes warming of the foliage (doubled CO₂ canopies of dry bean were 1.5°C warmer) (Prasad et al. 2002); doubled CO₂ canopies of soybean were 1–2°C warmer (Allen et al. 2003); doubled CO₂ canopies of sorghum averaged 2°C warmer during daytime period (Prasad et al. 2006a). The higher canopy temperature of rice, sorghum, and dry bean adversely affected fertility and grain-set. Increases in canopy temperature for wheat, rice, sorghum, cotton, poplar, potato, and soybean have been reported in FACE experiments (Kimball and Bernacchi 2006).

In cotton, there was progressively greater photosynthesis and vegetative growth response to CO₂ as temperature increased up to 34°C (Reddy 1995), but this response did not carry over to reproductive growth (Reddy et al. 1995). The reproductive enhancement from doubled CO₂ was largest (45 percent) at the 27°C optimum temperature for boll yield, and there was no beneficial interaction of increased CO₂ on reproductive growth at elevated temperature, reaching zero boll yield at 35°C (Reddy et al. 1995). Mitchell et al. (1993) conducted field studies of wheat grown at ambient and +4°C temperature differential, and at elevated versus ambient CO₂ in England. While interactions of CO₂ and temperature did not affect yield, higher temperatures reduced grain yield at both CO₂ levels such that

yields were significantly greater at ambient CO₂ and ambient temperature compared to elevated CO₂ and high temperature. Batts et al. (1997) similarly reported no beneficial interactions of CO₂ and temperature on wheat yield.

In studies with bean (Jifon and Wolfe 2005) and potato (Peet and Wolfe 2000), there were no significant beneficial effects of CO₂ on yield in high temperature treatments that negatively affected reproductive development, although the beneficial effects on vegetative biomass were maintained. These results suggest that in those regions and for those crops where climate change impairs crop reproductive development because of an increase in the frequency of high temperature stress events, the potential beneficial effects of elevated CO₂ on yield may not be fully realized.

For peanut, there was no interaction of elevated temperature with CO₂ increase, as the extent of temperature-induced decrease in pollination, seed-set, pod yield, seed yield, and seed harvest index was the same at ambient and elevated CO₂ levels (Prasad et al. 2003). For dry bean, Prasad et al. (2002) found no beneficial interaction of elevated temperature with CO₂ increase, as the temperature-induced decrease in pollination, seed-set, pod yield, seed yield, and seed harvest index were the same or even greater at elevated than at ambient CO₂ levels. The temperature-sensitivity of fertility (grain-set) and yield for sorghum was significantly greater at elevated CO₂ than at ambient CO₂ (Prasad et al. 2006a), thus showing a negative interaction with temperature associated with fertility and grain-set, but not photosynthesis.

2.2.1.3.3 Interactions of Elevated CO₂ with Nitrogen Fertility

For non-legumes like rice, there is clear evidence of an interaction of CO₂ enrichment with nitrogen (N) fertility regime. For *japonica* rice, Nakagawa et al. (1994) reported 17, 26, and 30 percent responses of biomass to CO₂ enrichment, at N applications of 40, 120, and 200 kg N ha⁻¹, respectively. For *indica* rice, 0, 29, and 39 percent responses of biomass to CO₂ enrichment were reported at N applications of 0, 90, and 200 kg N per hectare, respectively (Ziska et al. 1996). For C₄ bahiagrass (*Paspalum notatum*), Newman et al. (2006) observed no biomass



Table 2.8 Sensitivity of evapotranspiration (ET; percent change in ET per °C change in temperature or percent change in ET per percent change in variable other than temperature) to changes in weather and plant variables as calculated by Kimball (2007) from the ASCE standardized hourly reference equation for alfalfa (Allen et al. 2005). The weather data were from the AZMET network (Brown 1987) for Maricopa, AZ, on a clear summer day (21 June 2000), and for the whole 2000 year. Calculations were made hourly then summed for the clear summer day and whole year.

| Weather or Plant Variable | ET Sensitivity (°C or % change) | |
|---|---------------------------------|------------|
| | Summer Day | Whole Year |
| T _{ah} , air temperature with absolute humidity constant, EC | 2.394 | 3.435 |
| T _{rh} , air temperature with relative humidity constant, EC | 1.489 | 2.052 |
| R _s , solar radiation, % | 0.585 | 0.399 |
| e _a , absolute vapor pressure, % | -0.160 | -0.223 |
| u, wind speed, % | 0.293 | 0.381 |
| g _s , surface or canopy conductance, % | 0.085 | 0.160 |
| LAI, leaf area index, % | 0.085 | 0.160 |

response to doubled CO₂ at low N fertilization rate, but observed 7-17 percent increases with doubled CO₂ when fertilized with 320 kg N per hectare. Biomass production in that study was determined over four harvests in each of two years (the 7 percent response in year one was non-significant, but 17 percent response in year two was significant).

2.2.1.3.4 Effects of CO₂ Increase on Water Use and Water Use Efficiency

2.2.1.3.4.1 Changes in Crop Water Use due to Increasing Temperature, CO₂, and O₃

Water use (i.e., ET) of crop plants is a physical process but is mediated by crop physiological and morphological characteristics (e.g., Kimball 2007). It can be described by the Penman-Monteith equation, whose form was recently standardized (Allen et al. 2005) (Table 2.8). The equation reveals several mechanisms by which the climate change parameters – temperature, CO₂, and O₃ – can affect water use. These include: (1) direct effects on crop growth and leaf area, (2) alterations in leaf stomatal aperture and consequently their conductance for water vapor loss, and (3) physical changes in the vapor pressure inside leaves.

When plants are young and widely spaced, increases in leaf area are approximately propor-

tional to the increases in growth, and transpiration increases accordingly. More importantly, duration of leaf area will affect total seasonal crop water requirements. Thus, the lengthening of growing seasons due to global warming likely will increase crop water requirements. On the other hand, for some determinate cereal crops, increasing temperature can hasten plant maturity, thereby shortening the leaf area duration with the possibility of reducing the total season water requirement for such crops.

Elevated CO₂ causes partial stomatal closure, which decreases conductance, and reduces loss of water vapor from leaves to the atmosphere. Reviews of the effects of elevated CO₂ on stomatal conductance from chamber-based studies have reported that, on average, a doubling of CO₂ (from about 340 to 680 ppm) reduces stomatal conductance about 34 percent (e.g., Kimball and Idso 1983). Morison (1987) calculated an average reduction of about 40 percent, with no difference between C₃ and C₄ species. More recently, Wand et al. (1999) performed a meta-analysis on observations reported for wild C₃ and C₄ grass species, and found that with no stresses, elevated CO₂ reduced stomatal conductance by 39 and 29 percent for C₃ and C₄ species, respectively. The stomatal conductance of woody plants appears to decrease less than that of herbaceous plants in elevated CO₂, as



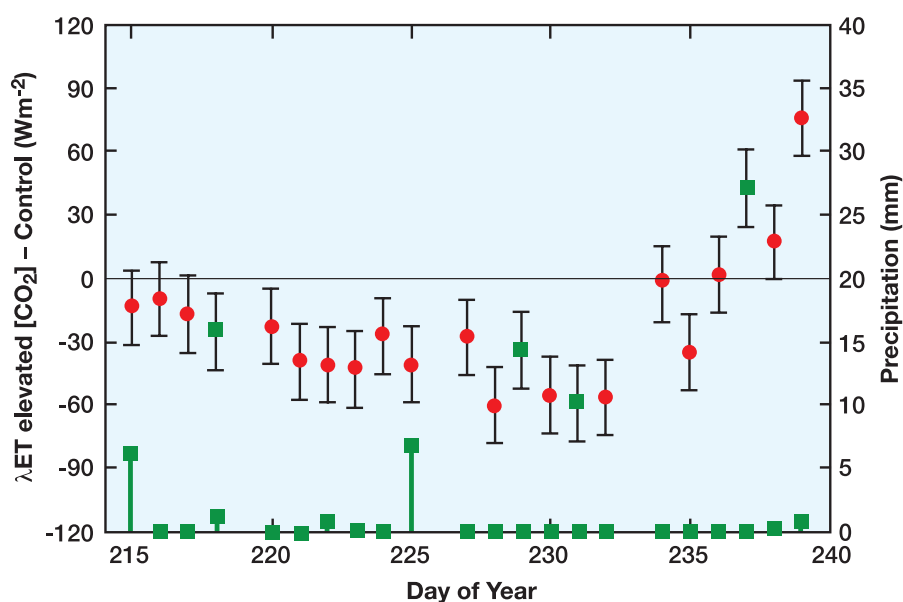


Figure 2.6 Differences in evapotranspiration rate (latent energy, $W m^{-2}$) between soybean plots enriched to 550 ppm from free-air CO_2 enrichment (FACE) and plots at today's ambient CO_2 levels at Urbana, IL, versus day of year (circles, left axis). Corresponding precipitation is also shown (squares, right axis). Adapted from Bernacchi et al. 2007.

indicated by an 11 percent reduction in the meta-analysis of woody plant data by Curtis and Wang (1998). Ainsworth et al. (2002) found an average reduction of about 40 percent in conductance of soybean for a wide range of CO_2 concentrations, with the reduction for a doubling being about 30 percent. Meta-analysis by Ainsworth and Long (2005) and Ainsworth and Rogers (2007) of data generated by free-air CO_2 enrichment experiments, for which the daytime concentrations were 550-600 ppm, versus ambient concentrations of about 360 ppm, produced an average reduction in stomatal conductance of 20 and 22 percent, respectively. They did not detect any significant difference between C_3 and C_4 species. Projecting out 30 years, the atmospheric CO_2 concentration likely will be about 440 ppm (see Introduction). Interpolating from these reviews, it appears very likely that an increase in CO_2 concentration from 380 to 440 ppm will cause reductions in stomatal conductance on the order of 10 percent compared to today's values.

However, as plants shift from vegetative to reproductive growth during their life cycles, proportionately more of the accumulating biomass is partitioned to other organs, such as developing grain. At this point, leaf area and biomass

accumulation are no longer proportional. Also, as plants grow and leaf area index (LAI) increases, the mutual shading and interference among the leaves within a plant canopy cause plant transpiration to plateau (Ritchie 1972; Villalobos and Fereres 1990; Sau et al. 2004). Further, considering that a doubling of CO_2 from present-day levels is likely to increase average C_3 species growth on the order of 30 percent (e.g., Kimball 1983, 2007; Kimball et al. 2002; Table 2.7), so projecting out 30 years to a CO_2 concentration of about 440 ppm suggests increases in C_3 plant growth only on the order of 10 percent. Therefore, because changes in growth affect ET mostly while plants are small (i.e., after planting),

and progressively less after canopy closure, changes in ET rates over the next 30 years due to leaf area index effects are likely to be minor (Figure 2.5).

Elevated CO_2 concentrations – approximately 550 ppm or about 180 ppm above ambient – in FACE experiments have reduced water use in experimental plots by about 2-13 percent, depending on species (Figure 2.6). Interpolating linearly to 440 ppm of CO_2 , the corresponding reductions likely would be about one-third of those observed in the FACE experiments (i.e., 1-4 percent). Because there are fetch considerations in extrapolating FACE plot data to larger areas (see discussion in Triggs et al. 2004), reductions in crop water requirements due to elevated CO_2 likely will be significant, but smaller yet.

Less research has been done on the effects of elevated O_3 on stomatal conductance compared to elevated CO_2 , but some pertinent work has been published. Barnes et al. (1995) and Balaguer et al. (1995) measured stomatal conductance of wheat exposed to elevated CO_2 (700 ppm), elevated O_3 (about 75 ppb), and combined elevated CO_2 plus O_3 in controlled environment chambers. The ozone treatment reduced

conductance by about 20 percent, while both CO₂ and CO₂+O₃ reduced conductance by 40 percent. Wheat was exposed by Donnelly et al. (2000) to elevated CO₂ (680 ppm) and O₃ (50 or 90 ppb) and CO₂+O₃ in open-top chambers, and they found that all three treatments produced reductions in stomatal conductance of approximately 50 percent, with relative order changing with days after sowing and year. Using open-top chambers with potato, both Lawson et al. (2002) and Finnan et al. (2002) report 50 percent reduction of stomatal conductance with elevated CO₂ (680 ppm) and a similar amount in combination with elevated O₃, but their results are variable and mutually inconsistent among treatments. In a FACE project that included both CO₂ and O₃ treatments, Noormets et al. (2001) measured stomatal conductance of aspen leaves. Results varied with leaf age and aspen clone, but generally it appears that conductance had the following treatment rank: Control>O₃>CO₂+O₃>CO₂. Morgan et al. (2003) performed a meta-analysis of 53 prior chamber studies in which O₃ was elevated by 70 ppm above clean air, and found that stomatal conductance was reduced by 17 percent on average. However, in a recent FACE soybean experiment in which O₃ was elevated by 50 percent above ambient conditions, Bernacchi et al. (2007) detected no significant effect of O₃ on stomatal conductance. Thus, while chamber studies comparing the effects of O₃ on stomatal conductance showed that reductions can occur, in the case of field-grown plants exposed to present-day ambient levels of O₃ that are considerably above zero, the effects on conductance of the additional increases in O₃ levels that are likely to occur in the next 30 years are likely to be rather small.

Water vapor pressure (e) inside leaves is tightly coupled to leaf temperature (T) and increases exponentially (e.g., as described by the Tetens' equation, $e=0.61078 \cdot \exp(17.269 \cdot T/(T+237.3))$). Therefore, anything that affects the energy balance and temperature of a crop's leaf canopy will affect leaf water vapor pressure, and ultimately water consumption. Consequently, so long as there are no significant concomitant compensatory changes in other factors such as humidity, it is virtually certain that air temperature increases will also increase crop canopy temperature, leaf water vapor pressure, and ET (Figure 2.5). Based on the sensitivity analysis

of Kimball (2007; Table 2.8), an increase of about 1.2°C with constant relative humidity, such as expected in 30 years (see Introduction), is likely to cause a small increase of about 1.8% in summer-day ET of a standard alfalfa reference crop if CO₂ concentrations were to remain at today's level. As already discussed, CO₂ concentrations of about 440 ppm are likely to cause small decreases in ET, so therefore, the net effect of increased temperature plus CO₂ likely will result in insignificant changes in ET within the next 30 years.

Another aspect to consider is the dynamics of crop water use and the timing of rain/irrigation events. The latent energy associated with ET from soybean was 10 to 60 W/m² less in the FACE plots compared to the control plots at ambient CO₂ when the crop had ample water (Figure 2.6).

However, on about Day-of-Year (DOY) 233, the control plots had exhausted the water supply, and their water use declined (Bernacchi et al. 2006) (Figure 2.6). In contrast, the water conservation in the elevated-CO₂ plots enabled plants to keep their stomata open and transpiring, and for DOYs 237-239, the FACE plots transpired more water than the controls. During this latter period, the FACE plants had their stomata open, while those of the control plots were closed. As a result, the FACE plots were able to continue photosynthesizing and growing while the controls were not. In other words, elevated concentrations of CO₂ can enable some conservation of soil water for rain-fed agriculture, which often experiences periods of drought, and can sustain crop productivity over more days than is true at today's CO₂ levels.

The net irrigation requirement is the difference between seasonal ET for a well-watered crop and the amounts of precipitation and soil water storage available during a growing season. A few researchers have attempted to estimate future changes in irrigation water requirements based on projected climate changes (including rainfall changes) from general circulation models (GCMs), and estimates of decreased stomatal conductance due to elevated CO₂ (e.g., Allen et al. 1991; Izaurrealde et al. 2003). Izaurrealde et al. (2003) used EPIC, a crop growth model, to calculate growth and yield, as well as future



irrigation requirements of corn and alfalfa. Following Stockle et al. (1992a, b), EPIC was modified to allow stomatal conductance to be reduced with increased CO₂ concentration (28 percent reduction corresponding to 560 $\mu\text{mol CO}_2 \text{ mol}^{-1}$), as well as increasing photosynthesis via improved radiation use efficiency. For climate change projections, they used scenarios generated for 2030 by the Hadley Centre's (HadCM2J) GCM, which was selected because its climate sensitivity is in the midrange of most of the GCMs. For corn, Izaurralde et al. (2003) calculated that by 2030 irrigation requirements will change from -1 (Lower Colorado Basin) to +451 percent (Lower Mississippi Basin), because of rainfall variation. Given the variation in the sizes and baseline irrigation requirements of U.S. basins, a representative figure for the overall U.S. increase in irrigation requirements is 64 percent if stomatal effects are ignored, or 35 percent if they are included. Similar calculations were made for alfalfa, for which overall irrigation requirements are predicted to increase 50 and 29 percent in the next 30 years in the cases of ignoring and including stomatal effects, respectively. These increases are more likely due to the decrease in rainfall during the growing season and the reduction in soil water availability.

2.2.1.3.4.2 *Implications for Irrigation and Water Deficit*

As mentioned above, stomatal conductance is reduced about 40 percent for doubling of CO₂ for both C₃ and C₄ species (Morison 1987), thus causing water conservation effects, and potentially less water deficit. However, actual reduction in crop transpiration and ET will not be as great as the reduction in stomatal conductance because warming of the foliage to solve the energy balance will increase both latent heat loss (transpiration) and sensible heat loss. Allen et al. (2003) concluded that both increased foliage temperature, and increased LAI associated with CO₂ enrichment were responsible for the compensatory effects on ET (small to non-existent reductions). Jones et al. (1985) reported 12 percent reduction in season-long transpiration and 51 percent increase in water use efficiency (WUE) measured for canopies of soybean crops grown in ambient and doubled CO₂ in sunlit, controlled environment chambers. In experimental studies in the same chambers, foliage temperatures measured by infrared

sensors have typically been increased 1-2°C for soybean, 1.5°C for dry bean, and 2°C for sorghum in response to doubled CO₂ (Pan 1996; Prasad et al. 2002; Prasad et al. 2006a). Similarly, in FACE experiments at about 550 ppm CO₂ foliage temperatures increased by an average 0.6°C for wheat (Kimball et al. 2002), 0.4°C for rice (Yoshimoto et al. 2005), 1.7°C for sorghum (Triggs et al. 2004), 0.8°C for cotton (Kimball et al. 2002), 0.8°C for potato (Magliu et al. 2003), and 0.2 to 0.5°C for soybean (Bernacchi et al. 2007).

Allen et al. (2003) reported that soybean foliage at doubled CO₂ was, on average, 1.3°C warmer at mid-day. Andre and du Cloux (1993) reported an 8 percent decrease in transpiration of wheat in response to doubled CO₂, which compares well to a 5 percent reduction in ET of wheat for a 200 ppm CO₂ increase in FACE studies (Hunsaker et al. 1997; Kimball et al. 1999) (Figure 2.5). Reddy et al. (2000), using similar chambers, found an 8 percent reduction in transpiration of cotton canopies at doubled CO₂, averaged over five temperature treatments, while Kimball et al. (1983) found a 4 percent reduction in seasonal water use of cotton at ambient versus 650 ppm CO₂ in lysimeter experiments in Arizona. Soybean canopies grown at 550 compared to 375 ppm in FACE experiments in Illinois had 9-16 percent decreases in ET depending on season. Their data show an average 12 percent reduction over three years (Bernacchi et al. 2007). Allen et al. (2003) observed 9 percent reduction in ET of soybean with doubling of CO₂ in the sunlit, controlled environment chambers for a 28/18°C treatment (about the same mean temperature as the Illinois site), but they observed no reduction in ET for a high temperature treatment 40/30°C. The extent of CO₂-related reduction in ET appears to be dependent on temperature. In their review, Horie et al. (2000) reported the same phenomenon in rice, where doubling CO₂ caused 15 percent reduction in ET at 26°C, but resulted in increased ET at higher temperatures (29.5°C). At 24-26°C, rice's WUE increased 50 percent with doubled CO₂, but the CO₂ enrichment effect declined as temperature increased. At higher temperature, CO₂-induced reduction in conductance lessened.

Using observed sensitivity of soybean stomatal conductance to CO₂ in a crop climate model,



Allen (1990) showed that CO₂ enrichment from 330 to 800 ppm should cause an increase in foliage temperature of about 1°C when air vapor pressure deficit is low, but an increase of about 2.5 and 4°C with air vapor pressure deficit of 1.5, and 3 kPa, respectively. At the higher vapor pressure deficit values, the foliage temperatures simulated with this crop climate model (Allen 1990) exceeded the differential observed under larger vapor pressure deficit in the sunlit, controlled-environment chambers (Prasad et al. 2002; Allen et al. 2003; Prasad et al. 2006a). Allen et al. (2003) found that soybean canopies increased their conductance (lower resistance) at progressively larger vapor pressure deficit (associated with higher temperature), such that foliage temperature did not increase as much as supposed by the crop-climate model. Concurrently, the anticipated degree of reduction in ET with doubling of CO₂, while being 9 percent less at cool temperatures (28/18°C), became progressively less and was non-existent (no difference) at very high temperatures (40/30°C and 44/34°C). In other words, the CO₂-induced reduction in conductance became less as temperature increased.

Boote et al. (1997) used a version of the CROPGRO-Soybean model with hourly energy balance and feedback of stomatal conductance on transpiration and leaf temperature (Pickering et al. 1995), to study simulated effects of 350 versus 700 ppm CO₂ for field weather from Ohio and Florida. The simulated transpiration was reduced 11-16 percent for irrigated sites and 7 percent for a rainfed site in Florida, while the ET was reduced 6-8 percent for irrigated sites and 4 percent for the rainfed site. Simulated water use efficiency was increased 53-61 percent, which matches the 50-60 percent increase in soybean WUE reported by Allen et al. (2003) for doubling of CO₂. The smaller reduction in transpiration and ET for the rainfed site was associated with more effective prolonged use of the soil water, also giving a larger yield response (44 percent) for rainfed crop than for irrigated (32 percent). The model simulated reductions in transpiration were close (11-16 percent) to those measured (12 percent) by Jones et al. (1985), and the reduction was much less than the reduction in leaf conductance. The model simulations also produced a 1°C higher foliage temperature at mid-day under doubled CO₂.

Interactions of CO₂ enrichment with climatic factors of water supply and evaporative demand will be especially evident under water deficit conditions. The reduction in stomatal conductance with elevated CO₂ will cause soil water conservation and potentially less water stress, especially for crops grown with periodic soil water deficit, or under high evaporative demand. This reduction in water stress effects on photosynthesis, growth, and yield has been documented for both C₃ wheat (Wall et al. 2006) and C₄ sorghum (Ottman et al. 2001; Wall et al. 2001; Triggs et al. 2004). Sorghum grown in the Arizona FACE site showed significant CO₂-induced enhancement of biomass and grain yield for water deficit treatments, but no significant enhancement for sorghum grown with full irrigation (Ottman et al. 2001). In the sorghum FACE studies, the stomatal conductance was reduced 32-37 percent (Wall et al. 2001), while ET was reduced 13 percent (Triggs et al. 2004).

2.2.1.4 CROP RESPONSE TO TROPOSPHERIC OZONE

Ozone at the land surface has risen in rural areas of the United States, particularly over the past 50 years, and is forecast to continue increasing during the next 50 years. The Midwest and eastern U.S. have some of the highest rural ozone levels on the globe. Average ozone concentrations rise toward the east and south, such that average levels in Illinois are higher than in Nebraska, Minnesota, and Iowa. Only western Europe and eastern China have similarly high levels. Argentina and Brazil, like most areas of the Southern Hemisphere, have much lower levels of ozone, and are forecast to see little increase over the next 50 years. Increasing ozone tolerance will therefore be important to the competitiveness of U.S. growers. Numerous models for future changes in global ozone concentrations have emerged that are linked to IPCC scenarios, so the impacts of ozone can be considered in the context of wider global change. For example, a model that incorporates expected economic development and planned emission controls in individual countries projects increases in annual mean surface ozone concentrations in all major agricultural areas of the Northern Hemisphere (Dentener et al. 2005).

Ozone is a secondary pollutant resulting from the interaction of nitrogen oxides with sunlight



Ozone at the land surface has risen in rural areas of the United States, particularly over the past 50 years, and is forecast to continue increasing during the next 50 years.

and hydrocarbons. Nitrogen oxides are produced in the high-temperature combustion of any fuel. They are stable and can be transported thousands of miles in the atmosphere. In the presence of sunlight, ozone is formed from these nitrogen oxides and, in contrast to most pollutants, higher levels are observed in rural than urban areas. This occurs because rural areas have more hours of sunshine and less haze, and city air includes short-lived pollutants that react with, and remove, ozone. These short-lived pollutants are largely absent from rural areas. Levels of ozone during the day in much of the Midwest now reach an average of 60 parts of ozone per billion parts of air (ppb), compared to less than 10 ppb 100 years ago. While control measures on emissions of NO_x and volatile organic carbons (VOCs) in North America and western Europe are reducing peak ozone levels, global background tropospheric ozone concentrations are on the rise (Ashmore 2005). Ozone is toxic to many plants, but studies in greenhouses and small chambers have shown soybean, wheat, peanut, and cotton are the most sensitive of our major crops (Ashmore 2002).

Ozone effects on soybean crops have been most extensively studied and best analyzed. This is because soybean is the most widely planted dicotyledonous crop, and is our best model of C₃ annual crops. The response of soybean to ozone can be influenced by the ozone profile and dynamics, nutrient and moisture conditions, atmospheric CO₂ concentration, and even the cultivar investigated, which creates a very complex literature to interpret. Meta-analytic methods are useful to quantitatively summarize treatment effects across multiple studies, and thereby identify commonalities. A meta-analysis of more than 50 studies of soybean, grown in controlled environment chambers at chronic levels of ozone, show convincingly that ozone exposure results in decreased photosynthesis, dry matter, and yield (Morgan et al. 2003). Even mild chronic exposure (40-60 ppb) produces such losses, and these losses increase linearly with ozone concentration (Morgan et al. 2003) as anticipated from the exposure/response relationship shown by Mills et al. (2000).

The meta-analytic summary further reveals that chronic ozone lowers the capacity of carbon

uptake in soybean by reducing photosynthetic capacity and leaf area. Soybean plants exposed to chronic ozone levels were shorter with less dry mass and fewer set pods, which contained fewer, smaller seeds. Averaged across all studies, biomass decreased 34 percent, and seed yield was 24 percent lower, but photosynthesis was depressed by only 20 percent. Ozone damage increased with the age of the soybean, consistent with the suggestion that ozone effects accumulate over time (Adams et al. 1996; Miller et al. 1998), and may additionally reflect greater sensitivity of reproductive developmental stages, particularly seed filling (Tingey et al. 2002). The meta-analysis did not reveal any interactions with other stresses, even stresses expected to lower stomatal conductance and therefore ozone entry into the leaf (Medlyn et al. 2001). However, all of the ozone effects on soybean mentioned above were less under elevated CO₂, a response generally attributed to lower stomatal conductance (Heagle et al. 1989).

Plant growth in chambers can be different compared to the open field (Long et al. 2006), and therefore the outcomes of chamber experiments have been questioned as a sole basis for projecting yield losses due to ozone (Elagöz and Manning 2005). FACE experiments in which soybeans were exposed to a 20 percent elevation above ambient ozone levels indicate that ozone-induced yield losses were at least as large under open air treatment. In 2003, the background ozone level in central Illinois was unusually low over the growing season, averaging 45 parts per billion (ppb). Elevation of ozone by 20 percent in this year raised the ozone concentration to the average of the previous 10 years. In the plots with elevated ozone in 2003, yields were reduced approximately 25 percent (Morgan et al. 2006). This suggests that, in a typical year under open-air field conditions, yield loss due to ozone is even greater than predictions from greenhouse experiments (Ashmore 2002).

Analysis in the soybean FACE results showed a significant decrease in leaf area (Dermody et al. 2006), a loss of photosynthetic capacity during grain filling, and earlier senescence of leaves (Morgan et al. 2004). This may explain why yield loss is largely due to decreased seed size rather than decreased seed number (Morgan



et al. 2006). On average, yield losses in Illinois soybean FACE experiments between 2002 and 2005 were 0.5 percent per ppb ozone increase over the 30 ppb threshold, which is twice the ozone sensitivity as determined in growth chamber studies (Ashmore 2002). These results suggest that during an average year, ozone is currently causing soybean yield losses of 10-25 percent in the Midwest, with even greater losses in some years. The IPCC forecasts that ozone levels will continue to rise in the rural Midwest by about 0.5 ppb per year, suggesting that soybean yields may continue to decline by 1 percent every two to four years. The IPCC also forecasts that ozone, which is low in South America, will remain low in that region over the next 50 years.

Meta-analysis has not been conducted for the effects of ozone on any crops other than soybean, or across different crops. Nevertheless, there is little doubt that current tropospheric ozone levels are limiting yield in many crops (e.g., Heagle 1989) and further increases in ozone will reduce yield in sensitive species further. The effect of exposure to ozone on yield and yield parameters from studies conducted prior to 2000 are compiled in Table 4 of Black et al. (2000), which reveals that, in addition to soybean, the yield of C₃ crops, such as wheat, oats, French and snap bean, pepper, rape, and various cucurbits, are highly sensitive to chronic ozone exposure. Yield of woody perennial cotton is also highly sensitive to ozone (e.g., Temple 1990; Heagle et al. 1996). While there are isolated reports that maize yield is reduced by ozone (e.g., Rudorff et al. 1996), C₄ crops are generally much less sensitive to ozone. Recent studies by Booker et al. (2007) and Burkey et al. (2007) on peanuts that evaluated the effect of ozone under CO₂ levels from 375 to 730 ppm, and ozone levels of 22-75 ppb, showed that CO₂ increases offset the effects of ozone. Increasing CO₂ levels overcame the effect of ozone on peanut yield; however, in none of the treatments was there a change in seed quality, or protein or oil content of the seed (Burkey et al. 2007).

2.2.2 Pastureland

In general, grassland species have received less attention than cropland species for their response to projected changes in temperature, precipitation, and atmospheric CO₂ concentration associated with climate change (Newman et al. 2001). Pastureland response to climate change is complex because, in addition to the major climatic drivers (CO₂ concentration, temperature, and precipitation), other plant and management factors affect this response (e.g., plant competition, perennial growth habits, seasonal productivity, etc.). Many of the studies in our review of published materials that report on temperate-climate pasture responses to changes in temperature, precipitation, and CO₂ concentrations originate from regions outside the United States.

An early comprehensive greenhouse study examined the photosynthetic response of 13 pasture species (Table 2.9) to elevated CO₂ (350 and 700 ppm) and temperature (12/7°C, 18/13°C, and 28/23°C for daytime/nighttime temperatures) (Greer et al. 1995). On average, photosynthetic rates increased by 40 percent under elevated CO₂ in C₃ species, while those for C₄ species remained largely unaffected. The response of C₃ species to elevated CO₂ decreased as temperatures increased from 12-28°C. However, the temperatures at which the maximum rates of photosynthesis occurred varied with species and level of CO₂ exposure. At 350 ppm, four species (*L. multiflorum*, *A. capillaris*, *C. intybus*, and *P. dilatatum*) showed maximum rates of photosynthesis at 18°C while, for the rest, the maximum occurred at 28°C. At 700 ppm, rates shifted upwards from 18-28°C in *A. capillaries*, and downward from 28-18°C in *L. perenne*, *F. arundinacea*, *B. wildenowii*, and *T. subterraneum*. However, little if any correlation existed between the temperature response of photosynthesis and climatic adaptations of the pasture species.

In Florida, a 3-year study examined the effects of elevated atmospheric CO₂ (360 and 700 ppm), and temperature (ambient temperature or baseline (B), B+1.5°C, B+3.0°C, and B+4.5°C) on dry matter yield of rhizoma peanut (a C₃ legume), and bahiagrass (a C₄ grass) (Newman et al. 2001). On average, yields increased by



Table 2.9 Pasture species studied for response to CO₂ and temperature changes. Adapted from Greer et al. (1995).

| Species | Common name | Photosynthetic pathway | Growth characteristics |
|-------------------------------|---------------------|------------------------|---------------------------------|
| <i>Lolium multiflorum</i> | Italian ryegrass | C ₃ | Cool season annual grass |
| <i>Bromus willdenowii</i> | | C ₃ | Cool season perennial grass |
| <i>Lolium perenne</i> | Ryegrass | C ₃ | Cool season perennial grass |
| <i>Phalaris aquatica</i> | | C ₃ | Cool season perennial grass |
| <i>Trifolium dubium</i> | | C ₃ | Cool season annual broadleaf |
| <i>Trifolium subterraneum</i> | Subterranean clover | C ₃ | Cool season annual broadleaf |
| <i>Agrostis capillaris</i> | | C ₃ | Warm season perennial grass |
| <i>Dactylis glomerata</i> | Orchardgrass | C ₃ | Warm season perennial grass |
| <i>Festuca arundinacea</i> | Tall fescue | C ₃ | Warm season perennial grass |
| <i>Cichorium intybus</i> | | C ₃ | Warm season perennial broadleaf |
| <i>Trifolium repens</i> | White clover | C ₃ | Warm season perennial broadleaf |
| <i>Digitaria sanguinalis</i> | Crabgrass | C ₄ | Warm season annual grass |
| <i>Paspalum dilatatum</i> | Dallisgrass | C ₄ | Warm season perennial grass |

25 percent in rhizoma peanut plots exposed to elevated CO₂, but exhibited only a positive trend in bahiagrass plots under the same conditions. These results are consistent with C₃- and C₄-type plant responses to elevated CO₂.

The response of forage species to elevated CO₂ may be affected by grazing and aboveground/belowground interactions (Wilsey 2001). In a phytotron study, Kentucky bluegrass and timothy (*Phleum pratense* L.) were grown together in pots during 12 weeks under ambient (360 ppm) and elevated CO₂ (650 ppm), with and without aboveground defoliation, and with and without the presence of *Pratylenchus penetrans*, a root-feeding nematode commonly found in old fields and pastures. Timothy was the only species that responded to elevated CO₂ with an increase in shoot biomass, leading to its predominance in the pots. This suggests that Kentucky bluegrass might be at the lower end of the range in the responsiveness of C₃ grasses to elevated CO₂, especially under low nutrient conditions. Defoliation increased productivity only under ambient CO₂; thus, the largest response to elevated CO₂ was observed in non-defoliated plants. Timothy was the only species that showed an increase in root biomass under elevated CO₂. Defoliation

reduced root biomass. Elevated CO₂ interacted with the presence of nematodes in reducing root biomass. In contrast, defoliation alleviated the effect of root biomass reduction caused by the presence of nematodes. This study demonstrates the importance of using aboveground/belowground approaches when investigating the environmental impacts of climate change (Wardle et al. 2004).

Kentucky bluegrass might not be the only species showing low response to elevated CO₂. Perennial ryegrass (*Lolium perenne*) has been reported to have low or even negative yield response to elevated CO₂ under field conditions but, contradictorily, often shows a strong response in photosynthetic rates (Suter et al. 2001). An experiment at the Swiss FACE examined the effects of ambient (360 ppm) and elevated (600 ppm) CO₂ on regrowth characteristics of perennial ryegrass (Suter et al. 2001). Elevated CO₂ increased root mass by 68 percent, pseudostems by 38 percent, and shoot necromass below cutting height by 45 percent during the entire regrowth period. Many of the variables measured (e.g., yield, dry matter, and leaf area index) showed a strong response to elevated CO₂ during the first regrowth period



but not during the second, suggesting a lack of a strong sink for the extra carbon fixed during the latter period.

When combined, rising CO₂ and projected changes in temperature and precipitation may significantly change the growth and chemical composition of plant species. However, it is not clear how the various forage species that harbor mutualistic relationships with other organisms would respond to elevated CO₂. Newman et al. (2003) studied the effects of endophyte infection, N fertilization, and elevated CO₂ on growth parameters and chemical composition of tall fescue. Fescue plants, with and without endophyte infection (*Neotyphodium coenophialum*), were transplanted to open chambers and exposed to ambient (350 ppm) and elevated (700 ppm) levels of CO₂. All chambers were fertilized with uniform rates of phosphorus (P) and potassium (K). Nitrogen fertilizer was applied at rates of 6.7 and 67.3 g m⁻². The results revealed complex interactions of the effects of elevated CO₂ on the mutualistic relationship between a fungus and its host, tall fescue. After 12 weeks of growth, plants grown under elevated CO₂ exhibited apparent photosynthetic rates 15 percent higher than those grown under ambient conditions. The presence of the endophyte fungus in combination with N fertilization enhanced the CO₂ fertilization effect. Elevated CO₂ accelerated the rate of tiller appearance and increased dry matter production by at least 53 percent (under the low N treatment). Contrary to previous findings, Newman et al. (2003) found that elevated CO₂ decreased lignin concentrations by 14 percent. Reduced lignin concentration would favor the diet of grazing animals, but hinder stabilization of carbon in soil organic matter (Six et al. 2002).

Climate change may cause reduction in precipitation and, in turn, induce soil moisture limitations in pasturelands. An experiment in New Zealand examined the interaction of elevated CO₂ and soil moisture limitations on the growth of temperate pastures (Newton et al. 1996). Intact turves (plural of turf) composed primarily of perennial ryegrass and dallisgrass (*Paspalum dilatatum*) were grown for 324 days under two levels of CO₂ (350 and 700 ppm), with air temperatures and photoperiod designed to emulate the monthly climate of the region.

After this equilibration period, half the turves in each CO₂ treatment underwent soil moisture deficit for 42 days. Turves under elevated CO₂ continued to exchange CO₂ with the atmosphere, while turves under ambient CO₂ did not. Root density measurements indicated that roots acted as sinks for the carbon fixed during the soil moisture deficit period. Upon rewatering, turves under ambient CO₂ had a vigorous rebound in growth while those under elevated CO₂ did not exhibit additional growth, suggesting that plants may exhibit a different strategy in response to soil moisture deficit depending on the CO₂ concentration.

2.2.2.1 PREDICTIONS OF PASTURELAND FORAGE YIELDS AND NUTRIENT CYCLING UNDER CLIMATE CHANGE

To evaluate the effect of climate scenarios on a forage crop, alfalfa production was simulated with the EPIC agroecosystem model (Williams 1995), using various climate change projections from the HadCM2 (Izaurralde et al. 2003), and GCMs from Australia's Bureau of Meteorology Research Centre (BMRC), and the University of Illinois, Urbana-Champaign (UIUC) (Thomson et al. 2005). All model runs were driven with CO₂ levels of 365 and 560 ppm without irrigation.

The results give an indication of pastureland crop response to changes in temperature, precipitation, and CO₂ for major regions of the United States (Table 2.10). Of these three factors, variation in precipitation had the greatest impact on regional alfalfa yield. Under the HadCM2 projected climate, alfalfa yields increase substantially in eastern regions, with declines through the central part of the country where temperature increases are greater and precipitation is lower. Slight alfalfa yield increases are predicted for western regions. The BMRC model projects substantially higher temperatures and consistent declines in precipitation over the next several decades, leading to a nationwide decline in alfalfa yields. In contrast, the UIUC model projects more moderate temperature increases along with higher precipitation, leading to modest increases in alfalfa yields throughout the central and western regions. While these results illustrate the uncertainty of model projections of crop yields due to the variation in

Climate change may cause reduction in precipitation and, in turn, induce soil moisture limitations in pasturelands.



global climate model projections of the future, they also underscore the primary importance of future precipitation changes on crop yield. Analysis of the results shown in Table 2.10 reveals that precipitation was the explanatory variable in yield changes followed by CO₂ and temperature change. Comparing the BMRC, HadCM2, and UIUC models showed that future changes in precipitation will be extremely important in alfalfa yields with a 1 percent decrease in alfalfa yields for every 4 mm decrease in annual precipitation.

Thornley and Cannell (1997) argued that experiments on elevated CO₂, and temperature effects on photosynthesis and other ecosystem processes may have limited usefulness for at least two reasons. First, laboratory or field experiments incorporating sudden changes in temperature or elevated CO₂ are short term and thus rarely produce quantitative changes in net primary productivity (NPP), ecosystem C, or other ecosystem properties connected to long-term responses to gradual climate change.

Table 2.10 Change in alfalfa yields in major U.S. regions as a percentage of baseline yield with average temperature and precipitation change under the selected climate model for early century (2030) climate change projections. Data in table from the simulations provided in Izaurrealde et al. (2003).

| Region | CO ₂ | HadCM2 | | | BMRC | | | UIUC | | |
|-------------------|-----------------|-----------------|-----------------|----------------|-----------------|-----------------|----------------|-----------------|-----------------|----------------|
| | | ΔT (°C) | ΔP (mm) | Yield % change | ΔT (°C) | ΔP (mm) | Yield % change | ΔT (°C) | ΔP (mm) | Yield % change |
| Great Lakes | 365 | 1.13 | 74 | 17.0 | 1.79 | -6 | -0.4 | 0.96 | 19 | -1.3 |
| | 560 | | | 20.6 | | | 0.0 | | | -1.0 |
| Ohio | 365 | 0.70 | 80 | 12.5 | 1.66 | -16 | -5.2 | 0.86 | 25 | -3.7 |
| | 560 | | | 13.9 | | | -5.0 | | | -3.8 |
| Upper Mississippi | 365 | 1.24 | 74 | 10.9 | 1.71 | -14 | -3.4 | 0.89 | 29 | -2.2 |
| | 560 | | | 14.8 | | | -2.5 | | | -2.1 |
| Souris-Red-Rainy | 365 | 1.40 | -30 | -30.7 | 1.73 | -3 | -1.9 | 0.96 | 12 | -0.4 |
| | 560 | | | -25.4 | | | 2.1 | | | 2.6 |
| Missouri | 365 | 1.42 | 34 | -9.2 | 1.50 | -18 | -9.4 | 0.92 | 41 | 3.5 |
| | 560 | | | -7.1 | | | -9.1 | | | 3.1 |
| Arkansas | 365 | 1.77 | -2 | -18.6 | 1.53 | -32 | -9.6 | 0.76 | 61 | 3.8 |
| | 560 | | | -14.2 | | | -7.3 | | | 5.1 |
| Rio Grande | 365 | 3.11 | 12 | 5.0 | 1.41 | -20 | -9.3 | 0.84 | 25 | 16.2 |
| | 560 | | | 5.3 | | | -8.7 | | | 17.8 |
| Upper Colorado | 365 | 2.21 | 76 | 5.0 | 1.48 | -18 | -15.3 | 0.97 | 40 | 16.2 |
| | 560 | | | 5.4 | | | -14.1 | | | 16.7 |
| Lower Colorado | 365 | 1.43 | 2 | 7.3 | 1.31 | -23 | -16.0 | 0.97 | 27 | 7.8 |
| | 560 | | | 11.9 | | | -19.4 | | | 4.7 |
| Great Basin | 365 | 0.62 | 21 | -4.7 | 1.36 | -15 | -6.3 | 1.07 | 45 | 24.2 |
| | 560 | | | -4.5 | | | -7.1 | | | 23.7 |
| Pacific Northwest | 365 | 0.45 | 3 | 0.4 | 1.24 | -6 | 2.0 | 1.11 | 54 | 8.4 |
| | 560 | | | 1.7 | | | 1.9 | | | 8.1 |
| California | 365 | 0.95 | 58 | 8.7 | 1.13 | -45 | -5.5 | 1.08 | 17 | 6.3 |
| | 560 | | | 9.3 | | | -3.5 | | | 4.6 |

Second, the difficulty of incorporating grazing in these experiments prevents a full analysis of its effects on ecosystem properties such as NPP, LAI, belowground process, and ecosystem C.

Thornley and Cannell (1997) used their Hurley Pasture Model to simulate ecosystem responses of ungrazed and grazed pastures to increasing trends in CO₂ concentrations and temperature. The simulations revealed three important results: 1) rising CO₂ induces a carbon sink, 2) rising temperatures alone produce a carbon source, and 3) a combination of the two effects is likely to generate a carbon sink for several decades (5-15 g C m⁻² yr⁻¹). Modeling the dynamics of mineral N availability in grazed pastures under elevated CO₂, Thornley and Cannell (2000) ascertained the role of the mineral N pool and its turnover rate in slowly increasing C content in plants and soils.

2.2.2.2 IMPLICATIONS OF ALTERED PRODUCTIVITY, NITROGEN CYCLE (FORAGE QUALITY), PHENOLOGY, AND GROWING SEASON ON SPECIES MIXES, FERTILIZER, AND STOCKING

In general, the response of pasture species to elevated CO₂ deduced from these studies is consistent with the general response of C₃ and C₄ type vegetation to elevated CO₂, although significant exceptions exist. Pasture species with C₃-type metabolism increased their photosynthetic rates by up to 40 percent, but not those with a C₄ pathway (Greer et al. 1995). The study of Greer et al. (1995) suggests shifts in optimal temperatures for photosynthesis under elevated CO₂, with perennial ryegrass and tall fescue showing a downward shift in their optimal temperature from 28-18°C. Unlike croplands, the literature for pasturelands is sparse in providing quantitative information to predict the yield change of pastureland species under a temperature increase of 1.2°C. The projected increases in temperature and the lengthening of the growing season should be, in principle, beneficial for livestock produced by increasing pasture productivity and reducing the need for forage storage during the winter period.

Naturally, changes in CO₂ and temperature will be accompanied by changes in precipitation, with the possibility of more extreme weather causing floods and droughts. Precipitation

changes will likely play a major role in determining NPP of pasture species as suggested by the simulated 1 percent change in yields of dryland alfalfa for every 4-mm change in annual precipitation (Izaurrealde et al. 2003; Thomson et al. 2005).

Another aspect that emerges from this review is the need for comprehensive studies of the impacts of climate change on the pasture ecosystem including grazing regimes, mutualistic relationships (e.g., plant roots-nematodes; N-fixing organisms), as well as C, nutrient, and water balances. Despite their complexities, the studies by Newton et al. (1996) and Wilsey (2001) underscore the importance, difficulties, and benefits of conducting multifactor experiments. To augment their value, these studies should include the use of simulation modeling (Thornley and Cannell 1997) in order to test hypotheses regarding ecosystem processes.

2.2.3 Rangelands

The overall ecology of rangelands is determined primarily by the spatial and temporal distribution of precipitation and consequences of precipitation patterns for soil water availability (Campbell et al. 1997; Knapp, Briggs and Koelliker 2001; Morgan 2005). Rising CO₂ in the atmosphere, warming and altered precipitation patterns all impact strongly on soil water content and plant water relations (Alley et al. 2007; Morgan et al. 2004b), so an understanding of their combined effects on the functioning of rangeland ecosystems is essential.

2.2.3.1 ECOSYSTEM RESPONSES TO CO₂ AND CLIMATE DRIVERS

2.2.3.1.1 Growing Season Length and Plant Phenology

Although responses vary considerably among species, in general warming should accelerate plant metabolism and developmental processes, leading to earlier onset of spring green-up, and lengthening of the growing season in rangelands (Badeck et al. 2004). The effects of warming are also likely to be seen as changes in the timing of phenological events such as flowering and fruiting. For instance, experimental soil warming of approximately 2°C in a tallgrass prairie (Wan et al. 2005) extended the growing season by three weeks, and shifted the timing and duration of



reproductive events variably among species; spring blooming species flowered earlier, late blooming species flowered later (Sherry et al. 2007). Extensions and contractions in lengths of the reproductive periods were also observed among the species tested (see also Cleland et al. 2006). Different species responses to warming suggest strong selection pressure for altering future rangeland community structure, and for the associated trophic levels that depend on the plants for important stages of their life cycles. Periods of drought stress may suppress warming-induced plant activity (Gielen et al. 2005), thereby effectively decreasing plant development time. CO₂ may also impact phenology of herbaceous plant species, although species can differ widely in their developmental responses to CO₂ (Huxman and Smith; 2001 Rae et al. 2006), and the implications for these changes in rangelands are not well understood. Thus, temperature is the primary climate driver that will determine growing season length and plant phenology, but precipitation variability and CO₂ may cause deviations from the overall patterns set by temperature.

2.2.3.1.2 *Net Primary Production*

Increases in CO₂ concentration and in precipitation and soil water content expected for rangelands generally enhance NPP, whereas increased air temperature may either increase or reduce NPP.

2.2.3.1.2.1 *CO₂ Enrichment*

Most forage species on rangelands have either the C₃ or C₄ photosynthetic pathway. Photosynthesis of C₃ plants, including most woody species and herbaceous broad-leaf species (forbs), is not CO₂-saturated at the present atmospheric concentration, so carbon gain and productivity usually are very sensitive to CO₂ in these species (Drake et al. 1997). Conversely, photosynthesis of C₄ plants, including many of the warm-season perennial grass species of rangelands, is nearly CO₂-saturated at current atmospheric CO₂ concentrations (approximately 380 ppm) when soil water is plentiful, although the C₄ metabolism does not preclude photosynthetic and growth responses to CO₂ (Polley et al. 2003). In addition, CO₂ effects on rates of water loss (transpiration) and plant WUE are at least as important as photosynthetic response to CO₂ for rangeland productivity. Stomata of

most herbaceous plants partially close as CO₂ concentration increases, thus reducing plant transpiration. Reduced water loss improves plant and soil water relations, increases plant production under water limitation, and may lengthen the growing season for water-limited vegetation (Morgan et al. 2004b).

CO₂ enrichment will stimulate NPP on most rangelands, with the amount of increase dependent on precipitation and soil water availability. Indeed, there is evidence that the historical increase in CO₂ of about 35 percent has already enhanced rangeland NPP. Increasing CO₂ from pre-industrial levels to elevated concentrations (250 to 550 ppm) increased aboveground NPP of mesic grassland in central Texas between 42-69 percent (Polley et al. 2003). Biomass increased by similar amounts at pre-industrial to current, and current to elevated concentrations. Comparisons between CO₂-induced production responses of semi-arid Colorado shortgrass steppe with the sub-humid Kansas tall grass prairie suggest that Great Plains rangelands respond more to CO₂ enrichment during dry than wet years, and that the potential for CO₂-induced production enhancements are greater in drier rangelands (Figure 2.7). However, in the still-drier Mojave Desert, CO₂ enrichment-enhanced shrub growth occurred most consistently during relatively wet years (Smith et al. 2000). CO₂ enrichment stimulated total biomass (aboveground + belowground) production in one study on annual grassland in California (Field et al. 1997), but elicited no production response in a second experiment (Shaw et al. 2002).

2.2.3.1.2.2 *Temperature*

Like CO₂ enrichment, increasing ambient air and soil temperatures may enhance rangeland NPP, although negative effects of higher temperatures also are possible, especially in dry and hot regions. Temperature directly affects plant physiological processes, but rising ambient temperatures may indirectly affect plant production by extending growing season length, increasing soil nitrogen (N) mineralization and availability, altering soil water content, and shifting plant species composition and community structure (Wan et al. 2005). Rates of biological processes for a given species typically peak at plant temperatures that are intermediate in the range over which a species is active, so direct effects



of warming likely will vary within and among years, and among plant species. Because of severe cold-temperature restrictions on growth rate and duration, warmer plant temperatures alone should stimulate production in high- and mid-latitude, and high-altitude rangelands. Conversely, increasing plant temperature during summer months may reduce NPP.

Increasing daily minimum air temperature and mean soil temperature (2.5 cm depth) by 2°C increased aboveground NPP of tallgrass prairie in Oklahoma between 0-19 percent during the first three years of study, largely by increasing NPP of C₄ grasses (Wan et al. 2005). Warming stimulated biomass production in spring and autumn, but aboveground biomass in summer declined as soil temperature increased. Positive effects of warming on production may be lessened by an accompanying increase in the rate of water loss. Warming reduced the annual mean of soil water content in tallgrass prairie during one year (Wan et al. 2005), but actually increased soil water content in California annual grassland by accelerating plant senescence (Zavaleta et al. 2003b).

2.2.3.1.2.3 Precipitation

Historic changes in climatic patterns have always been accompanied by changes in grassland vegetation because grasslands have both high production potential and a high degree of variability in precipitation (Knapp and Smith 2001). In contrast, aboveground NPP (ANPP) variability in forest systems appears to be limited by invariant rainfall patterns, while production potential more strongly limits desert and arctic/alpine systems. Projected altered rainfall regimes are likely to elicit important changes in rangeland ecology, including NPP.

On most rangelands where total annual precipitation is sufficiently low that soil water limits productivity more than other soil resources, the timing of precipitation can play an important role in regulating NPP. Increased rainfall variability caused by altered rainfall timing (no change in rainfall amount) led to lower and more variable soil water content (between 0-30 cm depth), an approximate 10 percent reduction in ANPP, which was species-specific, and increased root-to-shoot ratios in a native tallgrass prairie ecosystem in northeastern Kansas (Fay

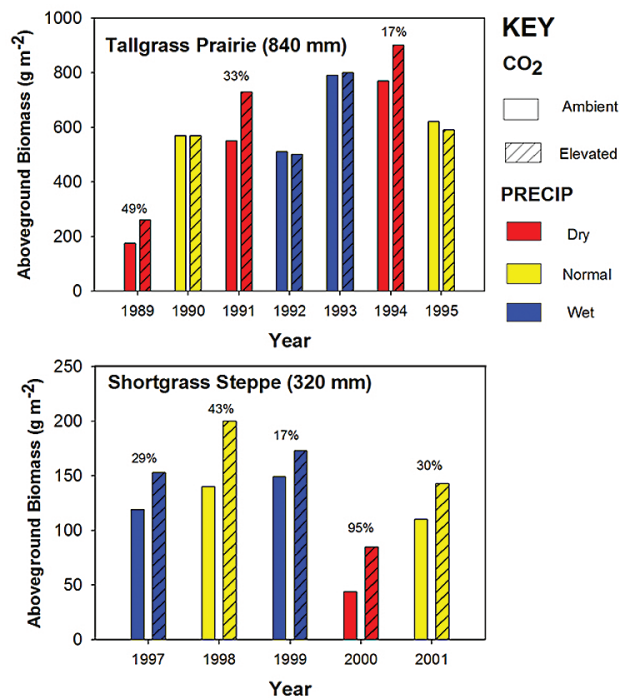


Figure 2.7 Aboveground plant biomass of native Kansas tallgrass prairie (Owensby et al. 1999; 1989-1995) and Colorado Shortgrass steppe (Morgan et al. 2004a; 1997-2001), harvested during summer-time seasonal peak. These grasses were grown in similarly-designed Open Top Chambers maintained at present (ambient, approximately 370 parts per million CO₂ in air; no cross-hatches) and elevated (approximately 720 parts per million CO₂ in air; cross-hatches) atmospheric CO₂ concentrations. Histograms from different years are color-coded (red for dry; yellow for normal; blue for wet) according to the amount of annual precipitation received during that particular year compared to long-term averages for the two sites (840 mm for the tallgrass prairie, and 320 mm for shortgrass steppe). Where production increases due to elevated CO₂ were observed, the percentage-increased production is given within a year above the histograms. The involvement of water in the CO₂ responses is seen in two ways: the relative plant biomass responses occur more commonly and in greater magnitude in the shortgrass steppe than in the tallgrass prairie, and the relative responses in both systems are greater in dry than wet years.

et al. 2003). In general, vegetation responses to rainfall timing (no change in amount) were at least equal to changes caused by rainfall quantity (30 percent reduction, no change in timing). Reduced ANPP most likely resulted from direct effects of soil moisture deficits on root activity, plant water status, and photosynthesis.

The seasonality of precipitation is also an important factor determining NPP through its affects on locally adapted species, which can differ depending on the particular ecosystem. For example, herbaceous plants in the Great Basin are physiologically adapted to winter/early spring precipitation patterns, where reliable soil water recharge occurs prior to the growing season



(Svejcar et al. 2003). Similarly, Northern Great Plains grasslands are dominated by cool-season plant species that complete most of their growth by late spring to early summer, and NPP primarily depends on sufficient soil moisture going into the growing season (Heitschmidt and Haferkamp 2003). Productivity of herbaceous species in both of these rangeland systems is highly dependent on early spring soil moisture, which can be significantly affected by winter precipitation. In contrast, oak savannas of the southwestern United States experience a strongly seasonal pattern of precipitation, with a primary peak in summer and lesser peak in winter (Weltzin and McPherson 2003). Here, herbaceous biomass is more sensitive to summer precipitation than to winter precipitation.

2.2.3.1.3 *Environmental Controls on Species Composition*

At regional scales, species composition of rangelands is determined mostly by climate and soils, with fire regime, grazing, and other land uses locally important. The primary climatic control on the distribution and abundance of plants is water balance (Stephenson 1990). On rangelands in particular, species composition is highly correlated with both the amount of water plants use and its availability in time and space.

Each of the global changes considered here – CO₂ enrichment, altered precipitation regimes, and higher temperatures – may change species composition by altering water balance. Unless stomatal closure is compensated by atmospheric or other feedbacks, CO₂ enrichment should affect water balance by slowing canopy-level ET (Polley et al. 2007) and the rate or extent of soil water depletion (Morgan et al. 2001; Nelson et al. 2004). The resultant higher soil water content has been hypothesized to favor deep-rooted woody plants in future CO₂-enriched atmospheres because of their greater access to stored soil water compared to relatively shallow-rooted grasses (Polley 1997). A warmer climate will likely be characterized by more rapid evaporation and transpiration, and an increase in frequency of extreme events like heavy rains and droughts. Changes in timing and intensity of rainfall may be especially important on arid rangelands where plant community dynamics are ‘event-driven’ and the seasonality of

precipitation determines which plant growth strategies are successful. The timing of precipitation also affects the vertical distribution of soil water, which regulates relative abundances of plants that root at different depths (Ehleringer et al. 1991; Weltzin and McPherson 1997), and influences natural disturbance regimes, which feed back to regulate species composition. For example, grass-dominated rangelands in the eastern Great Plains were historically tree-free due to periodic fire. Fires occurred frequently because the area is subject to summer droughts, which desiccated the grasses and provided abundant fuel for wildfires.

In addition to its indirect effect on water balance, the direct effect of temperature on plant physiology has long been acknowledged as an important determinant of plant species distribution. A good example of this is the distribution of cool-season, C₃ grasses being primarily at northern latitudes and warm-season, C₄ grasses at southern latitudes (Terri and Stowe 1976). Thus, the relative abundances of different plants types (C₃ grasses, C₄ grasses, and shrubs) in grasslands and shrublands of North America are determined in large part by soil water availability and temperatures (Paruelo and Lauenroth 1996).

Observational evidence that global changes are affecting rangelands and other ecosystems is accumulating. During the last century, juniper trees in the arid West grew more than expected from climatic conditions, implying that the historical increase in atmospheric CO₂ concentration stimulated juniper growth (Knapp et al. 2001). The apparent growth response of juniper to CO₂ was proportionally greater during dry than wet years, consistent with the notion that access to deep soil water, which tends to accumulate under elevated CO₂ (Morgan et al. 2004b), gives a growth advantage to deep-rooted woody vegetation (Polley 1997; Morgan et al. 2007). Such observational reports in combination with manipulative experimentation (Morgan et al. 2004b, 2007) suggest that expansion of shrublands over the past couple hundred years has been driven in part by a combination of climate change and increased atmospheric CO₂ concentrations (Polley 1997; Archer et al. 1995).

On rangelands in particular, species composition is highly correlated with both the amount of water plants use and its availability in time and space.



2.2.3.1.4 Nitrogen Cycle Feedbacks

Plant production on rangelands often is limited by nitrogen (N). Because most terrestrial N occurs in organic forms that are not readily available to plants, rangeland responses to global changes will depend partly on how quickly N cycles between organic and inorganic N compounds. Plant material that falls to the soil surface, or is deposited belowground as the result of root exudation or death, is subject to decomposition by soil fauna and micro flora and enters the soil organic matter (SOM) pool. During decomposition of SOM, mineral and other plant-available forms of N are released. Several of the variables that regulate N-release from SOM may be affected by CO₂ enrichment and climate change, and thus are likely to be important factors determining the long-term responses of rangelands.

For instance, while CO₂ enrichment above present atmospheric levels is known to increase photosynthesis, particularly in C₃ species, soil feedbacks involving nutrient cycling may constrain the potential CO₂ fertilization response (Figure 2.8). The Progressive Nitrogen Limitation (PNL) hypothesis holds that CO₂ enrichment is reducing plant-available N by increasing plant demand for N, and enhancing sequestration of N in long-lived plant biomass and SOM pools (Luo et al. 2004). The greater plant demand for N is driven by CO₂-enhanced plant growth. Accumulation of N in organic compounds at elevated CO₂ may eventually reduce soil N availability and limit plant growth response to CO₂ or other changes (Reich et al. 2006a, 2006b; van Groenigen et al. 2006; Parton et al. 2007a). Alternatively, greater C input may stimulate N accumulation in soil/plant systems. A number of processes may be involved, including increased biological fixation of N, greater retention of atmospheric N deposition, reduced losses of N in gaseous or liquid forms, and more complete exploration of soil by expanded root systems (Luo et al. 2006). Rangeland plants often compensate for temporary imbalances in C and N availability by maximizing the amount of C retained in the ecosystem per unit of N. Thus, N concentration of leaves or aboveground tissues declined on shortgrass steppe, tallgrass prairie, and mesic grassland at elevated CO₂, and on tallgrass prairie with warming, but total N content of aboveground tissues increased with

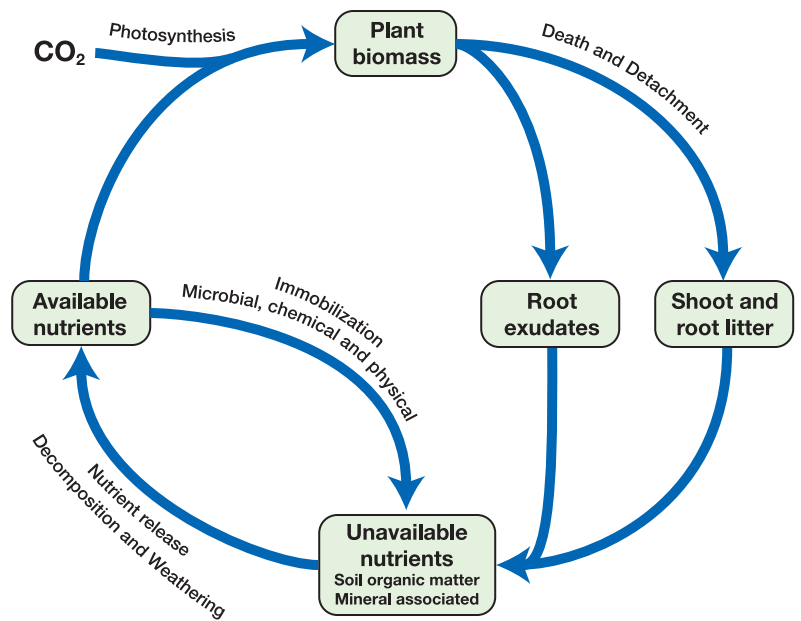


Figure 2.8 Nutrient Cycling Feedbacks. While CO₂ enrichment may lead to increased photosynthesis and enhanced plant growth, the long-term response will depend on nutrient cycling feedbacks. Litter from decaying plants and root exudates enter a large soil nutrient pool that is unavailable to plants until they are broken down and released by microbial activity. Soil microbes may also fix available nutrients into new microbial biomass, thereby temporarily immobilizing them. The balance between these and other nutrient release and immobilization processes determines available nutrients and ultimate plant response. Figure reprinted with permission from *Science* (Morgan 2002).



plant biomass in these ecosystems and on annual grasslands (Owensby et al. 1993; Hungate et al. 1997; King et al. 2004; Wan et al. 2005; Gill et al. 2006). The degree to which N may respond to rising atmospheric CO₂ is presently unknown, but may vary among ecosystems (Luo et al. 2006), and has important consequences for forage quality and soil C storage, as both depend strongly on the available soil N.

Warmer temperatures generally increase SOM decomposition, especially in cold regions (Reich et al. 2006b; Rustad et al. 2001), although warming also may limit microbial activity by drying soil or enhancing plant growth (Wan et al. 2005). Wan et al. (2005) found that warming stimulated N mineralization during the first year of treatment on Oklahoma tallgrass prairie, but in the second year, caused N immobilization by reducing plant N concentration, stimulating plant growth, and increasing allocation of carbon (C) compounds belowground (Wan et al. 2005). Warming can also affect decomposition processes by extending the growing season (Wan et

al. 2005). However, as water becomes limiting, decomposition becomes more dependant on soil water content and less on temperature (Epstein et al. 2002; Wan et al. 2005), with lower soil water content leading to reduced decomposition rates. A recent global model of litter decomposition (Parton et al. 2007b) indicates that litter N-concentration, along with temperature and water, are the dominant drivers behind N release and immobilization dynamics, although UV-stimulation of decomposition (Austin and Vivanco 2006) is especially important in controlling surface litter decomposition dynamics in arid systems like rangelands.

Nutrient cycling also is sensitive to changes in plant species composition; this may result because species differ in sensitivity to global changes. Soil microorganisms require organic material with relatively fixed proportions of C and N. The ratio of C to N (C:N) in plant residues thus affects the rate at which N is released during decomposition in soil. Because C:N varies among plant species, shifts in species composition can strongly affect nutrient cycling (Allard et al. 2004; Dijkstra et al. 2006; Gill et al. 2006; King et al. 2004; Schaeffer et al. 2007; Weatherly et al. 2003). CO₂ enrichment may reduce decomposition by reducing the N concentration in leaf litter (Gill et al. 2006), for example, although litter quality may not be the best predictor of tissue decomposition (Norby et al. 2001). Like CO₂, climatic changes may alter litter quality by causing species change (Murphy et al. 2002; Semmartin et al. 2004; Weatherly et al. 2003). Elevated atmospheric CO₂ and/or temperature may also alter the amounts and proportions of micro flora and fauna in the soil microfood web (e.g., Hungate et al. 2000; Sonnemann and Wolters 2005), and/or the activities of soil biota (Billings et al. 2004; Henry et al. 2005; Kandeler et al. 2006). Although changes in microbial communities are bound to have important feedbacks on soil nutrient cycling and C storage, the full impact of global changes on microbes remains unclear (Niklaus et al. 2003; Ayers et al., in press).

Computer simulation models that incorporate decomposition dynamics and can evaluate incremental global changes agree that combined effects of warming and CO₂ enrichment during

the next 30 years will stimulate plant production, but disagree on the impact on soil C and N. The Daycent Model predicts a decrease in soil C stocks, whereas the Generic Decomposition And Yield Model (G'Day) predicts an increase in soil C (Pepper et al. 2005). Measurements of N isotopes from herbarium specimens collected over the past hundred years indicate that rising atmospheric CO₂ has been accompanied by increased N fixation and soil N mineralization, decreased soil N losses, and a decline in shoot N concentration (Peñuelas and Estiarte 1997). Collectively, these results indicate that soil N may constrain the responses of some terrestrial ecosystems to CO₂.

2.2.4 Temperature Response of Animals

2.2.4.1 THERMAL STRESS

The optimal zone (thermoneutral zone) for livestock production is a range of temperatures and other environmental conditions for which the animal does not need to significantly alter behavior or physiological functions to maintain a relatively constant core body temperature. As environmental conditions result in core body temperature approaching and/or moving outside normal diurnal boundaries, the animal must begin to conserve or dissipate heat to maintain homeostasis. This is accomplished through shifts in short-term and long-term behavioral, physiological, and metabolic thermoregulatory processes (Mader et al. 1997b; Davis et al. 2003). The onset of a thermal challenge often results in declines in physical activity and an associated decline in eating and grazing activity (for ruminants and other herbivores). Hormonal changes, triggered by environmental stress, result in shifts in cardiac output, blood flow to extremities, and passage rate of digesta. Adverse environmental stress can elicit a panting or shivering response, which increases maintenance requirements of the animal and contributes to decreases in productivity. Depending on the domestic livestock species, longer term adaptive responses include hair coat gain or loss through growth and shedding processes, respectively. In addition, heat stress is directly related to respiration and sweating rate in most domestic animals (Gaughan et al. 1999, 2000, and 2005).



Adverse environmental stress can elicit a panting or shivering response, which increases maintenance requirements of the animal and contributes to decreases in productivity.

Production losses in domestic animals are largely attributed to increases in maintenance requirement associated with sustaining a constant body temperature, and altered feed intake (Mader et al. 2002; Davis et al. 2003; Mader and Davis 2004). As a survival mechanism, voluntary feed intake increases (after a one- to two-day decline) under cold stress, and decreases almost immediately under heat stress (NRC 1987). Depending on the intensity and duration of the environmental stress, voluntary feed intake can average as much as 30 percent above normal under cold conditions, to as much as 50 percent below normal in hot conditions.

Domestic livestock are remarkable in their adaptive ability. They can mobilize coping mechanisms when challenged by environmental stressors. However, not all coping capabilities are mobilized at the same time. As a general model for mammals of all species, respiration rate serves as an early warning of increasing thermal stress, and increases markedly above a threshold as animals try to maintain homeothermy by dissipating excess heat. At a higher threshold, body temperature begins to increase as a result of the animal's inability to adequately dissipate the excess heat load by increased respiratory vaporization (Brown-Brandl et al. 2003; Davis et al. 2003; Mader and Kreikemeier 2006). There is a concomitant decrease in voluntary feed intake as body temperature increases, which ultimately results in reduced performance (i.e., production, reproduction), health and well-being if adverse conditions persist (Hahn et al. 1992; Mader 2003).

Thresholds are species dependent, and affected by many factors, as noted in Figure 2.9. For shaded *Bos taurus* feeder cattle, Hahn (1999) reported respiration rate as related to air temperature typically shows increases above a threshold of about 21°C, with the threshold for increasing body temperature and decreasing voluntary feed intake being about 25°C. Recent studies (Brown-Brandl et al. 2006) clearly show the influences of animal condition, genotype, respiratory pneumonia, and temperament on respiration rate of *Bos taurus* heifers.

Even though voluntary feed intake reduction usually occurs on the first day of hot conditions,

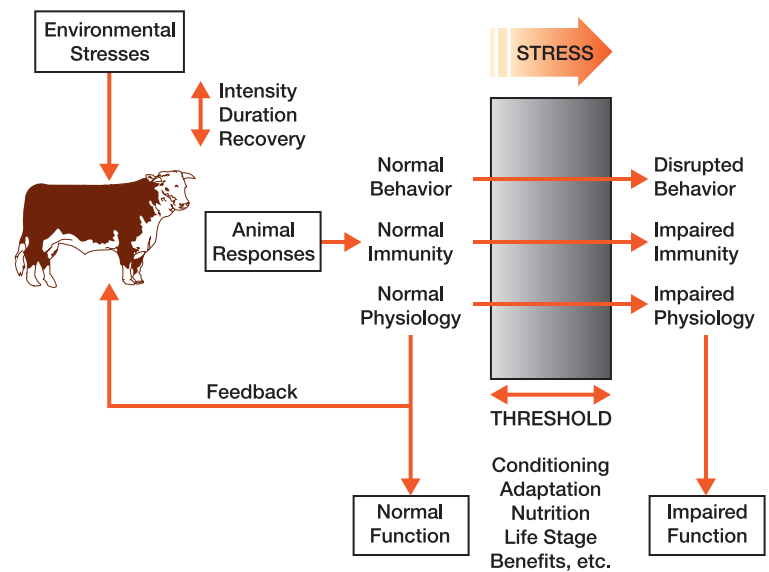


Figure 2.9. Response model for farm animals with thermal environmental challenges (Hahn 1999).

the animals' internal metabolic heat load generated by digesting existing rumen contents adds to the increased external, environmental heat load. Nighttime recovery also has been shown to be an essential element of survival when severe heat challenges occur (Hahn and Mader 1997; Amundson et al. 2006). After about three days, the animal enters the chronic response stage, with mean body temperature declining slightly and voluntary feed intake reduced in line with heat dissipation capabilities. Diurnal body temperature amplitude and phase remain altered. These typical thermoregulatory responses, when left unchecked during a severe heat wave with excessive heat loads, can lead to impaired performance or death (Hahn and Mader 1997; Mader 2003).

2.2.4.1.1 Methods to Identify

Environmentally Stressed Animals

Temperature provides a measure of the sensible heat content of air, and represents a major portion of the driving force for heat exchange between the environment and an animal. However, latent heat content of the air, as represented by some measure of the insensible heat content (e.g., dewpoint temperature), thermal radiation (short- and long-wave), and airflow, also impacts the total heat exchange. Because of the limitations of air temperature alone as a measure of the thermal environment, there have been many efforts to combine the effects of two or more thermal



measures representing the influence of sensible and latent heat exchanges between the organism and its environment. It is important to recognize that all such efforts produce index values rather than a true temperature (even when expressed on a temperature scale). As such, an index value represents the effect produced by the heat exchange process, which can alter the biological response that might be associated with changes in temperature alone. In the case of humans, the useful effect is the sensation of comfort; for animals, the useful effect is the impact on performance, health, and well-being.

Contrary to the focus of human-oriented thermal indices on comfort, the primary emphasis for domestic animals has been on indices to support rational environmental management decisions related to performance, health, and well-being. Hahn and Mader (1997), Hahn et al. (1999), and Hahn et al. (2001) have used retrospective climatological analyses to evaluate the characteristics of prior heat waves causing extensive livestock losses. Although limited by lack of inclusion of wind speed and thermal radiation effects, the Temperature-Humidity Index (THI) has been a particularly useful tool for profiling and classifying heat wave events (Hahn and Mader 1997; Hahn et al. 1999). In connection with extreme conditions associated with heat waves, the THI has recently been used to evaluate spatial and temporal aspects of their

development (Hubbard et al. 1999; Hahn and Mader 1997). For cattle in feedlots, a THI-based classification scheme has also been developed to assess the potential impact of heat waves (Hahn et al. 1999) (Table 2.11). The classifications are based on a retrospective analysis of heat waves that have resulted in extensive feedlot cattle deaths, using a THI-hours approach to assess the magnitude (intensity x duration) of the heat wave events that put the animals at risk. When calculated hourly from records of temperature and humidity, this classification scheme can be used to compute cumulative daily THI-hrs at or above the Livestock Weather Safety Index (LWSI) thresholds for the “Danger” and “Emergency” categories. The THI-hrs provide a measure of the magnitude of daytime heat load (intensity and duration), while the number of hours below THI thresholds of 74 and 72 indicate the opportunity for nighttime recovery from daytime heat.

As applied to *Bos taurus* feedlot cattle during the 1995 Nebraska-Iowa heat wave event, evaluation of records for several weather stations in the region using the THI-hrs approach reinforced the LWSI thresholds for the Danger and Emergency categories of risk and possible death (Hahn and Mader 1997). Based on that event, analysis indicated that over a successive, three-day span, 15 or more THI-hrs per day above a THI base level of 84 could be lethal for vulnerable animals

Table 2.11 Heat wave categories for *Bos taurus* feedlot cattle exposed to single heat wave events (Hahn et al. 1999).

| Category | Descriptive Characteristics | | | |
|-------------|--------------------------------------|--------------------|--|---------------------------------------|
| | Duration | THI*-hrs ≥ 79 | THI-hrs $\geq 84^*$ | Nighttime recovery (hrs # 72 THI*) |
| 1. Slight | Limited: 3-4 days | 10-25/day | None | Good: 5-10 hr/night |
| 2. Mild | Limited: 3-4 days | 18-40/day | #5/day | Some: 3-8 hr/night |
| 3. Moderate | More persistent (4-6 days usual) | 25-50/day | #6/day | Reduced: 1-6 hr/night |
| 4. Strong | Increased persistence (5-7 days) | 33-65/day | #6/day | Limited: 0-4 hr/night |
| 5. Severe | Very persistent (usually 6-8 days) | 40-80/day | 3-15/day on 3 or more successive days | Very limited: 0-2 hr per night |
| 6. Extreme | Very persistent (usually 6-10+ days) | 50-100/day | 15-30/day on 3 or more successive days | Nil: #1 for 3 or more successive days |

***Temperature Humidity Index (THI).** Daily THI-hrs are the summation of the differences between the THI and the base level at each hr of the day. For example, if the THI value at 1300 is 86.5 and the base level selected is 84, THI-hr = 2.5. The accumulation for the day is obtained by summing all THI-hr ≥ 84 , and can exceed 24.

(especially those that were ill, recently placed in the feedlot, or nearing market weight). The extreme daytime heat in 1995 was exacerbated by limited nighttime relief (only a few hrs with THI ≤ 74), high solar radiation loads (clear to mostly clear skies), and low to moderate wind speeds in the area of highest risk. During this same period, for cattle in other locations enduring 20 or more daily THI-hrs in the Emergency category (THI ≥ 84) over one or two days, the heat load was apparently dissipated with minimal or no mortality, although these environmental conditions can markedly depress voluntary feed intake (Hahn 1999; NRC 1981) with resultant reduced performance.

Similar analysis of a single heat wave in August 1992 further confirmed that 15 or more THI-hrs above a base level of 84 can cause deaths of vulnerable animals (Hahn et al. 1999). A contributing factor to losses during that event was lack of acclimation to hot weather, as the summer had been relatively cool. In the region under study, only four years between 1887-1998 had fewer days during the summer when air temperature was $\geq 32.2^{\circ}\text{C}$ (High Plains Regional Climate Center 2000).

There are limitations to the THI caused by airflow and changing solar radiation loads. Modifications to the THI have been proposed to overcome shortcomings related to airflow and radiation heat loads. Based on recent research, Mader et al. (2006) and Eigenberg et al. (2005) have proposed corrections to the THI for use with feedlot cattle, based on measures of wind-speed and solar radiation. While the proposed adjustment-factor differences are substantial, there were marked differences in the types and number of animals used in the two studies. Nevertheless, the approach appears to merit further research to establish acceptable THI corrections, perhaps for a variety of animal parameters.

By using body temperatures, a similar approach was developed to derive an Apparent Equivalent Temperature (AET) from air temperature and vapor pressure to develop “thermal comfort zones” for transport of broiler chickens (Mitchell et al. 2001). Experimental studies to link the AET with increased body temperature during exposure to hot conditions indicated potential for improved transport practices.

Gaughan et al. (2002) developed a Heat Load Index (HLI) as a guide to management of unshaded *Bos taurus* feedlot cattle during hot weather ($>28^{\circ}\text{C}$). The HLI was developed following observation of behavioral responses (respiration rate and panting score) and changes in dry-matter intake during prevailing thermal conditions. The HLI is based on humidity, wind-speed, and predicted black globe temperature. As a result of its demonstrated broad success, the THI is currently the most widely accepted thermal index used for guidance of strategic and tactical decisions in animal management during moderate to hot conditions. Biologic response functions, when combined with likelihood of occurrence of the THI for specific locations, provide the basis for economic evaluation to make cost-benefit comparisons for rational strategic decisions among alternatives (Hahn 1981). Developing a climatology of summer weather extremes (in particular, heat waves) for specific locations also provides the livestock manager with information about how often those extremes (with possible associated death losses) might occur (Hahn et al. 2001). The THI has also served well for making tactical decisions about when to apply available practices and techniques (e.g., sprinkling) during either normal weather variability or weather extremes, such as heat waves. Other approaches, such as the AET proposed by Mitchell et al. (2001) for use in poultry transport, also may be appropriate. An enthalpy-based alternative thermal index has been suggested by Moura et al. (1997) for swine and poultry.

Panting score is one observation method used to monitor heat stress in cattle (Table 2.12). As the temperature increases, cattle pant more to increase evaporative cooling. Respiration dynamics change as ambient conditions change, and surroundings surfaces warm. This is a relatively easy method for assessing genotype differences and determining breed acclimatization rates to higher temperatures. In addition, shivering score or indices also have potential for use as thermal indicators of cold stress. However, recent data were not found regarding cold stress indicators for domestic livestock.



Table 2.12 Panting scores assigned to steers (Mader et al. 2006).

| Score | Description |
|-------|--|
| 0 | Normal respiration |
| 1 | Elevated respiration |
| 2 | Moderate panting and/or presence of drool or a small amount of saliva |
| 3 | Heavy open-mouthed panting, saliva usually present |
| 4 | Severe open-mouthed panting accompanied by protruding tongue and excess salivation; usually with neck extended forward |

2.2.5 Episodes of Extreme Events

**2.2.5.1 ELEVATED TEMPERATURE OR RAIN
FALL DEFICIT**

Episodic increases in temperature would have greatest effect when occurring just prior to, or during, critical crop pollination phases. Crop sensitivity and ability to compensate during later, improved weather will depend on the synchrony of anthesis in each crop; for example, maize has a highly compressed phase of anthesis, while spikelets on rice and sorghum may achieve anthesis over a period of a week or more. Soybean, peanut, and cotton will have several weeks over which to spread the success of reproductive structures. For peanut, the sensitivity to elevated temperature for a given flower extends from six days prior to opening (pollen cell division and formation) up through the day of anthesis (Prasad et al. 2001). Therefore, several days of elevated temperature may affect fertility of many flowers, whether still in their formative 6-day phase or just achieving anthesis today. In addition, the first six hours of the day were more critical during pollen dehiscence, pollen tube growth, and fertilization.

For rice, the reproductive processes that occur within one to three hours after anthesis (dehiscence of the anther, shedding of pollen, germination of pollen grains on stigma, and elongation of pollen tubes) are disrupted by daytime air temperatures above 33°C (Satake and Yoshida 1978). Since anthesis occurs between about 9 a.m. and 11 a.m. in rice (Prasad et al. 2006b), damage from temperatures exceeding 33°C may already be common, and may become more prevalent in the future. Pollination processes in other cereals, maize, and sorghum may have a similar sensitivity to elevated daytime tempera-

ture as rice. Rice and sorghum have the same sensitivity of grain yield, seed harvest index, pollen viability, and success in grain formation in which pollen viability and percent fertility is first reduced at instantaneous hourly air temperature above 33°C, and reaches zero at 40°C (Kim et al. 1996; Prasad et al. 2006a, 2006b). Diurnal max/min, day/night temperatures of 40/30°C (35°C mean) can cause zero yield for those two species, and the same response would likely apply to maize.

2.2.5.2 INTENSE RAINFALL EVENTS

Historical data for many parts of the United States indicate an increase in the frequency of high-precipitation events (e.g., >5 cm in 48 hours), and this trend is projected to continue for many regions. One economic consequence of excessive rainfall is delayed spring planting, which jeopardizes profits for farmers paid a premium for early season production of high value horticultural crops such as melon, sweet corn, and tomatoes. Field flooding during the growing season causes crop losses associated with anoxia, increases susceptibility to root diseases, increases soil compaction (due to use of heavy farm equipment on wet soils), and causes more runoff and leaching of nutrients and agricultural chemicals into groundwater and surface water. More rainfall concentrated into high precipitation events will increase the likelihood of water deficiencies at other times because of the changes in rainfall frequency (Hatfield and Prueger 2004). Heavy rainfall is often accompanied by wind gusts in storm events, which increases the potential for lodging of crops. Wetter conditions at harvest time could increase the potential for decreasing quality of many crops.



2.3 POSSIBLE FUTURE CHANGES AND IMPACTS

2.3.1 Projections Based on Increment of Temperature and CO₂ for Crops

Using the representative grain crops – maize, soybean, etc. – some expected effects resulting from the projected rise in CO₂ of 380 to 440 ppm along with a 1.2°C rise in temperature over the next 30 years are explored.

The responsiveness of grain yield to temperature is dependent on current mean temperatures during the reproductive phase in different regions (crops like soybean and maize are dominant in both the Midwest and southern regions, while others, like cotton, sorghum, and peanut, are only grown in southern regions). Grain yield response to CO₂ increase of 380 to 440 ppm was 1.0 percent for C₄, and 6.1 to 7.4 percent for C₃ species, except for cotton, which had 9.2 percent response.

For maize, under water sufficiency conditions in the Midwest, the net yield response is -3.0 percent, assuming additivity of the -4.0 percent from 1.2°C rise, and +1.0 percent from CO₂ of 380 to 440 ppm (Table 2.7). The response of maize in the South is possibly more negative. For soybean under water sufficiency in the Midwest, net yield response is +9.9 percent, assuming additivity of the +2.5 percent from 1.2°C rise above current 22.5°C mean, and +7.4 percent from CO₂ increase.

For soybean under water sufficiency in the South, the temperature effect will be detrimental, -3.5 percent, with 1.2°C temperature increment above 26.7°C, with the same CO₂ effect, giving a net yield response of +3.9 percent. For wheat (with no change in water availability), the net yield response would be +0.1 percent coming from -6.7 percent with 1.2°C rise, and +6.8 percent increase from CO₂ increase. For rice in the South, net yield response is -5.6 percent, assuming additivity of the -12.0 percent from 1.2°C rise and +6.4 percent from CO₂ increase. For peanut in the South, the net yield response is +1.3 percent, assuming additivity of the -5.4 percent from 1.2°C rise and +6.7 percent from CO₂ increase. For cotton in the South, the net yield response is +3.5 percent, assuming ad-

ditivity of the -5.7 percent from 1.2°C rise and +9.2 percent from CO₂ increase. The sorghum response is less certain, although yield reduction caused by shortening filling period is dominant, giving a net yield decrease of 8.4 percent in the South. Dry bean yield response in all regions is less certain, with net effect of -2.5 percent, coming from -8.6 percent response to 1.2°C rise and +6.1 percent from CO₂ increase. The confidence in CO₂ responses is likely to very likely, while the confidence in temperature responses is generally likely, except for less knowledge concerning maize and cotton sensitivity to temperature when these responses are possible.

Projections of crop yield under water deficit should start with the responses to temperature and CO₂ for the water-sufficient cases. However, yield will likely be slightly increased to the same extent (percentage) that increased CO₂ causes reduction in ET but decreased to the extent that rainfall is decreased (but that requires climate scenarios and simulations not presented in Table 2.7). Model simulations with CROPGRO-Soybean with energy balance option and stomatal feedback from CO₂ enrichment (350 to 700 ppm, without temperature increase) resulted in a 44 percent yield increase for water-stressed crops compared to fully-irrigated crops (32 percent). The yield increment was nearly proportional to the decrease in simulated transpiration (11-16 percent). Based on this assumption, the 380 to 440 ppm CO₂ increment would likely further increase yield of C₃ crops (soybean, rice, wheat, and cotton) by an additional 1.4 to 2.1 percent (incremental reduction in ET from CO₂ in Table 2.7). However, the projected 1.2°C would increase ET by 1.8 percent, thereby partially negating this water-savings effect of CO₂.

2.3.2 Projections for Weeds

Many weeds respond more positively to increasing CO₂ than most cash crops, particularly C₃ “invasive” weeds that reproduce by vegetative means (roots, stolons, etc.) (Ziska and George 2004; Ziska 2003). Recent research also suggests that glyphosate, the most widely used herbicide in the United States, loses its efficacy on weeds grown at CO₂ levels that likely will occur in the coming decades (Ziska et al. 1999). While many weed species have the C₄ photosynthetic pathway, and therefore show a smaller response



To date, for all weed/crop competition studies where the photosynthetic pathway is the same, weed growth is favored as CO₂ increases.



to atmospheric CO₂ relative to C₃ crops, in most agronomic situations crops are in competition with a mix of both C₃ and C₄ weeds. In addition, the worst weeds for a given crop are often similar in growth habit or photosynthetic pathway. To date, for all weed/crop competition studies where the photosynthetic pathway is the same, weed growth is favored as CO₂ increases (Ziska and Runion 2006).

The habitable zone of many weed species is largely determined by temperature, and weed scientists have long recognized the potential for northward expansion of weed species' ranges as the climate changes (Patterson et al. 1999). More than 15 years ago, Sasek and Strain (1990) utilized climate model projections of the -20°C minimum winter temperature zone to forecast the northward expansion of kudzu (*Pueraria lobata*, var. *montana*), an aggressive invasive weed that currently infests more than one million hectares in the southeastern U.S. While temperature is not the only factor that could constrain spread of kudzu and other invasive weeds, a more comprehensive assessment of potential weed species migration based on the latest climate projections for the United States seems warranted.

2.3.3 Projections for Insects and Pathogens

Plants do not grow in isolation in agroecosystems. Beneficial and harmful insects, microbes, and other organisms in the environment will also be responding to changes in CO₂ and climate. Studies conducted in Western Europe and other regions have already documented changes in spring arrival and/or geographic range of many insect and animal species due to climate change (Montaigne 2004; Goho 2004; Walther et al. 2002). Temperature is the single most important factor affecting insect ecology, epidemiology, and distribution, while plant pathogens will be highly responsive to humidity and rainfall, as well as temperature (Coakley et al. 1999).

There is currently a clear trend for increased insecticide use in warmer, more southern regions of the United States, compared to cooler, higher latitude regions. For example, the frequency of pesticide sprays for control of lepidopteran insect pests in sweet corn currently ranges from 15 to 32 applications per year in Florida (Aerts et al.

1999), to four to eight applications in Delaware (Whitney et al. 2000), and zero to five applications per year in New York (Stivers 1999). Warmer winters will likely increase populations of insect species that are currently marginally over-wintering in high latitude regions, such as flea beetles (*Chaetocnema pulicaria*), which act as a vector for bacterial Stewart's Wilt (*Erwinia stewartii*), an economically important corn pathogen (Harrington et al. 2001).

An overall increase in humidity and frequency of heavy rainfall events projected for many parts of the United States will tend to favor some leaf and root pathogens (Coakley et al. 1999). However, an increase in short- to medium-term drought will tend to decrease the duration of leaf wetness and reduce some forms of pathogen attack on leaves.

The increasing atmospheric concentration of CO₂ alone may affect plant-insect interactions. The frequently observed higher carbon-to-nitrogen ratio of leaves of plants grown at high CO₂ (Wolfe 1994) can require increased insect feeding to meet nitrogen (protein) requirements (Coviella and Trumble 1999). However, slowed insect development on high CO₂-grown plants can lengthen the insect life stages vulnerable to attack by parasitoids (Coviella and Trumble 1999). In a recent FACE study, Hamilton et al. (2005) found that early season soybeans grown at elevated CO₂ had 57 percent more damage from insects, presumably due in this case to measured increases in simple sugars in leaves of high CO₂-grown plants.

2.3.4 Projections for Rangelands

2.3.4.1 NET PRIMARY PRODUCTION AND PLANT SPECIES CHANGES

By stimulating both photosynthesis and water use efficiency, rising CO₂ has likely enhanced plant productivity on most rangelands over the past 150 years, and will likely continue to do so over the next 30 years. The magnitude of this response will depend on how CO₂ enrichment affects the composition of plant communities and on whether nutrient limitations to plant growth develop as the result of increased carbon input to rangelands. Increasing temperature will likely have both positive and negative effects on plant productivity, depending on the prevailing

climate and the extent to which warmer temperature leads to desiccation. Like CO₂ enrichment, warming will induce species shifts because of differing species sensitivities and adaptabilities to temperatures. Modeling exercises suggest generally positive NPP responses of Great Plains native grasslands to increases in CO₂ and temperature projected for the next 30 years (Pepper et al. 2005; Parton et al. 2007a), a response which is supported by experimental results from shortgrass steppe (Morgan et al. 2004a). An important exception to these findings is California annual grasslands, where production appears only minimally responsive to CO₂ or temperature (Dukes et al. 2005). Alterations in precipitation patterns will interact with rising CO₂ and temperature, although uncertainties about the nature of precipitation shifts, especially at regional levels, and the lack of multiple global change experiments that incorporate CO₂, temperature and precipitation severely limit our ability to predict consequences for rangelands. However, if annual precipitation changes little or declines in the southwestern United States as currently predicted (Christensen et al. 2007), plant production in rangelands of that region may respond little to combined warming and rising CO₂, and may even decline due to increased drought.

Plants with the C₃ photosynthetic pathway, forbs and possibly legumes will be favored by rising CO₂, although rising temperature and changes in precipitation patterns may affect these functional group responses to CO₂ (Morgan 2005; Polley 1997). In general, plants that are less tolerant of water stress than current dominants may also be favored in future CO₂-enriched atmospheres where CO₂ significantly enhances plant water use efficiency and seasonal available soil water (Polley et al. 2000). Deep-rooted forbs and shrubs may be particularly favored because of their strong carbon-allocation and nitrogen-use strategies (Polley et al. 2000; Bond and Midgley 2000; Morgan et al. 2007), including the ability of their roots to access deep soil water, which is predicted to be enhanced in future CO₂-enriched environments. Shifts in precipitation patterns toward wetter winters and drier summers, which are predicted to favor woody shrubs over herbaceous vegetation in the desert southwest (Neilson 1986), may reinforce

some of the predicted CO₂-induced changes in plant community dynamics. In grasslands of the Northern Great Plains, enhanced winter precipitation may benefit the dominant cool-season, C₃ grass species that rely on early-season soil moisture to complete most of their growth by late spring to early summer (Heitschmidt and Haferkamp 2003). Greater winter precipitation, in addition to rising CO₂, may also benefit woody plants that are invading many grasslands of the central and northern Great Plains (Briggs et al. 2005; Samson and Knopf 1994). However, by itself, warmer temperature will tend to favor C₄ species (Epstein et al. 2002), which may cancel out the CO₂-advantage of C₃ plants in some rangelands.

There is already some evidence that climate change-induced species changes are underway in rangelands. The worldwide encroachment of woody plants into grasslands remains one of the best examples of the combined effects of climate change and management in driving a species change that has had a tremendous negative impact on the range livestock industry. In the southwestern arid and semi-arid grasslands of the United States, mesquite (*Prosopis glandulosa*) and creosote (*Larrea tridentate*) bushes have replaced most of the former warm season, perennial grasses (Figure 2.10), whereas in more mesic grasslands of the Central Great Plains, trees and large shrubs are supplanting C₃ grasslands (Figure 2.11). While both of these changes are due to complex combinations of management (grazing and fire) and a host of environmental factors (Briggs et al. 2005; Peters et al. 2006), evidence is accumulating that rising CO₂ and climate change are very likely important factors influencing these transitions (Briggs et al. 2005; Knapp et al. 2001; Polley et al. 2002; Morgan et al. 2007; Peters et al. 2006; Polley 1997). In contrast, the observed loss of woody species and spread of the annual grass *Bromus tectorum* (cheatgrass) throughout the Intermountain region of western North America also appears driven at least in part by the species sensitivity to rising atmospheric CO₂ (Smith et al. 2000; Ziska et al. 2005), and has altered the frequency and timing of wildfires, reducing establishment of perennial herbaceous species by pre-empting soil water early in the growing season (Young 1991).





Figure 2.10 Today, in most areas of the Chihuahuan desert, mesquite bushes have largely replaced perennial, warm-season grasses that dominated this ecosystem two centuries ago (photograph courtesy of Jornada Experimental Range photo gallery).

2.3.4.2 LOCAL AND SHORT-TERM CHANGES

Our ability to predict vegetation changes at local scales and over shorter time periods is more limited because at these scales the response of vegetation to global changes depends on a variety of local processes, including soils and disturbance regimes, and how quickly various species can disperse seeds across sometimes fragmented landscapes. Nevertheless, patterns of vegetation response are beginning to emerge.

- Directional shifts in the composition of vegetation occur most consistently when global change treatments alter water availability (Polley et al. 2000; Morgan et al. 2004b).

- Effects of CO₂ enrichment on species composition and the rate of species change will very likely be greatest in disturbed or early-successional communities where nutrient and light availability are high and species change is influenced largely by growth-related parameters (e.g., Polley et al. 2003).
- Weedy and invasive plant species likely will be favored by CO₂ enrichment (Smith et al. 2000; Morgan et al. 2007) and perhaps by other global changes because these species possess traits (rapid growth rate, prolific seed production) that permit a large growth response to CO₂.
- CO₂ enrichment will likely accelerate the rate of successional change in species composition following overgrazing or other severe disturbances (Polley et al. 2003).
- Plants do not respond as predictably to temperature or CO₂ as to changes in water, N, and other soil resources (Chapin et al. 1995). Progress in predicting the response of vegetation to temperature and CO₂ thus may require a better understanding of indirect effects of global change factors on soil resources. At larger scales, effects of atmospheric and climatic change on fire frequency and intensity and on soil water and N availability will likely influence botanical



Figure 2.11 *Gleditsia triacanthos* tree islands in Kansas tallgrass prairie (photograph courtesy of Alan K. Knapp).

composition to a much greater extent than global change effects on production. (See Chapter 3, Arid Lands Section for a more complete discussion on the interactions and implications of fire ecology, invasive weeds, and global change for rangelands.)

- Rangeland vegetation will very likely be influenced more by management practices (land use) than by atmospheric and climatic change. Global change effects will be superimposed on and modify those resulting from land use patterns in ways that are as of yet uncertain.

2.3.4.3 FORAGE QUALITY

2.3.4.3.1 Plant-animal Interface

Animal production on rangelands, as in other grazing systems, depends on the quality as well as the quantity of forage. Key quality parameters for rangeland forage include fiber content and concentrations of crude protein, non-structural carbohydrates, minerals, and secondary toxic compounds. Ruminants require forage with at least 7 percent crude protein (as a percentage of dietary dry matter) for maintenance, 10-14 percent protein for growth, and 15 percent protein for lactation. Optimal rumen fermentation also requires a balance between ruminally-available protein and energy. The rate at which digesta pass through the rumen decreases with increasing fiber content, which depends on the fiber content of forage. High fiber content slows passage and reduces animal intake.

2.3.4.3.2 Climate Change Effects on Forage Quality

Based on expected vegetation changes and known environmental effects on forage protein, carbohydrate, and fiber contents, both positive and negative changes in forage quality are possible as a result of atmospheric and climatic change (Table 2.13). Non-structural carbohydrates can increase under elevated CO₂ (Read et al. 1987), thereby potentially enhancing forage quality. However, plant N and crude protein concentrations often decline in CO₂-enriched atmospheres, especially when plant production is enhanced by CO₂. This reduction in crude protein reduces forage quality and counters the positive effects of CO₂ enrichment on plant production and carbohydrates (Cotrufo et al. 1998; Milchunas et al. 2005). Limited evidence suggests that the decline is greater when soil nitrogen availability is low than high (Bowler and Press 1996; Wilsey 1996), implying that rising CO₂ possibly reduces the digestibility of forages that are already of poor quality for ruminants. Experimental warming also reduces tissue N concentrations (Wan et al. 2005), but reduced precipitation typically has the opposite effect. Such reductions in forage quality could possibly have pronounced negative effects on animal growth, reproduction, and mortality (Milchunas et al. 2005; Owensby et al. 1996), and could render livestock production unsustainable unless animal diets are supplemented with N (e.g., urea, soybean meal). On shortgrass steppe, for example, CO₂ enrichment reduced the crude protein concentration of autumn forage below



Table 2.13 Potential changes in forage quality arising from atmospheric and climatic change.

| Change | Examples of positive effects on forage quality | Examples of negative effects on forage quality |
|---|---|--|
| Life-form distributions | Decrease in proportion of woody shrubs and increase in grasses in areas with increased fire frequency. | Increase in the proportion of woody species because of elevated CO ₂ , increases in rainfall event sizes and longer intervals between rainfall events. |
| Species or functional group distributions | Possible increase in C ₃ grasses relative to C ₄ grasses at elevated CO ₂ . | Increase in the proportion of C ₄ grasses relative to C ₃ grasses at higher temperatures. Increase in abundance of perennial forb species or perennial grasses of low digestibility at elevated CO ₂ . Increase in poisonous or weedy plants. |
| Plant biochemical properties | Increase in non-structural carbohydrates at elevated CO ₂ . Increase in crude protein content of forage with reduced rainfall. | Decrease in crude protein content and digestibility of forage at elevated CO ₂ or higher temperatures. No change or decrease in crude protein in regions with more summer rainfall. |

critical maintenance levels for livestock in three out of four years and reduced the digestibility of forage by 14 percent in mid-season and by 10 percent in autumn (Milchunas et al. 2005). Significantly, the grass most favored by CO₂ enrichment also had the lowest crude protein concentration. Plant tissues that re-grow following defoliation generally are of higher quality than older tissue, so defoliation could ameliorate negative effects of CO₂ on forage quality. This however did not occur on shortgrass steppe (Milchunas et al. 2005). Changes in life forms, species, or functional groups resulting from differential responses to global changes will very likely vary among rangelands depending on the present climate and species composition, with mixed consequences for domestic livestock (Table 2.13).

2.3.5 Climatic Influences on Livestock

Climate changes, as suggested by some GCMs, could impact the economic viability of livestock production systems worldwide. Surrounding environmental conditions directly affect mechanisms and rates of heat gain or loss by all animals (NRC 1981). Lack of prior conditioning to weather events most often results in catastrophic losses in the domestic livestock industry. In the central U.S. in 1992, 1995, 1997, 1999, 2005, and 2006, some feedlots (intensive cattle feeding operations) lost in excess of 100 head each during severe heat episodes. The heat waves of 1995 and 1999 were particularly severe with documented cattle losses in individual states approaching 5,000 head each year (Hahn and Mader 1997; Hahn et al. 2001). The intensity and/or duration of the 2005 and 2006 heat waves were just as severe as the 1995 and 1999 heat waves, although the extent of losses could not be adequately documented.

The winter of 1996-97 also caused hardship for cattle producers because of greater than normal snowfall and wind velocity, with some feedlots reporting losses in excess of 1,000 head. During that winter, up to 50 percent of the newborn calves were lost, and more than 100,000 head of cattle died in the Northern Plains of the United States.

Additional snowstorm losses were incurred with the collapse of and/or loss of power to buildings

that housed confined domestic livestock. Early snowstorms in 1992 and 1997 resulted in the loss of more than 30,000 head of feedlot cattle each year in the southern plains of the United States (Mader 2003).

Economic losses from reduced cattle performance (morbidity) likely exceed those associated with cattle death losses by several-fold (Mader 2003). In addition to losses in the 1990s, conditions during the winter of 2000-2001 resulted in decreased efficiencies of feedlot cattle in terms of overall gain and daily gain of approximately 5 and 10 percent, respectively, from previous years as a result of late autumn and early winter moisture, combined with prolonged cold stress conditions (Mader 2003). In addition, the 2006 snowstorms, which occurred in the southern plains around year end, appear to be as devastating as the 1992 and 1997 storms. These documented examples of how climate can impact livestock production illustrate the potential for more drastic consequences of increased variability in weather patterns, and extreme events that may be associated with climate change.

2.3.5.1 POTENTIAL IMPACT OF CLIMATE CHANGE ON LIVESTOCK

The risk potential associated with livestock production systems due to global warming can be characterized by levels of vulnerability, as influenced by animal performance and environmental parameters (Hahn 1995). When combined performance level and environmental influences create a low level of vulnerability, there is little risk. As performance levels (e.g., rate of gain, milk production per day, eggs/day) increase, the vulnerability of the animal increases and, when coupled with an adverse environment, the animal is at greater risk. Combining an adverse environment with high performance pushes the level of vulnerability and consequent risk to even higher levels. Inherent genetic characteristics or management scenarios that limit the animal's ability to adapt to or cope with environmental factors also puts the animal at risk. At very high performance levels, any environment other than near-optimal may increase animal vulnerability and risk.

The potential impacts of climatic change on overall performance of domestic animals can be



determined using defined relationships between climatic conditions and voluntary feed intake, climatological data, and GCM output. Because ingestion of feed is directly related to heat production, any change in voluntary feed intake and/or energy density of the diet will change the amount of heat produced by the animal (Mader et al. 1999b). Ambient temperature has the greatest influence on voluntary feed intake. However, individual animals exposed to the same ambient temperature will not exhibit the same reduction in voluntary feed intake. Body weight, body condition, and level of production affect the magnitude of voluntary feed intake and ambient temperature at which changes in voluntary feed intake begin to be observed. Intake of digestible nutrients is most often the limiting factor in animal production. Animals generally prioritize available nutrients to support maintenance needs first, followed by growth or milk production, and then reproduction.

Based on predicted climate outputs from GCM scenarios, production and response models for growing confined swine and beef cattle, and milk-producing dairy cattle have been developed (Frank et al. 2001). The goal in the development of these models was to utilize climate projections – primarily average daily temperature – to generate an estimate of direct climate-induced changes in daily voluntary feed intake and subsequent performance during summer in the central portion of the United States (the dominant livestock producing region of the country), and across the entire country. The production response models were run for one current (pre-1986 as baseline) and two future climate scenarios: doubled CO₂ (~2040) and a triple of CO₂ (~2090) levels. This data base employed the output from two GCMs – the Canadian Global Coupled (CGC) Model, Version I, and the United Kingdom Meteorological Office/Hadley Center for Climate Prediction and Research model – for input to the livestock production/response models. Changes in production of swine and beef cattle data were represented by the number of days to reach the target weight under each climate scenario and time period. Dairy production is reported in kilograms of milk produced per cow per season. Details of this analysis are reported by Frank (2001) and Frank et al. (2001).

In the central U.S. (MINK region = Missouri, Iowa, Nebraska, and Kansas), days-to-slaughter weight for swine associated with the CGC 2040 scenario increased an average of 3.7 days from the baseline of 61.2 days. Potential losses under this scenario averaged 6 percent and would cost swine producers in the region \$12.4 million annually. Losses associated with the Hadley scenario are less severe. Increased time-to-slaughter weight averaged 1.5 days, or 2.5 percent, and would cost producers \$5 million annually. For confined beef cattle reared in the central U.S., time-to-slaughter weight associated with the CGC 2040 scenario increased 4.8 days (above the 127-day baseline value) or 3.8 percent, costing producers \$43.9 million annually. Climate changes predicted by the Hadley model resulted in loss of 2.8 days of production, or 2.2 percent. For dairy, the projected CGC 2040 climate scenario would result in a 2.2 percent (105.7 kg/cow) reduction in milk output, and cost producers \$28 million annually. Production losses associated with the Hadley scenarios would average 2.9 percent and cost producers \$37 million annually. Figures 2.12, 2.13, and 2.14 indicate predicted changes in productivity in swine, beef and dairy, respectively, for the various regions of the United States.

Across the entire United States, percent increase in days to market for swine and beef, and the percent decrease in dairy milk production for the 2040 scenario, averaged 1.2 percent, 2.0 percent, and 2.2 percent, respectively, using the CGC model, and 0.9 percent, 0.7 percent, and 2.1 percent, respectively, using the Hadley model. For the 2090 scenario, respective changes averaged 13.1 percent, 6.9 percent, and 6.0 percent using the CGC model, and 4.3 percent, 3.4 percent, and 3.9 percent using the Hadley model. In general, greater declines in productivity are found with the CGC model than with the Hadley model. Swine and beef production were affected most in the south-central and southeastern United States. Dairy production was affected the most in the U.S. Midwest and Northeast regions.

In earlier research, Hahn et al. (1992) also derived estimates of the effects of climate change of swine growth rate and dairy milk production during summer, as well as other periods during the year. In the east-central United States, per animal milk production was found to decline



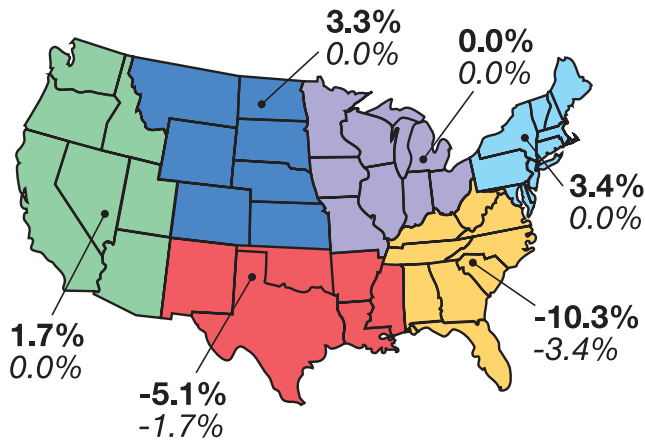


Figure 2.12 Percent change from baseline to 2040 of days for swine to grow from 50 to 110 kg, beginning June 1 under CGC (bold text) and Hadley (italicized text) modeled climate (Frank 2001; Frank et al. 2001).

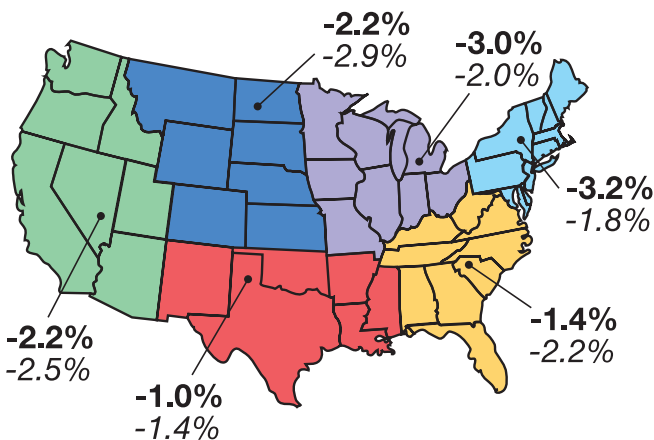


Figure 2.13 Numerical values represent changes in beef productivity based on the number of days required to reach finish weights from baseline to 2040, beginning June 1 under CGC (bold text) and Hadley (italicized text) modeled climate (Frank 2001; Frank et al. 2001).

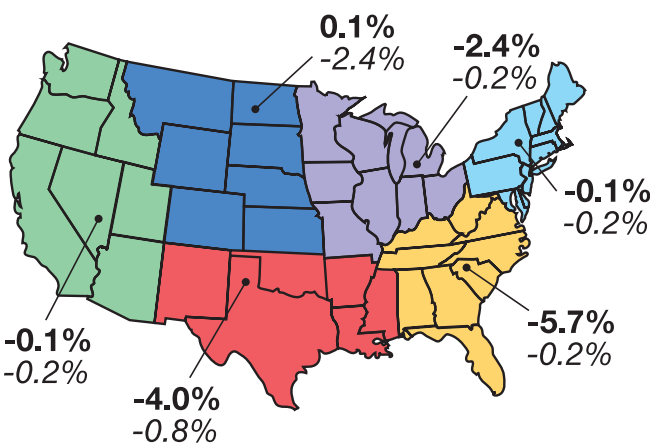


Figure 2.14 Percent change of kg fat-corrected milk (FCM) yield/cow/season (June 1 to October 31) from baseline to 2040, under CGC (bold text) and Hadley (italicized text) modeled climate (Frank 2001; Frank et al. 2001).

388 kg (~4 percent) for a July through April production cycle, and 219 kg (~2.2 percent) for an October through July production cycle as a result of global warming. Swine growth rate in this same region was found to decline 26 percent during the summer months, but increased nearly 12 percent during the winter months as a result of global warming. Approximately one-half of these summer domestic livestock production declines are offset by improvements in productivity during the winter. In addition, high producing animals will most likely be affected to a greater extent by global climate change than animals with lower production levels.

A production area in which global climate change may have negative effects that are not offset by positive winter effects is conception rates, particularly in instances when the breeding season primarily occurs in the spring and summer months. (This will particularly affect cattle.)

Hahn (1995) reported that conception rates in dairy cows were reduced 4.6 percent for each unit change when the THI reaches above 70. Amundson et al. (2005) reported a decrease in pregnancy rates of *Bos taurus* cattle of 3.2 percent for each increase in average THI above 70, and a decrease of 3.5 percent for each increase in average temperature above 23.4°C. These data were obtained from beef cows in a range or pasture management system. Amundson et al. (2006) also reported that of the environmental variables studied, minimum temperature had the greatest influence on the percent of cows getting pregnant. Clearly, increases in temperature and/or humidity have the potential to affect conception rates of domestic animals not adapted to those conditions. Summertime conception rates are considerably lower in the Gulf States compared with conception rates in the Northern Plains (Sprott et al. 2001).

In an effort to maintain optimum levels of production, climate change will likely result in livestock producers selecting breeds and breed types that have genetically adapted to conditions that are similar to those associated with the climate change. However, in warmer climates, breeds that are found to be more heat tolerant are generally those that have lower productivity levels, which is likely the mechanism by which

they were able to survive as a dominant regional breed. In addition, climate change and associated variation in weather patterns will likely result in more livestock being managed in or near facilities that have capabilities for imposing microclimate modifications (Mader et al. 1997a, 1999a; Gaughan et al. 2002). Domestic livestock, in general, can cope with or adapt to gradual changes in environmental conditions; however, rapid changes in environmental conditions or extended periods of exposure to extreme conditions drastically reduce productivity and are potentially life threatening.

Estimates of livestock production efficiency suggest that negative effects of hotter weather in summer outweigh positive effects of warmer winters (Adams et al. 1999). The largest change occurred under a 5°C increase in temperature, when livestock yields fell by 10 percent in cow-calf and dairy operations in Appalachia, the Southeast, Mississippi Delta, and southern Plains regions of the United States. The smallest change was one percent under 1.5°C warming in the same regions.

Another area of concern is the influence of climate change on diseases and parasites that affect domestic animals. Incidences of disease, such as bovine respiratory disease, are known to be increasing (Duff and Gaylean 2007). However, causes for this increase can be attributed to a number of non-environmentally related factors. As for parasites, similar insect migration and over-wintering scenarios observed in cropping systems may be found for some parasites that affect livestock.

Baylis and Githeko (2006) describe the potential of how climate change could affect parasites and pathogens, disease hosts, and disease vectors for domestic livestock. The potential clearly exists for increased rate of development of pathogens and parasites due to spring arriving earlier and warmer winters that allow greater proliferation and survivability of these organisms. For example, bluetongue was recently reported in Europe for the first time in 20 years (Baylis and Githeko 2006). Warming and changes in rainfall distribution may lead to changes in spatial or temporal distributions of those diseases sensitive to moisture such as anthrax, blackleg, haemorrhagic septicaemia, and vector-borne diseases.

However, these diseases, as shown by climate-driven models designed for Africa, may decline in some areas and spread to others (Baylis and Githeko 2006).

2.4 OBSERVING/MONITORING SYSTEMS

2.4.1 Monitoring Relevant to Crops

2.4.1.1 ENVIRONMENTAL STRESS ON CROP PRODUCTION

Stress symptoms on crop production include warmer canopies associated with increased CO₂ (but the increment may be too small to detect over 30 years), smaller grain size or lower test weight from heat stress, more failures of pollination associated with heat stress, and greater variability in crop production. However, elevated CO₂ will have a helpful effect via reduced water consumption.

Heat stress could potentially be monitored by satellite image processing over the 30-year span, but causal factors for crop foliage temperature need to be properly considered (temporary water deficit from periodic low rainfall periods, effects of elevated CO₂ to increase foliage temperature, direct effects of elevated air temperature, offset by opposite effect from prolonged water extraction associated with CO₂-induced water conservation). Increased variability in crop yield and lower test weight associated with greater weather variability relative to thresholds for increased temperature can be evaluated both at the buying point, and by using annual USDA crop statistics for rainfed crops. Assessments of irrigated crops can be done in the same way, but with less expectation of water deficit as a causal factor for yield loss. The extent of water requirement for irrigated crops could be monitored by water management district records and pumping permits, but the same issue is present for understanding the confounding effects of temperature, radiation, vapor pressure deficit, rainfall, and CO₂ effects.

2.4.1.2 PHENOLOGICAL RESPONSES TO CLIMATE CHANGE

A recent analysis of more than 40 years of spring bloom data from the northeastern United States, the “lilac phenology network,” which was established by the USDA in the 1960s, provided robust evidence of a significant biological



response to climate change in the region during the latter half of the 20th century (Wolfe et al. 2005).

2.4.1.3 CROP PEST RANGE SHIFTS IN COLLABORATION WITH INTEGRATED PEST MANAGEMENT (IPM) PROGRAMS

IPM specialists, and the weather-based weed, insect, and pathogen models they currently utilize, will provide an important link between climate science and the agricultural community. The preponderance of evidence indicates an overall increase in the number of outbreaks and northward migration of a wide variety of weeds, insects, and pathogens. The existing IPM infrastructure for monitoring insect and disease populations could be particularly valuable for tracking shifts in habitable zone of potential weed, insect, and disease pests, and for forecasting outbreaks.

2.4.2 Monitoring Relevant to Pasturelands

Efforts geared toward monitoring the long-term response of pasturelands to climate change should be as comprehensive as possible. When possible, monitoring efforts should include observation of vegetation dynamics, grazing regimes, animal behavior (e.g., indicators of animal stress to heat), mutualistic relationships (e.g., plant-root nematodes; N-fixing organisms), and belowground processes, such as development and changes in root mass, carbon inputs and turnover, nutrient cycling, and water balance. To augment their value, these studies should include use of simulation modeling in order to test hypotheses regarding ecosystem processes as affected by climate change. The development of protocols for monitoring the response of pasturelands to climate change should be coordinated with the development of protocols for rangelands and livestock.

2.4.3 Monitoring Relevant to Rangelands

Soil processes are closely linked to rangeland productivity and vegetation dynamics. As a result, future efforts to track long-term rangeland-vegetation responses to climate change and CO₂ should also involve monitoring efforts directed toward tracking changes in soils. While

considerable progress has been made in the application of remote sensing for monitoring plant phenology and productivity, there remains a need for tracking critical soil attributes, which will be important in driving ecological responses of rangelands to climate change.

Nationwide, rangelands cover a broad expanse and are often in regions with limited accessibility. Consequently, ranchers and public land managers need to periodically evaluate range resources (Sustainable Rangeland Roundtable Members 2006). Monitoring of rangelands via remote sensing is already an important research activity, albeit with limited rancher acceptance (Butterfield and Malmstrom 2006). A variety of platforms are currently being evaluated, from low-flying aerial photography (Booth and Cox 2006) to satellite imagery (Afinowicz et al. 2005; Everitt et al. 2006; Phillips et al. 2006; Weber 2006), plus hybrid approaches (Afinowicz et al. 2005) for use in evaluating a variety of attributes considered important indicators of rangeland health – plant cover and bare ground, presence of important plant functional groups or species – documenting changes in plant communities including weed invasion, primary productivity, and forage N concentration.

Although not explicitly developed for global change applications, the goal of many of these methodologies to document changing range conditions suggests tools that could be employed for tracking vegetation change in rangelands, and correlated to climatic or CO₂ data, as done by Knapp et al. (2001). For example, state-and-transition models (Bestelmeyer et al. 2004; Briske et al. 2005) could be expanded to incorporate knowledge of rangeland responses to global change. Integration of those models with existing monitoring efforts and plant developmental data bases, such as the National Phenology Network, could provide a cost-effective monitoring strategy for enhancing knowledge of how rangelands are being impacted by global change, as well as offering management options.

Fundamental soil processes related to nutrient cycling – which may ultimately determine how rangeland vegetation responds to global change – are more difficult to assess. At present, there are no easy and reliable means by which to



accurately ascertain the mineral and carbon state of rangelands, particularly over large land areas. The Natural Resources Conservation Service (NRCS) National Soil Characterization Data Base is an especially important baseline of soils information that can be useful for understanding how soils might respond to climate change. However, this data base does not provide a dynamic record of responses through time. Until such information is easily accessible, or reliable methodologies are developed for monitoring rangeland soil properties, predictions of rangeland responses to future environments will be limited. However, much can be ascertained about N cycling responses to global change from relatively easily determined measures of leaf-N chemistry (Peñuelas and Estiarte 1997). As a result, sampling of ecologically important target species in different rangeland ecosystems would be a comparatively low-cost measure to monitor biogeochemical response to global change.

2.5 INTERACTIONS AMONG SYSTEMS

2.5.1 Climate Change and Sustainability of Pasturelands

The current land use system in the United States requires high resource inputs, from the use of synthetic fertilizer on crops to the transport of crops to animal feeding operations. In addition to being inefficient with regard to fuel use, this system creates environmental problems from erosion to high nutrient degradation of water supplies. Recently, scientists have been examining the potential for improved profitability and improved sustainability with a conversion to integrated crop-livestock farming systems (Russelle et al. 2007). This could take many forms. One possible scenario involves grain crops grown in rotation with perennial pasture that also integrates small livestock operations into the farming system. Planting of perennial pastures decreases nitrate leaching and soil erosion, and planting of perennial legumes also reduces the need for synthetic N fertilizer. Diversifying crops also reduces incidence of pests, diseases, and weeds, imparting resilience to the agro-ecosystem. This resilience will become increasingly important as a component of farm adaptation to climate change.

2.6 FINDINGS AND CONCLUSIONS

2.6.1 Crops

2.6.1.1 GRAIN AND OILSEED CROPS

Crop yield response to temperature and CO₂ for maize, soybean, wheat, rice, sorghum, cotton, peanut, and dry bean in the United States was assembled from the scientific literature. Cardinal base, optimum, and upper failure-point temperatures for crop development, vegetative, and reproductive growth and slopes-of-yield decline with increase in temperature were reviewed. In general, the optimum temperature for reproductive growth and development is lower than that for vegetative growth. Consequently, life cycle will progress more rapidly, especially given a shortened grain-filling duration and reduced yield as temperature rises. Furthermore, these crops are characterized by an upper failure-point temperature at which pollination and grain-set processes fail. Considering these aspects, the optimum mean temperature for grain yield is fairly low for the major agronomic crops: 18–22°C for maize, 22–24°C for soybean, 15°C for wheat, 23–26°C for rice, 25°C for sorghum, 25–26°C for cotton, 20–26°C for peanut, 23–24°C for dry bean, and 22–25°C for tomato.

Without the benefit of CO₂, the anticipated 1.2°C rise in temperature over the next 30 years is projected to decrease maize, wheat, sorghum, and dry bean yields by 4.0, 6.7, 9.4, and 8.6 percent, respectively, in their major production regions. For soybean, the 1.2°C temperature rise will increase yield 2.5 percent in the Midwest where temperatures during July, August, September average 22.5°C, but will decrease yield 3.5 percent in the South, where mean temperature during July, August, and September averages 26.7°C. Likewise, in the South, that same mean temperature will result in reduced rice, cotton, and peanut yields, which will decrease 12.0, 5.7, and 5.4 percent, respectively. An anticipated CO₂ increase from 380 to 440 ppm will increase maize and sorghum yield by only 1 percent, whereas the listed C₃ crops will increase yield by 6.1 to 7.4 percent, except for cotton, which shows a 9.2 percent increase. The response to CO₂ was developed from interpolation of extensive literature summarization of

Diversifying crops also reduces incidence of pests, diseases, and weeds, imparting resilience to the agro-ecosystem. This resilience will become increasingly important as a component of farm adaptation to climate change.



response to ambient versus doubled CO₂. The net effect of rising temperature and CO₂ on yield will be maize (-3.0 percent), soybean (Midwest, +9.9 percent; South, +3.9 percent), wheat (+0.1 percent), rice (-5.6 percent), sorghum (-8.4 percent), cotton (+3.5 percent), peanut (+1.3 percent), and dry bean (-2.5 percent). The CO₂-induced decrease in measured ET summarized from chamber and FACE studies, from 380 to 440 ppm, gives a fairly repeatable reduction in ET of 1.4 to 2.1 percent, although the 1.2°C rise in temperature would increase ET by 1.8 percent, giving an unimportant net -0.4 to +0.3 percent reduction in ET. This effect could lead to a further small -0.4 to +0.3 percent change in yield under rainfed production. A similar small change in crop water requirement will occur under irrigated production.

Thus, the benefits of CO₂ rise over the next 30 years mostly offset the negative effects of temperature for most C₃ crops except rice and bean, while the C₄ crop yields are reduced by rising temperature because they have little response to the CO₂ rise. The two factors also nearly balance out on crop transpiration requirements. Thus, the 30-year outlook for crop production is relatively neutral. However, the outlook for the next 100 years would not be as optimistic, if rise in temperature and CO₂ continue, because the C₃ response to rising CO₂ is reaching a saturating plateau, while the negative temperature effects will become progressively more severe. There are continual changes in the genetic resources of crop varieties and horticultural crops that will provide increases in yield due to increased resistance to water and pest stresses. These need to be considered in any future assessments of the climatic impacts; however, the genetic modifications have not altered the basic temperature response or CO₂ response of the biological system.

As temperature rises, crops will increasingly begin to experience upper failure point temperatures, especially if climate variability increases and if rainfall lessens or becomes more variable. Under this situation, yield responses to temperature and CO₂ would move more toward the negative side. Despite increased CO₂-responsiveness of photosynthesis/biomass as temperature increases, there were no published beneficial interactions of increased CO₂ upon

grain yield as temperature increased because temperature effects on reproductive processes, especially pollination, are so dominant. On the other hand, there are cases of negative interactions on pollination associated with the rise in canopy temperature caused by lower stomatal conductance. For those regions and crops where climate change impairs reproductive development because of an increase in the frequency of high temperature stress events (e.g., >35°C), the potential beneficial effects of elevated CO₂ on yield may not be fully realized.

No direct conclusions were made relative to anticipated effects of rainfall change on crop production. Such assessment requires use of global climate models and the climate outputs to be directed as inputs to crop growth models to simulate production for the different crops.

2.6.1.2 HORTICULTURAL CROPS

Although horticultural crops account for more than 40 percent of total crop market value in the United States (2002 Census of Agriculture), there is relatively little information on their response to CO₂, and few reliable crop simulation models for use in climate change assessments compared to that which is available for major grain and oilseed crops. The marketable yield of many horticultural crops is likely to be more sensitive to climate change than grain and oilseed crops because even short-term, minor environmental stresses can negatively affect visual and flavor quality. Perennial fruit and nut crop survival and productivity will be highly sensitive to winter, as well as summer, temperatures.

2.6.2 Weeds

The potential habitable zone of many weed species is largely determined by temperature. For example, kudzu (*Pueraria lobata*, var. *montana*) is an aggressive species that has a northern range currently constrained by the -20°C minimum winter temperature isocline. While other factors such as moisture and seed dispersal will affect the spread of invasive weeds such as kudzu, climate change is likely to lead to a northern migration in at least some cases.

Many weeds respond more positively to increasing CO₂ than most cash crops, particularly C₃ invasive weeds that reproduce by vegetative means (roots, stolons, etc.). Recent research also suggests that glyphosate loses its efficacy



on weeds grown at elevated CO_2 . While there are many weed species that have the C_4 photosynthetic pathway and therefore show a smaller response to atmospheric CO_2 relative to C_3 crops, in most agronomic situations, crops are in competition with a mix of both C_3 and C_4 weeds.

2.6.3 Insects and Disease Pests

In addition to crops and weeds, beneficial and harmful insects, invasives, microbes and other organisms present in agroecosystems will be responding to changes in CO_2 and climate. Numerous studies have already documented changes in spring arrival, over-wintering, and/or geographic range of several insect and animal species due to climate change. Disease pressure from leaf and root pathogens may increase in regions where increases in humidity and frequency of heavy rainfall events are projected, and decrease in regions projected to encounter more frequent drought.

2.6.4 Pasturelands

Today, pasturelands in the United States extend over 117 million acres; however, the area under pasturelands has experienced an 11 percent decrease over the last 25 years due mainly to expansion of urban areas. Consequently, future reductions in pastureland area will require an increase in pasture productivity in order to meet production needs.

In general, pasture species have been less studied than cropland species in terms of their response to climate change variables including atmospheric CO_2 concentration, temperature, and precipitation. Pastureland response to climate change will likely be complex because, in addition to the main climatic drivers, other plant and management factors might also influence the response (e.g., plant competition, perennial growth habits, seasonal productivity, and plant-animal interactions).

Results of studies evaluating the response of pasture species to elevated CO_2 are consistent with the general response of C_3 and C_4 type vegetation to elevated CO_2 but important exceptions exist. C_3 pasture species such as Italian ryegrass, orchardgrass, rhizoma peanut, tall fescue, and timothy have exhibited increased

photosynthetic rates under elevated CO_2 . Other studies suggest that Kentucky bluegrass might be at the lower end of the range in the responsiveness of C_3 grasses to elevated CO_2 , especially under low nutrient conditions. Perennial ryegrass has shown a positive response in terms of photosynthetic rate, but a low or even negative response in terms of plant yield. The C_4 pasture species bahiagrass, an important pasture species in Florida, appears marginal in its response to elevated CO_2 . Also, shifts in optimal temperatures for photosynthesis might be expected under elevated CO_2 . Species like perennial ryegrass and tall fescue may show a downward shift in their optimal temperatures for photosynthesis.

This review has not yielded sufficient quantitative information for predicting the yield change of pastureland species under a future temperature increase of 1.2°C . However, projected increases in temperature and the lengthening of the growing season should, in principle, extend forage production into late fall and early spring, thereby decreasing the need for accumulation of forage reserves during the winter season. In addition, water availability may play a major role in the response of pasturelands to climate change. Dallisgrass appears to better withstand conditions of moisture stress under elevated CO_2 than under ambient conditions. Simulation modeling of alfalfa yield response to climate change suggests that future alterations in precipitation will be very important in determining yields. Roughly, for every 4 mm change in annual precipitation, the models predict a 1 percent change in dryland alfalfa yields.

In studies using defoliation as a variable, increases in plant productivity under defoliation were only observed under ambient CO_2 while the largest response to elevated CO_2 was observed in non-defoliated plants. The effect of elevated CO_2 on pasture yield may be affected by the presence of mutualistic interactions with other organisms. Tall fescue plants infected with an endophyte fungus and exposed to elevated CO_2 showed a 15 percent higher yield response than under ambient conditions.

An improved understanding of the impacts of climate change on pastureland might be obtained



through comprehensive studies that include grazing regimes, mutualistic relationships (e.g., plant roots-nematodes; N-fixing organisms), as well as the balance of carbon, nutrients and water.

2.6.5 Rangelands

The evidence from manipulative experiments, modeling exercises, and long-term observations of rangeland vegetation over the past two centuries provide indisputable evidence that warming, altered precipitation patterns, and rising atmospheric CO₂ are virtually certain to have profound impacts on the ecology and agricultural utility of rangelands.

As CO₂ levels and temperatures continue to climb, and precipitation patterns change, sensitivity of different species to CO₂ will direct shifts in plant community species composition. However, lacking multiple global change experiments that incorporate CO₂, temperature, and precipitation, our knowledge about how global change factors and soil nutrient cycling will interact and affect soil N availability is limited, and reduces our ability to predict species change.

Based on current evidence, plants with the C₃ photosynthetic pathway – forbs, woody plants, and possibly legumes – seem likely to be favored by rising CO₂, although interactions of species responses with rising temperature and precipitation patterns may affect these functional group responses (Morgan 2005, 2007). (For instance, warmer temperatures and drier conditions will tend to favor C₄ species, which may cancel out the CO₂ advantage of C₃ grasses.)

There is already some evidence that climate change-induced species shifts are underway in rangelands. For instance, encroachment of woody shrubs into former grasslands is likely due to a combination of over-grazing, lack of fire, and rising levels of atmospheric CO₂. Combined effects of climate and land management change can drive species change that can have a tremendous negative impact on the range livestock industry (Bond and Midgley 2000; Morgan et al. 2007; Polley, 1997). In turn, this has altered the frequency and timing of wildfires by reducing establishment of perennial herbaceous species by pre-empting soil water early in the growing season (Young 1991). It seems

likely that plant species changes will have as much or more impact on livestock operations as alterations in plant productivity.

One of our biggest concerns is in the area of how grazing animals affect ecosystem response to climate change. Despite knowledge that large grazing animals have important impacts on the productivity and nutrient cycling for rangelands (Augustine and McNaughton 2004, 2006; Semmartin et al. 2004), little global change research has addressed this particular problem. Manipulative field experiments in global change research are often conducted on plots too small to incorporate grazing animals, so these findings do not reflect the effect grazing domestic livestock can have on N cycling due to diet selectivity, species changes, and nutrient cycling, all of which can interact with CO₂ and climate (Allard et al. 2004; Semmartin et al. 2004). The paucity of data presently available on livestock-plant interactions under climate change severely compromises our ability to predict the consequences of climate change on livestock grazing.

Another important knowledge gap concerns the responses of rangelands to multiple global changes. To date, only one experiment has examined four global changes: rising CO₂, temperature, precipitation, and N deposition (Dukes et al. 2005; Zavaleta et al. 2003a). Although interactions between global change treatments on plant production were rare, strong effects on relative species abundances and functional plant group responses suggest highly complex interactions of species responses to combined global changes that may ultimately impact nutrient cycling with important implications for plant community change and C storage. Such results underscore an emerging acknowledgment that while there is certainty that rangeland ecosystems are responding to global change, our ability to understand and predict responses to future changes is limited.

Rangelands are used primarily for grazing. For most domestic herbivores, the preferred forage is grass. Other plants – including trees, shrubs, and other broadleaf species – can lessen livestock production and profitability by reducing availability of water and other resources to grasses, making desirable plants unavailable to livestock or physically complicating livestock



management, or poisoning grazing animals (Dahl and Sosebee 1991).

In addition to livestock grazing, rangelands provide many other goods and services, including biodiversity, tourism, and hunting. They are also important as watershed catchments. Carbon stores are increasingly being considered as an economic product (Liebig et al. 2005; Meeting et al. 2001; Moore et al. 2001; Schuman et al. 2001). However, there is still uncertainty about the greenhouse gas sink capacity of rangelands, how it will be altered by climate change – including rising atmospheric CO₂ – and, ultimately, the economics of rangeland C sequestration (Schlesinger 2006; van Kooten 2006). While the ability to accurately predict the consequences of all aspects of climate change for rangelands is limited, a recent list of management options (Morgan 2005) suggests the types of choices ranchers and land managers will need to consider in the face of climate change (Table 2.14).

A challenge for rangeland scientists, public land managers, ranchers, and others interested in rangelands will be to understand how the dynamics of climate change and land management translate into ecological changes that impact long-term use and sustainability. Perhaps more than most occupations, ranching in the present-day United States is as much a lifestyle choice as it is an economic decision (Bartlett et al. 2002), so economics alone will not likely drive decisions that ranchers make in response to climate change. Nevertheless, ranchers are already looking to unconventional rangeland uses like tourism or C storage. In regions where vegetation changes are especially counter-productive to domestic livestock agriculture, shifts in enterprises will occur. Shifts between rangeland and more intensive agriculture may also occur, depending on the effects of climate-induced environmental changes and influence of economics that favor certain commodities. However, once a native rangeland is disturbed, whether intentionally through intensive agriculture or unintentionally through climate change, restoration can be prohibitively costly, and in some cases, impossible. Therefore, management decisions on the use of private and public rangelands will need to be made with due diligence paid toward their long-term ecological impacts.

2.6.6 Animal Production Systems

Increases in air temperature reduce livestock production during the summer season with partial offsets during the winter season. Current management systems usually do not provide as much shelter to buffer the effects of adverse weather for ruminants as for non-ruminants. From that perspective, environmental management for ruminants exposed to global warming needs to consider: 1) general increase in temperature levels, 2) increases in nighttime temperatures, and 3) increases in the occurrence of extreme events (e.g., hotter daily maximum temperature and more/longer heat waves).

In terms of environmental management needed to address global climate change, the impacts can be reduced by recognizing the adaptive ability of the animals and by proactive application of appropriate countermeasures (sunshades, evaporative cooling by direct wetting or in conjunction with mechanical ventilation, etc.). Specifically, the capabilities of livestock managers to cope with these effects are quite likely to keep up with the projected rates of change in global temperature and related climatic factors. However, coping will entail costs such as application of environmental modification techniques, use of more suitably adapted animals, or even shifting animal populations.

Climate changes affect certain parasites and pathogens, which could result in adverse effects on host animals. Interactions exist among temperature, humidity, and other environmental factors which, in turn, influence energy exchange. Indices or measures that reflect these interactions remain ill-defined, but research to improve them is underway. Factors other than thermal (i.e., dust, pathogens, facilities, contact surfaces, technical applications) also need better definition. Duration and intensity of potential stressors are of concern with respect to the coping and/or adaptive capabilities of an animal. Further, exposure to one type of stressor may lead to altered resistance to other types. Other interactions may exist, such that animals stressed by heat or cold may be less able to cope with other stressors (restraint, social mixing, transport, etc). Improved stressor characterization is needed to provide a basis for refinement of sensors providing input to control systems. Innovations in electronic system capabilities



will undoubtedly continue to be exploited for the betterment of livestock environments with improved economic utilization of environmental measures, and mitigation strategies. There is much potential for application of improved sensors, expert systems, and electronic stockmanship. Continued progress should be closely tied to animal needs based on rational criteria, and must include further recognition of health criteria for animal caretakers as well. The ability of the animal's target tissues to respond to disruptions in normal physiological circadian rhythms may be an important indicator of stress.

Also, the importance of obtaining multiple measures of stress is also becoming more apparent. However, inclusion and weighting of multiple factors (e.g., endocrine function, immune function, behavior patterns, performance measures, health status, vocalizations) is not an easy task in developing integrated stress measures. Establishing threshold limits for impaired functions that may result in reduced performance or health are essential. Improved modeling of physiological systems as our knowledge base expands will help the integration process.

Table 2.14 CO₂ and climate change responses and management options for grazing land factors. Adapted from Morgan (2005).

| Factor | Responses to rising CO ₂ and climate change | Management options |
|--|---|--|
| Primary production | <p>Increase or little change with rising CO₂: Applies to most systems, especially water-limited rangelands. N may limit CO₂ response in some systems.</p> <p>Increases or little change with temperature: Applies to most temperate and wet systems.</p> <p>Decreases with temperature: Applies to arid and semi-arid systems that experience significantly enhanced evapotranspiration and drought, particularly where precipitation is not expected to increase.</p> <p>Variable responses with precipitation: Depends on present climate, and nature of precipitation change. Increases in production in regions where water is limiting, but increasing temperatures and more intense precipitation events will reduce this.</p> | <p>Adjust forage harvesting: Stocking rates. Grazing systems.</p> <p>Develop and utilize adapted forage species (e.g. legumes, C₄ grasses where appropriate, more drought-resistant species and cultivars).</p> <p>Enterprise change (e.g. movement to more or less intensive agricultural practices).</p> |
| Plant community species composition | <p>Global changes will drive competitive responses that alter plant communities: In some systems, legumes and C₃ species may be favoured in future CO₂-enriched environments, but community reactions will be variable and highly site specific. Warmer environments will favor C₄ metabolisms. Both productive and reproductive responses will be featured in community changes. Ultimate plant community responses will probably reflect alterations in soil nutrients and water, and involve complex interactions between changes in CO₂, temperature and precipitation. Weed invasions may already be underway, due to rising atmospheric CO₂. Proximity to urban areas will add complex interactions with ozone and N deposition.</p> | <p>All of the above.</p> <p>Weed control: Fire management and/or grazing practices to convert woody lands to grasslands. Herbicides where appropriate to control undesirables.</p> <p>Enterprise change or emphasis: Change between intensive/extensive practices. C storage strategy. Tourism, hunting, wildlife. Biodiversity.</p> |
| Forage quality | <p>Increasing CO₂ will alter forage quality. In N-limited native rangeland systems, CO₂-induced reduction in N and increased fiber may lower quality.</p> | <p>Utilize/interseed legumes where N is limiting and practice is feasible.</p> <p>Alter supplemental feeding practices.</p> |
| Animal performance to altered climate | <p>Increased temperature, warm regions: Reduced feed intake, feed efficiency, animal gain, milk production and reproduction. Increased disease susceptibility, and death.</p> <p>Increased temperature, cold regions: Enhanced animal performance, lowered energy costs.</p> | <p>Animal usage: Select adapted animal breeds from different world regions to match new climate. Improve animal genetics. Select different animal species (i.e. camels, sheep and goats for more drought-prone areas).</p> <p>Alter management (e.g., timing of breeding, calving, weaning)</p> <p>Enterprise change (above)</p> |