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2 **Agriculture**

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5

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24 **2.1 Introduction**

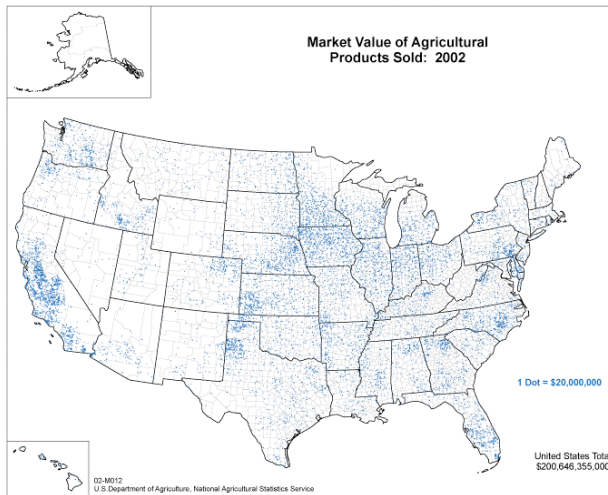


Figure 2.1 Market value of all agricultural products sold in 2002. (USDA National Agricultural Statistics Service).

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59 by the United States Department of Agriculture (USDA) National Agricultural Statistics
60 Service, and four different livestock

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Agriculture within the United States is varied and produces a large value (\$200 billion in 2002) of production across a wide range of plant and animal production systems. Because of this diversity, changes in climate will likely impact agriculture in many U.S. regions. U.S. agriculture is complex: many crops are grown in different climates and soils, and different livestock types are produced in numerous ways. There are 116 different plant commodity groups listed

2 groupings (i.e., dairy, poultry,
 4 specialty livestock, and livestock that
 6 contain a variety of different animal
 8 types or products derived from animal
 10 production, e.g., cheese or eggs). The
 12 extensive and intensive nature of U.S.
 14 agriculture is best represented in the
 16 context of the value of the production
 18 of crops and livestock. Market value
 20 of agricultural production within the
 22 United States represents a combination
 24 of all crops and their distribution
 26 (Figure 2.1). U.S. agriculture was
 28 distributed among these different
 30 commodities with 52 percent of the
 32 value generated from livestock, 21
 34 percent from fruit and nut, 20 percent
 36 from grain and oilseed, two
 38 percent from cotton, and five
 40 percent from other commodity
 42 production, not including
 43 pastureland or rangeland production. Figure 2.2 illustrates that crops and livestock
 44 represent approximately equal portions of the commodity value (Figure 2.2).

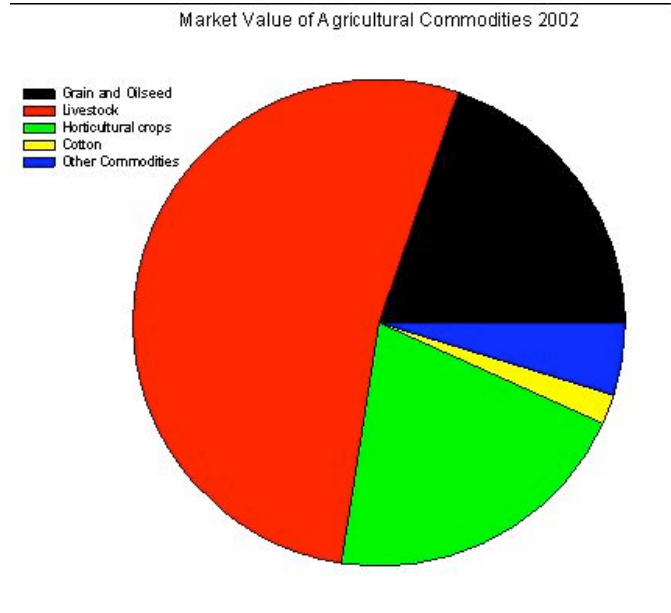


Figure 2.2. Market value distribution of livestock, grain and oilseed, horticultural crops, cotton and other crops for the United States in 2002. (USDA National Agricultural Statistics Service).

46 Distribution of crops across the United States is dependent upon the suitability of the soil
 47 and climate for efficient production. Corn (*Zea mays* L.) is the most widely distributed

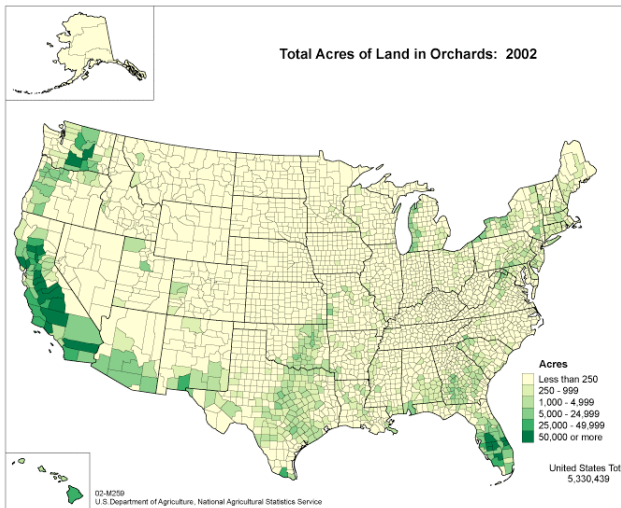


Figure 2.3. Distribution of orchards across the United States in 2002. (USDA National Agricultural Statistics Service).

49 crop across the United States,
 51 next to pastureland and
 53 rangeland. Wheat, while grown in
 55 most states has a concentration in
 57 the upper Great Plains and
 59 Northwest United States. In
 61 contrast to grain crops, orchard
 63 crops are restricted to regions in
 65 which there are moderate winter
 67 temperatures (Figure 2.3). For
 69 example, citrus crops are grown
 71 in the southern regions of the
 73 United States where winter
 75 temperatures are mild, and
 77 occurrence of freezing
 79 temperatures is minimal.

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1 However, orchards are distributed in the Northeast U.S. and intensive areas along the
2 Great Lakes to take advantage of the moderating effect of the lakes. The local
3 microclimate, induced by the regional climate, creates areas in which orchards that have
4 specific requirements for winter chilling create opportunities for these crops as part of the
5 production system. Shifts in the climate that cause changes in these conditions will have a
6 major impact on fruit production and risks due to variations in temperature during the
7 spring (flowering) and fall (fruit maturity).

9
11 Distribution of beef cows across the
13 United States is indicative of a livestock
15 commodity produced across a range of
17 climates (Figure 2.4). Every state has
19 some beef cows with the majority in
21 states that have an abundance of native
23 or planted pastures, which provide easily
25 accessible feed supplies for the grazing
27 animals. Linkage exists between the
29 amount of pasture and grazing land
31 (Figure 2.5) and beef cow numbers
33 because of the combination of
35 production systems and the use of
37 animals to directly consume grass or
39 hay. In contrast, areas classified as rangeland, v
40 precipitation, are concentrated in the western p

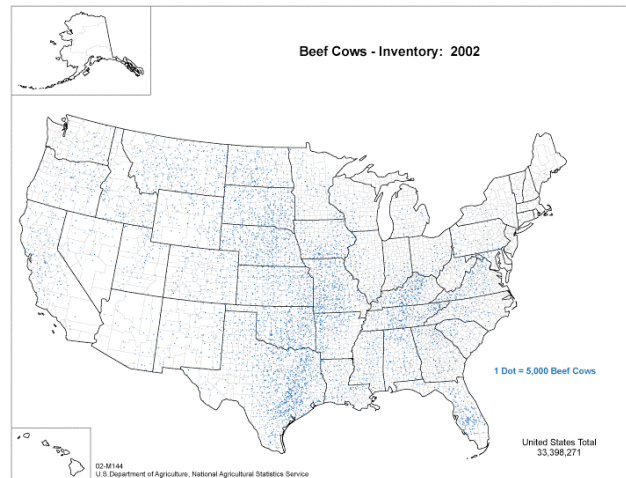


Figure 2.4. Distribution of beef cow inventory across the United States in 2002. (USDA National Agricultural Statistics Service).

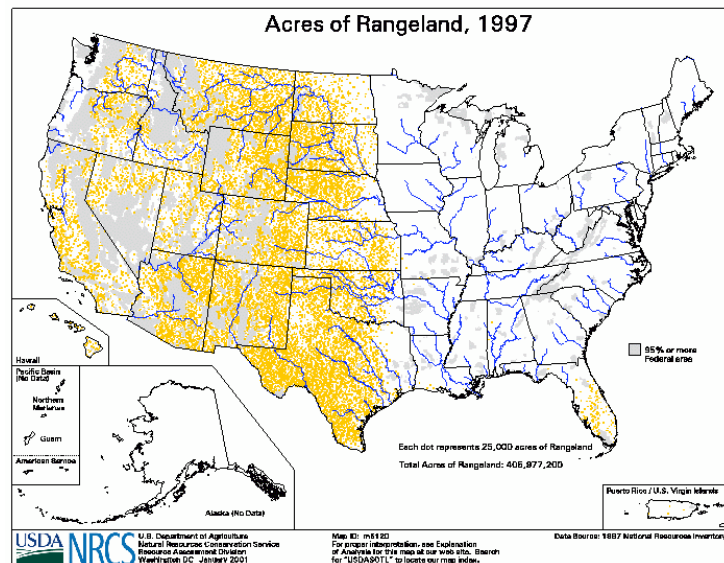
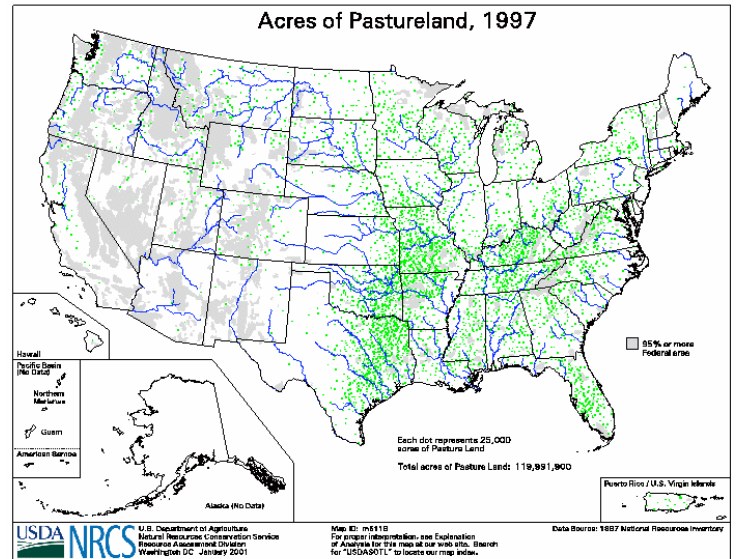


Figure 2.5. Distribution of pastureland across the United States in 1997 (www.nrcs.usda.gov/technical)

2 Climate affects crop, vegetable, and fruit
 4 production, pasture production,
 6 rangeland production, and livestock
 8 production systems significantly because
 10 of the direct effects of temperature,
 12 precipitation, and CO₂ on plant growth
 14 and the direct impacts of temperature
 16 and water availability to livestock.
 18 Variations in production among years in
 20 any of the commodity is a direct result of
 22 weather within the growing season and
 24 often an indirect effect from weather
 26 effects on insects, diseases or weeds.



30 There has been a decline in land
 32 classified as rangeland, pastureland,
 34 or grazed forest land over the past
 35 25 years. These changes are unrelated to climate change but illustrate changes in U.S.
 36 land use characteristics (Table 2.1). These shifts seem to more related to changes in
 37 population growth since much of the decline has occurred in the eastern United States.
 38 (Table 2.2).

1997 (www.nrcs.usda.gov/technical)

40 Climate has direct and indirect impacts on agriculture and the goal in this section is to
 41 provide a synthesis of the potential impacts of climate on agriculture that can be used a
 42 baseline to understand the consequences of climate variability.

Table 2.1. Non-Federal grazing land

	Rangeland	Pastureland (millions of acres)	Grazed Forest land (millions of acres)	Total (millions of acres)
Year: 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 2.1. Non-federal grazing land (in millions of acres). Source:
www.nrcs.usda.gov/technical/land/nri03/national_landuse.html

Table 2.2. Changes in pasturelands

	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
	131.1	125.2	117.0

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

Temperature changes will affect U.S. agriculture. There are direct effects of temperature on crop and livestock production. In these analyses, a 0.8 °C temperature increase was assumed to be consistent with projections for the United States for the next 30 years as reported in Intergovernmental Panel on Climate Change (IPCC) 2001. There is certainty in this degree of change over the next 30 years, although regional differences will vary. This value represents one of several potential scenarios for temperature change and characterizes the mid-range of the values. If temperature increases are less than this value, some effects will not be realized within the next decades; however, if this value is conservative, then impacts on agriculture will be hastened. Temperature ranges selected in the analyses for the various crops and livestock were based on reported temperature ranges from NOAA records across the United States. Further changes in climate beyond these 30 years are expected, and it is important to realize that long-term climate impact on agriculture and regional variations will occur.

A major temperature effect will be increased likelihood of extreme events, which will have local and regional effects on agricultural systems. Precipitation is critical to agriculture, and regional differences in the changes in precipitation patterns are likely to occur. Changes in CO₂ have occurred during the past 100 years, and continued increases in CO₂ concentrations are expected. For the analyses below, we used the expected values reported by IPCC (2001).

2.2 Key Points from the Literature

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 progresses as fast as possible. Temperatures above the optimum cause the growth rate to slow and finally cease at the maximum temperature. Progression of a crop through its life cycle

1 (phenological) phases is accelerated by increasing temperature up to the species-
2 dependent optimum temperature beyond which development rate slows. Faster
3 development of non-perennial crops is not necessarily ideal because a shorter life cycle
4 results in smaller plants, shorter reproductive phase duration, and lower yield potential.
5 Because of this, the optimum temperature for yield is nearly always lower than the
6 optimum temperature for leaf appearance rate, vegetative growth, or reproductive
7 progression. Temperature affects crop life cycle duration and the fit of given cultivars to
8 production zones. Higher temperatures during the reproductive stage of development
9 affect pollen viability, fertilization, and grain or fruit formation. Chronic exposures to
10 high temperatures during the pollination stage of initial grain or fruit set will reduce yield
11 potential. Exposure to extremely high temperatures during these phases can impact
12 growth and yield; however, acute exposure from extreme events may be most detrimental
13 during the reproductive stages of development.

14
15 For most perennial temperate fruit and nut crops, winter temperatures play a significant
16 role in productivity. There is considerable genotypic variation among fruit and nut crops
17 in their winter hardiness (ability to survive specific low temperature extremes), and
18 variation in their “winter chilling” requirement for optimum flowering and fruit set in the
19 spring and summer. Marketable yield of horticultural crops is highly sensitive to minor
20 environmental stresses, related to temperatures outside of the optimal range, which
21 negatively affect visual and flavor quality.

22
23 Reviews of the early enclosure CO₂ studies indicate that the average yield increase over
24 many C3 crops with doubling of CO₂ was reported to be 33 percent (Kimball, 1983), at a
25 time when doubling meant increase from 330 to 660 ppm CO₂. The general phenomenon
26 was expressed as increased number of tillers-branches, panicles-pods, and numbers of
27 seeds, with minimal effect on seed size. The C4 species response to doubling of CO₂ was
28 reported to be 10 percent (Kimball, 1983). High temperature stress during reproductive
29 development can negate CO₂ beneficial effects on yield even though total biomass
30 accumulation maintains a CO₂ benefit (e.g., for *Phaseolus* bean, Jifon and Wolfe 2000).
31 Unrestricted root growth, optimum fertility, and excellent control of weeds, insects, and
32 disease are also required to maximize CO₂ benefits (Wolfe, 1994). Most C3 weeds
33 benefit more than C3 crop species from elevated CO₂ (Ziska, 2003). The literature
34 suggests that increasing temperatures are likely to increase ET; at the same time,
35 increasing CO₂ will decrease stomatal conductance so as to decrease ET by about same
36 amount that temperature would raise it, resulting in little net effect.

37
38 The response of pasture species to climate change variables including atmospheric CO₂
39 concentration, temperature, and precipitation is uncertain and will likely be complex. In
40 in addition to the main climatic drivers, other plant and management factors will
41 influence future pasture-yield response (e.g., plant competition, perennial growth habits,
42 seasonal productivity, and plant-animal interactions). Elevated CO₂ will likely result in a
43 positive growth response in many but not all pasture species, to an extent consistent with
44 the general response of C3 and C4 vegetation to elevated CO₂. C3 pasture species such as
45 Italian ryegrass, orchardgrass, rhizoma peanut, tall fescue, and timothy almost certainly
46 will exhibit increased photosynthetic rates under elevated CO₂. The C3 grasses Kentucky

1 bluegrass and perennial ryegrass and the C4 species bahiagrass are unlikely to respond
2 strongly to elevated atmospheric CO₂.

3
4 Water availability exerts primary control on productivity and plant species composition
5 of rangelands. CO₂ enrichment, altered precipitation regimes, and higher temperatures,
6 influence water balance, and thus likely will affect plant productivity and species
7 composition. Plant productivity of most U.S. rangelands has likely increased (perhaps by
8 >20 percent) as a result of the 285 to 380 ppm increase in CO₂ over the past 200 years.
9 Productivity will likely continue to increase in many rangelands during the next 30 years
10 if, as predicted, atmospheric CO₂ climbs to ~440 ppm and average temperatures increase
11 ~ 1 °C during this time. Global change, particularly rising atmospheric CO₂, has already
12 caused important shifts in species composition of rangelands. Such species changes likely
13 will have as much or more impact on the ecology and utility of rangeland ecosystems
14 than changes in net primary productivity (NPP). Warmer temperatures likely will
15 lengthen growing seasons and affect development rates of individual species, but effects
16 of warming will vary among species.

17
18 Animal response to climate varies according to the type of thermal challenge: short-term
19 adaptive changes in behavioral, physiological, and immunological functions (survival-
20 oriented) are the initial responses to acute events, while longer-term challenges impact
21 performance-oriented responses (e.g., altered feed intake and heat balance, which affect
22 growth, reproduction, and efficiency). Within limits, domestic livestock can likely cope
23 with many acute thermal challenges through short-term acclimation and possibly
24 subsequent compensatory mechanisms. Chronic challenges may require more
25 fundamental responses, such as genetic adaptation and/or alteration. Combined
26 temperature-humidity and other thermally-based indices are beneficial in assessing the
27 impact of environmental stressors on domestic livestock. These indices serve as guides
28 for strategic management decisions by characterizing past events, and provide guidance
29 for tactical actions based on the intensity and duration of current adverse events.
30

31 *2.3 Summary of Findings and Conclusions*

32
33 Based on climate model predictions, temperature increases in the central United States
34 are projected to create summer-time losses by 2040 of \$12.4 million, \$43.9 million, and
35 \$37 million dollars annually for confined swine, beef and dairy animals, respectively.
36 These losses are a result of reductions in performance associated with lower feed intake
37 and increases in maintenance energy requirements. Notably, these losses do not account
38 for increased livestock mortality associated with major adverse weather events, which
39 can exceed \$25 million per event. Across the entire United States, the percent increase in
40 days to market for swine and beef, and the percent decrease in dairy milk production for
41 the 2040 climate scenario averaged 1.2 percent, 2.0 percent, and 2.2 percent, respectively,
42 using a Canadian climate model, and 0.9 percent, 0.7 percent, and 2.1 percent,
43 respectively, using a U.K. climate model. Pregnancy rates of *Bos taurus* cattle may be
44 reduced by up to 3.2 percent for each increase in the average breeding season

1 temperature-humidity index above 70, and decrease by 3.5 percent for each increase in
2 average temperature above 23.4°C.

3
4 An analysis of crop responses to temperatures suggests that a 0.8°C rise in temperature
5 over the next 30 years will decrease corn, wheat, sorghum, dry bean, rice, cotton, and
6 peanut yields by 2.5, 4.4, 6.2, 6.8, 8.0, 3.5, and 3.3 percent, respectively, in their regions
7 of production. It is estimated that a 0.8°C temperature rise will increase soybean yield 1.7
8 percent in the Midwest, but decrease yield by 2.4 percent in the South where mean air
9 temperature during reproductive growth is 4°C higher.

10
11 Increases in CO₂ from 380 to 440 ppm will increase corn and sorghum yield 1 percent,
12 whereas the yield of the other C3 crops will increase 6.1 to 7.4 percent. Cotton is more
13 responsive to increased CO₂ than other major C3 crops. Most C3 weeds are also highly
14 responsive to CO₂ and may be more resistant to control by herbicides as CO₂ levels
15 continue to rise. Benefits of CO₂ rise will offset decreases from rising temperature, giving
16 a net yield increase for most C3 crops (average 3.5 percent, range -1.6 to +9.1 percent),
17 but negative responses for corn (-1.5 percent) and sorghum (-5.2 percent).

18
19 As temperature rises and weather variability and drought periods increase, crops will be
20 more frequently exposed to daily maximum temperatures above 33°C, a point at which
21 pollination and grain-set processes in most crops began to fail, and quality of horticultural
22 crops can be negatively affected. Grain yield is reduced as a result of decreased grain-set,
23 and shortened duration of grain fill. Regional climate variability will augment variation in
24 crop production between regions during the growing season.

25
26 Causes for yield decline with rising temperature include decreased grain-set and shorter
27 duration of grain fill, or reduced marketable yield of horticultural crops because of
28 reduced quality. Pollination, grain-set processes, and fruit quality of horticultural crops
29 are affected as daily maximum temperature rises above 33°C, a situation that will occur
30 more frequently during episodes of drought stress and increased weather variability. Crop
31 water use (requirement) will increase 1.2 percent from a 0.8°C temperature rise, and
32 reduced 1.4 to 2.1 percent by the rise in CO₂ from 380 to 440 ppm, giving a net 0.2 to 0.9
33 percent reduction in water requirement for irrigated crops. For rainfed crops, this
34 increment of water conservation would enhance yields an additional 0.2 to 0.9 percent,
35 depending on rainfall variability and rainfall amount.

36
37 Warmer winters could negatively affect the yields of some temperate fruit crops that
38 require an extended “winter chill” period for maximum flowering. Also, more variable
39 winter temperatures can lead to premature leaf-out or bloom and subsequent frost damage
40 in perennial crops.

41
42 Increased winter temperatures will allow increased winter survival and earlier seasonal
43 onset of insect pests in northern regions. Pathogens will likely tend to increase in regions
44 where warmer, wetter summer conditions prevail, and will likely decline in regions that
45 become drier. As climate zones shift, the potential habitable zone of weed, insect, and
46 disease could shift northward.

1 The IPCC forecasts that ozone levels will continue to rise in the rural Midwest by about
2 0.5 ppb per year. This suggests that yields of soybean and other sensitive C3 crops
3 (wheat, oats, French and snap bean, pepper, canola, and various cucurbits) may continue
4 to decline by 1 percent every two to four years. However, this may be partially offset by
5 rising CO₂. C4 crops are, in general, much less sensitive to ozone.

6 In general, pasture species have been less studied than cropland species in terms of their
7 response to climate change variables, including atmospheric CO₂ concentration,
8 temperature, and precipitation. The response of pasturelands to climate change might be
9 complex because, in addition to the main climatic drivers, other plant and management
10 factors might also influence the response (e.g., plant competition, perennial growth
11 habits, seasonal productivity, and plant-animal interactions). C3 pasture species such as
12 Italian ryegrass, orchardgrass, rhizoma peanut, tall fescue, and timothy have exhibited
13 increased photosynthetic rates under elevated CO₂. Other studies suggest that Kentucky
14 bluegrass might be at the lower end of the range in the responsiveness of C3 grasses to
15 elevated CO₂, especially under low nutrient conditions. Perennial ryegrass has shown a
16 positive response in terms of photosynthetic rate but a low or even negative response in
17 terms of plant yield. The C4 pasture species bahiagrass, an important pasture species in
18 Florida, appears marginal in its response to elevated CO₂.

19 Shifts in optimal temperatures for photosynthesis appear very likely under elevated CO₂.
20 Species like perennial ryegrass and tall fescue very likely will show a downward shift in
21 their optimal temperatures for photosynthesis. The literature is sparse on the prediction of
22 yield change of pastureland species under a future temperature increase of 0.8 °C.
23 Increases in increases in temperature and the lengthening of the growing season very
24 likely will extend forage production into late fall and early spring, thereby decreasing the
25 need for accumulation of forage reserves during the winter season.

26 Water availability very likely will play a major role in the response of pasturelands to
27 climate change. Dallisgrass appears to withstand conditions of moisture stress under
28 elevated CO₂ more readily than under ambient conditions. Simulation modeling of the
29 response of alfalfa yields to climate change suggests that future alterations in
30 precipitation will be very important in determining yields. Roughly, for every 4 mm
31 increase in annual precipitation, the models predict a 1 percent increase in dryland alfalfa
32 yields.

33
34 Water availability exerts primary control on productivity and plant species composition
35 of rangelands, each of the global changes, CO₂ enrichment, altered precipitation regimes,
36 and higher temperatures affect plant productivity and species composition by altering the
37 water balance. Plant productivity in most U.S. rangelands has likely increased at least 20
38 percent due to increases in CO₂ from 285 to 380 ppm over the past 200 years, and will
39 continue to increase in the next 30 years when atmospheric CO₂ is predicted to reach 440
40 ppm and average temperatures increase approximately 1 °C. Climate change, particularly
41 rising atmospheric CO₂, has already caused important shifts in species composition of
42 rangelands and may impact forage quality. Warmer temperatures are certain to lengthen
43 growing seasons and affect development rates of individual species, with variable and
44 mostly unpredictable outcomes in regards to the future importance of all species,

1 depending in large part on changes in the synchronization of resource acquisition and
2 reproductive events among species.
3

4 **2.4 Observed Changes and Responses**

5 **2.4.1 Scope of the Agricultural Systems**

6

7 Agriculture is a diverse system that covers a wide range of species and production
8 systems across the United States. The scope of this report covers those species in which
9 information is available from the literature to evaluate observed responses. In the crops
10 section, the focus is on maize (corn), soybean (*Glycine max* (L.) Merr.), wheat (*Triticum*
11 *aestivum* L.), rice (*Oryza sativa* L.), sorghum (*Sorghum bicolor* (L.) Moench.), cotton
12 (*Gossypium hirsutum* L.), peanut (*Arachis hypogea* L.), red kidney bean (*Phaseolus*
13 *vulgaris* var. *vulgaris*), cowpea (*Vigna unguiculata* (L.) Walp.), and tomato
14 (*Lycopersicon esculentum* Mill.). In the pastureland section, 13 species were considered
15 in the analysis. For rangeland, species covered include a complex mixture of grasses and
16 forbs, depending upon the location.
17

18 Animal production systems cover beef, dairy, swine, and poultry as the primary classes of
19 animals. While climate changes affects all of these animals, the literature available
20 predominantly addresses beef, dairy, and swine. Poultry is primarily grown under
21 confined operations, so the effect of climate change more directly affects the energy
22 requirements for building operations compared to a direct effect on the animal. Similar
23 statements can be made for swine production since the vast majority of the production is
24 under confinement. There is an effect of temperature on animals being moved from
25 confinement buildings to processing plants; however, the short-term effects of stress on
26 these animals has not been studied and is not considered a major problem because these
27 animals are being moved quickly from production to processing.

28 **2.4.2 Plant Response to Temperature**

29 **2.4.2.1 General response**

30

31 Crop species differ in their cardinal temperatures (critical temperature range) for life
32 cycle development. There is a base temperature for vegetative development at which
33 growth commences and an optimum temperature at which the plant progresses as fast as
34 possible. Temperatures above the optimum cause the growth rate to slow and finally
35 cease at the maximum temperature. Vegetative development (node and leaf appearance
36 rate) is hastened by increasing temperature up to a species optimum temperature.
37 Vegetative development usually has a higher optimum temperature than does
38 reproductive development (Table 2.3). Progression of a crop through its life cycle
39 (phenological) phases is generally accelerated by increasing temperature up to the
40 species-dependent optimum temperature beyond which development rate slows. Cardinal
41 temperature values for selected annual (non-perennial) crops are presented in Tables 2.3
42 and 2.4 for conditions in which temperature is the only limiting variable.

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Table 2.3. Cardinal base and optimum temperatures

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

Table 2.3. 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, for economically important crops. 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.

¹Kiniry and Bonhomme (1991), Badu-Apraku et al., 1983; 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); ¹²Alocilja and Ritchie (1991); ¹³Baker et al. (1995); ¹⁴Matsushima et al. (1964); ¹⁵Horie et al. (2000); ¹⁶Alagarswamy 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).

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Table 2.4. Temperature thresholds for selected vegetable crops

<u>Climatic Classification</u>	<u>Crop</u>	<u>Acceptable Temp (C) For Germination</u>	<u>Opt Temp (C) For Yield</u>	<u>Acceptable Temp(C) Growth Range</u>	<u>Frost Sensitivity</u>
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	+
	Potato				
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		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	-

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).

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Table 2.5. Winter chill requirement, winter hardiness (minimum winter temperature), and minimum frost-free period

<u>Crop</u>	<u>Winter Chill Requirement (hours) ¹</u>		<u>Minimum Winter Temp (C)</u>	<u>Minimum Frost-Free Period (days)</u>
	<u>Common Varieties</u>	<u>Other</u>		
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

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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).

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Faster development of non-perennial crops is not necessarily ideal because 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 have a significant impact on yield. Temperature affects crop life cycle duration and the fit of given cultivars to production zones. Daylength sensitivity also plays a major role in life cycle progression in many crops,

¹ Winter 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 chilling requirement, and temperatures above 15 °C may even negate previously accumulated chill.

1 especially for soybean. Higher temperatures during the reproductive stage of
2 development affect pollen viability, fertilization, and grain or fruit formation. Chronic
3 exposure to high temperatures during the pollination stage of initial grain or fruit set will
4 reduce yield potential. This stage of development is one of the most critical stages of
5 growth in response to temperatures extremes. Each crop has a specific temperature range
6 for vegetative and reproductive growth to proceed at the optimal rate and exposures to
7 extremely high temperatures during these phases can impact growth and yield; however,
8 acute exposure from extreme events may be most detrimental during the reproductive
9 stages of development.

10
11 For most perennial temperate fruit and nut crops, winter temperatures play a significant
12 role in productivity (Westwood, 1993). There is considerable genotypic variation among
13 fruit and nut crops in their winter hardiness (ability to survive specific low temperature
14 extremes), and variation in their “winter chilling” requirement for optimum flowering and
15 fruit set in the spring and summer (Table 2.5). Marketable yield of horticultural crops is
16 highly sensitive to minor environmental stresses, related to temperatures outside of the
17 optimal range, which negatively affect visual and flavor quality (Peet and Wolfe, 2000).

18 ***2.4.2.2 Temperature effects on crop yield***

19
20 Yield responses to temperature vary among species based on the crop’s cardinal
21 temperature requirements. Plants that have an optimum range at cooler temperatures will
22 exhibit significant decreases in yield as the temperature increases above this range.
23 However, reductions in yield with increasing temperature in field conditions may not be
24 due to temperature alone, as high temperatures are often associated with lack of rainfall
25 in many climates. The interactions of temperature and water deficits negatively affect
26 crop yield.

27 28 ***Maize***

29 Increasing temperature causes maize life cycle and the reproductive phase duration to be
30 shortened, resulting in decreased grain yield (Badu-Apraku et al., 1993; Muchow et al.,
31 1990). In the analyses of Muchow et al. (1990), the highest observed (and simulated)
32 grain yields occurred at locations with relatively cool temperature (growing season mean
33 of 18.0 to 19.8°C at Grand Junction, CO) that allowed long maize life cycle, compared to
34 warmer sites (e.g., 21.5 to 24.0°C in Champaign, IL), or compared to warm tropical sites
35 (26.3 to 28.9°C). For the IL location, simulated yield decreased 5 to 8 percent per 2°C
36 temperature increase. Using this relationship, a temperature rise of 0.8°C over the next 30
37 years in the Midwest may decrease yield by 2 to 3 percent (2.5 percent, Table 6) under
38 irrigated or water-sufficient management. The Muchow et al. (1990) model may
39 underestimate yield reduction with rising temperature because it had no temperature
40 modification on assimilation or respiration, and did not provide for any failures in grain-
41 set with rising temperature. Lobell and Asner (2003) evaluated maize and soybean
42 production relative to climatic variation in the United States, reporting a 17 percent
43 reduction in yield for every 1°C rise in temperature because of the confounding effect
44 with other yield-limiting factors. In a recent evaluation of global maize production
45 response to both temperature and rainfall over the period 1961-2002, Lobell and Field

(2007) reported 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 and 15 days after anthesis of maize. If rainfall was low (zero to 44mm per 8 days), yield was reduced by 1.2 to 3.2 percent per 1°C rise. Alternately, if temperature was warm (Tmax of 35°C), yield was reduced 9 percent per 25.4 mm rainfall decline.

Table 2.6. Percent grain yield response to increased temperature

Crop	Temperature (0.8 °C)	CO ₂ (380 to 440 ppm) ²	Temp/CO ₂ Combined Irrigated	Temp on ET of Rainfed	CO ₂ on ET of Rainfed
			----- % change -----		
Corn -Midwest (22.5°C)	-2.5	+1.0	-1.5	+1.2 ³	
Corn - South (26.7°C)	-2.5	+1.0	-1.5	+1.2 ³	
Soybean – Midwest (22.5°C)	+1.7	+7.4	+9.1	+1.2 ³	-2.1
Soybean – South (26.7°C)	-2.4	+7.4	+5.0	+1.2 ³	-2.1

Table 2.6. Percent grain yield response to increased temperature (0.8 °C), increased CO₂ (380 to 440 ppm), net effect of temperature and increased CO₂ on irrigated yield assuming additivity, and change in ET of rainfed crops with temperature and CO₂. Current mean air temperature during reproductive growth is shown in parentheses for each crop/region to give starting reference, although yield of all the cereal crops declines with a temperature slope that originates below current mean air temperatures during grain filling.

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 placed back in 30°C (Jones et al. 1984). Temperatures above 30°C increasingly damaged 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 with minimal sensitivity of quantum efficiency to elevated temperature (Oberhuber and Edwards, 1993; Edwards and Baker,

² Response to CO₂ increment, with Michaelis-Menten rectangular hyperbola interpolation.

³ Response of ET to temperature increment 1.489 x 0.8°C from Table 6.

1 1993), although photosynthesis rate is reduced above 38°C (Crafts-Brandner and
2 Salvucci, 2002).

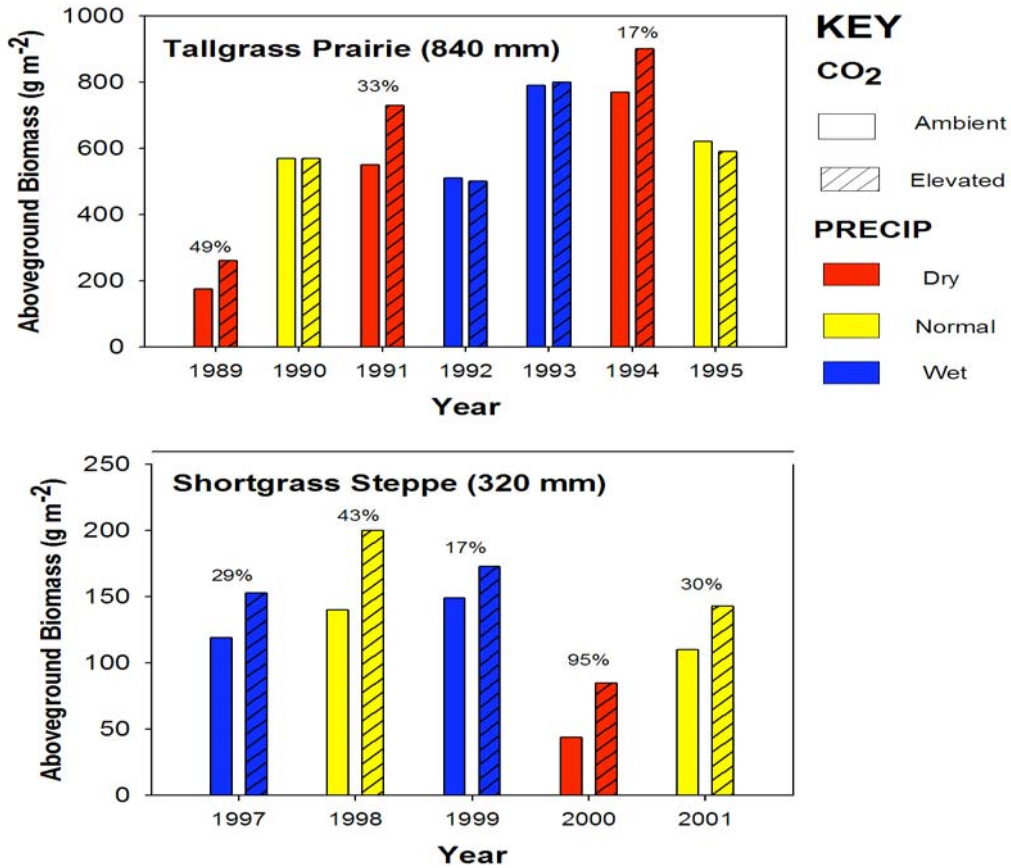
3 *Soybean*

4 Reproductive development (time to anthesis) in soybean has cardinal temperatures that
5 are somewhat lower, a base of 6°C and optimum of 26°C are used in the CROPGRO-
6 soybean model (Boote et al., 1998), based in part on values of 2.5°C and 25.3°C
7 developed by Grimm et al. (1993). The post-anthesis phase for soybean has a surprisingly
8 low optimum temperature of about 23°C and life cycle is slower and longer if mean daily
9 temperature is above 23°C (Pan, 1996; Grimm et al. 1994). This 23°C optimum cardinal
10 temperature for post-anthesis period matches closely to the optimum temperature for
11 single seed growth rate (23.5°C) reported by Egli and Wardlaw (1980), and the 23°C
12 optimum temperature for seed size (Egli and Wardlaw, 1980, Baker et al. 1989; Pan,
13 1996; Thomas, 2001; Boote et al. 2005). As mean temperature increases above 23°C,
14 seed growth rate, seed size, and intensity of partitioning to grain (seed harvest index) in
15 soybean decrease until reaching zero at 39°C mean (Pan, 1996; Thomas, 2001). The
16 CROPGRO-soybean model parameterized with the Egli and Wardlaw (1980) temperature
17 effect on seed growth sink strength and the Grimm et al. (1993, 1994) temperature effect
18 on reproductive development, predicts highest grain yield of soybean at 23-24°C, with
19 progressive decline in yield, seed size, and harvest index as temperature increases further
20 until reaching zero yield at 39°C (Boote et al. 1997, Boote et al. 1998). Soybean yield
21 produced per day of season, when plotted against the mean air temperature at 829 sites
22 over the United States (soybean regional trials, Piper et al. 1998) showed highest
23 productivity at 22°C.

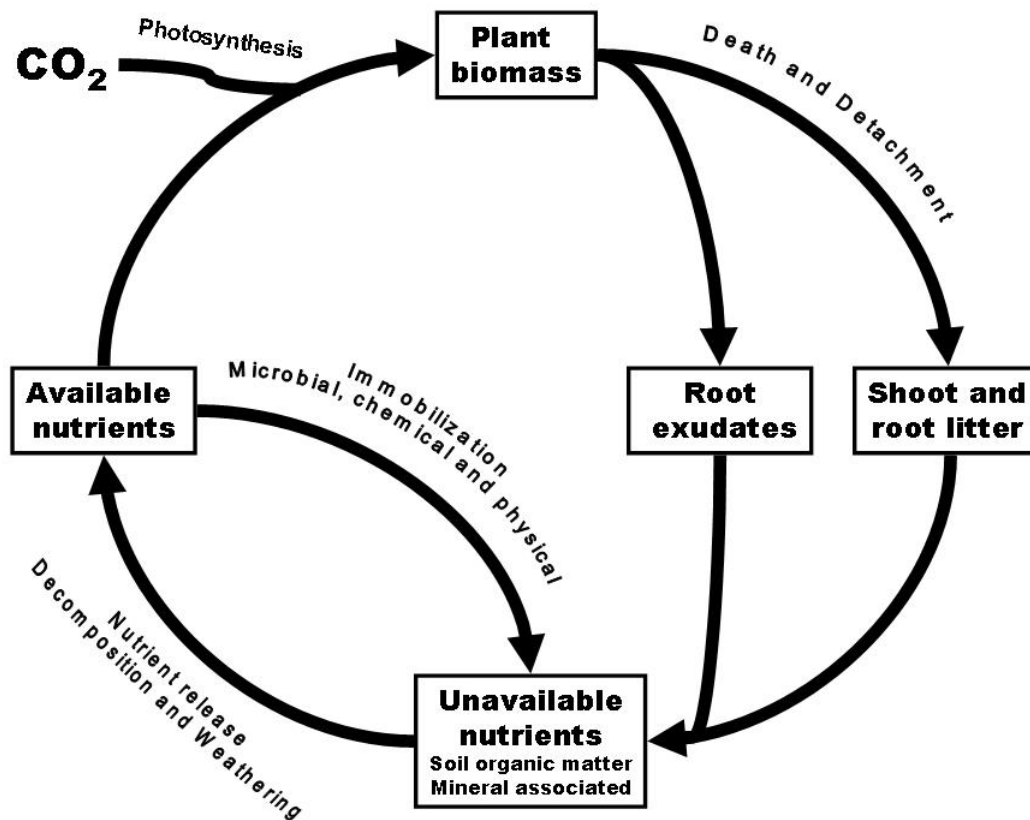
24
25 Pollen viability of soybean is reduced by instantaneous temperatures above 30°C (Topt),
26 but with a long decline slope to failure at 47°C (Salem et al. 2007). Averaged over many
27 cultivars, the cardinal temperatures (base temperature (Tb), optimum temperature (Topt),
28 maximum temperature (Tmax)) were 13.2°C, 30.2°C, and 47.2°C, respectively, for pollen
29 germination and 12.1°C, 36.1°C, and 47.0°C, respectively, for pollen tube growth. Minor
30 cultivar differences in cardinal temperatures and tolerance of elevated temperature were
31 present, but differences were not very large or meaningful. Salem et al. (2007) evaluated
32 soybean grown and assayed at 38/30°C versus 30/22°C (day/night) temperatures. The
33 elevated temperature reduced pollen production 34 percent, pollen germination by 56
34 percent, and pollen tube elongation by 33 percent. The progressive reduction in seed size
35 (single seed growth rate) above 23°C, along with reduction in fertility above 30°C, results
36 in reduction in seed harvest index (HI) at temperatures above 23°C (Baker et al. 1989) or
37 above 27°C, reaching zero HI at 39°C (Pan, 1996, Thomas, 2001, Boote et al. 2005).

38
39 The implication of a temperature change on soybean yield is thus strongly dependent on
40 the prevailing mean temperature during the post-anthesis phase of soybean in different
41 regions. For the upper Midwest, where mean soybean growing season temperatures are
42 about 22.5°C, soybean yield may actually increase (1.7 percent) with a 0.8°C rise (Table
43 6). By contrast, for soybean production in the southern United States where mean
44 growing season temperatures are 25°C to 27°C, the soybean yield would be progressively
45 reduced, 2.4 percent for 0.8°C increase from 26.7°C current mean (Table 2.6). These

1 slopes of soybean yield response to temperature were taken from Figs. 2.10-11 of Boote
 2 et al. (1997) and Figure 2.5 of Boote et al. (1996). Lobell and Field (2007) reported a 1.3
 3 percent decline in soybean yield per 1°C increase in temperature, taken from global
 4 production against global average temperature during July-August, weighted by
 5 production area.
 6



7
 8 **Figure 2.10.** Aboveground plant biomass harvested during summer at the approximately time of peak
 9 seasonal aboveground plant biomass from native Kansas tallgrass prairie (Owensby et al., 1999; 1989-
 10 1995) and Colorado Shortgrass steppe (Morgan et al., 2004a; 1997-2001) grown in similarly-designed Open
 11 Top Chambers maintained at present Ambient (approximately 370 parts per million CO₂ in air; no cross-
 12 hatches) and Elevated (approximately 720 parts per million CO₂ in air; cross-hatches) atmospheric CO₂
 13 concentrations. Histograms from different years are color-coded (red for dry; yellow for normal; blue for wet)
 14 according to the amount of annual precipitation receive that particular year compared to long-term averages
 15 for the two sites, 840 mm for the tallgrass prairie and 320 mm for shortgrass steppe. Where production
 16 increases due to elevated CO₂ were observed, the percentage increased production is given within a year
 17 above the histograms. The involvement of water in the CO₂ responses is seen in two ways; the relative plant
 18 biomass responses occur more commonly and in greater magnitude in the shortgrass steppe than in the
 19 tallgrass prairie, and the relative responses in both systems are greater in dry than wet years.
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4 **Figure 2.11** Nutrient Cycling Feedbacks. While CO₂ enrichment may lead to increased photosynthesis and
5 enhanced plant growth, the long-term response will depend on nutrient cycling feedbacks. Litter from
6 decaying plants and root exudates enters a large soil nutrient pool that is unavailable to plants until they are
7 broken down and released by microbial activity. Soil microbes may also fix available nutrients into new
8 microbial biomass, thereby temporarily immobilizing them. The balance between these and other nutrient
9 release and immobilization processes determines available nutrients and ultimate plant response.

10
11 Source: Figure reprinted with permission from *Science* (Morgan, 2002).

12 **Wheat**

13 Grain-filling period of wheat and other small grains is dramatically shortened with rising
14 temperature (Sofield et al., 1974, 1977; Chowdhury and Wardlaw, 1978; Goudrian and
15 Unsworth, 1990). Sofield et al. (1974, 1977) attributed the shortened grain filling
16 duration to factors other than assimilate limitation (documented by sink removal studies).
17 Assuming no difference in daily photosynthesis, yield will decrease in direct proportion
18 to the shortening of grain filling period as temperature increases. This temperature effect
19 is already a major reason for the much higher wheat yield potential in northern Europe
20 than in the Midwest (even with the water limitation removed).

21
22 The optimum temperature for photosynthesis in wheat is 20-30°C (Kobza and Edwards,
23 1987). This is 10°C higher than the optimum (15°C) for grain yield and single grain
24 growth rate (Chowdhury and Wardlaw, 1978). Any increase of temperature above 25°C
25 to 35°C that are common during grain filling of wheat will reduce wheat yields because

1 of shorter grain filling period. Applying the nonlinear slope of reduction in grain filling
2 period from Chowdhury and Wardlaw (1978) relative to the mean temperatures during
3 grain fill in the wheat growing regions of the Great Plains, the reduction in yield is about
4 7 percent per 1°C increase in air temperature between 18 to 21°C and about 4 percent per
5 1°C increase in air temperature above 21°C, not considering any reduction in
6 photosynthesis or grain-set. Similarly, Lawlor and Mitchell (2000) stated that a 1°C rise
7 would shorten reproductive phase by 6 percent and grain filling duration by 5 percent and
8 reduce grain yield and HI proportionately. Bender et al. (1999) analyzed spring wheat
9 grown at nine sites in Europe and found a 6 percent decrease in yield per 1°C temperature
10 rise. Lobell and Field (2007) reported a 5.4 percent decrease in global mean wheat yield
11 per 1°C increase in temperature. Grain size will also be reduced slightly. Effects of rising
12 temperature on photosynthesis should be viewed as an additional reduction factor on
13 wheat yield, primarily influenced via water deficit effects (Paulsen, 1994). Temperatures
14 of 36/31°C for two to three days prior to anthesis causes small unfertilized kernels with
15 symptoms of parthenocarpy, small shrunken kernels with notching and chalking of
16 kernels (Tashiro and Wardlaw, 1990). Increased temperature reduces starch synthesis in
17 wheat endosperm, caused by decreased starch synthase and ADP glucose
18 pyrophosphorylase enzyme activities (Coley et al. 1990).

19 **Rice**

20 The response of rice to temperature has been well studied (Baker and Allen, 1993a,
21 1993b; Baker et al. 1995; Horie et al. 2000). Leaf-appearance rate of rice increases with
22 temperature from a base of 8°C, until reaching 36-40°C (the thermal threshold of
23 survival) (Alocilja and Ritchie, 1991; Baker et al. 1995), with biomass increasing up to
24 33°C (Matsushima et al. 1964); however, the optimum temperature for grain formation
25 and yield of rice is lower (25°C) (Baker et al. 1995). Baker et al. (1995) summarized
26 many of their experiments from sunlit controlled-environment chambers and concluded
27 the optimum mean temperature for grain formation and grain yield of rice is 25°C and
28 grain yield is reduced about 10 percent per 1°C temperature increase above 25°C until
29 reaching zero yield at 35-36°C mean temperature, using a 7°C day/night temperature
30 differential (Baker and Allen, 1993a; Peng et al. 2004). Grain number, percent filled
31 grains, and grain HI followed nearly the same optimum and failure curve points.
32 Declining yield above 25°C is attributed, initially, to shorter grain filling duration
33 (Chowdhury and Wardlaw, 1978; Snyder, 2000) and then to progressive failure to
34 produce filled grains, the latter caused by pollen viability and reduced production of
35 pollen (Kim et al., 1996; Matsui et al., 1997; Prasad et al. 2006b). Pollen viability and
36 production begins to decline as daytime maximum temperature (Tmax) exceeds 33°C and
37 reaches zero at Tmax of 40°C (Kim et al. 1996). Because flowering occurs at mid-day in
38 rice, the Tmax is the best indicator of heat-stress on spikelet sterility. Grain size of rice
39 tends to hold mostly constant, declining only slowly across increasing temperature, until
40 the pollination failure point (Baker and Allen, 1993a). Rice ecotypes, *japonica* and
41 *indica*, mostly do not differ in the upper temperature threshold (Snyder, 2000; Prasad et
42 al. 2006b), although the *indica* types are more sensitive to cool temperature (night
43 temperature less than 19°C) (Snyder, 2000). Screening of rice genotypes and ecotypes for
44 heat tolerance (33.1/27.3°C versus 28.3/21.3°C mean day/night temperatures) by Prasad
45 et al. (2006b) demonstrated significant genotypic variation in heat tolerance for percent
46

1 filled grains, pollen production, pollen shed, and pollen viability. The most tolerant
2 cultivar had the smallest decreases in spikelet fertility, grain yield and harvest index at
3 elevated temperature. This increment of temperature caused, for the range of 14 cultivars,
4 9 to 86 percent reduction in spikelet fertility, 0 to 93 percent reduction in grain weight per
5 panicle, and 16 to 86 percent reduction in HI. Mean air temperatures during the rice grain
6 filling phase in summer in the southern USA and many tropical regions are about 26-
7 27°C which are above the 25°C optimum, thus illustrating that elevated temperature
8 above current will reduce rice yield in USA and tropical regions, by about 10 percent per
9 1°C rise, or about 8 percent for a 0.8°C rise.

10 ***Sorghum***

11 The base and optimum temperatures for vegetative development are 8°C and 34°C,
12 respectively (Alagarswamy and Ritchie, 1991), while the optimum temperature for
13 reproductive development is 31°C (Prasad et al., 2006a). The optimum temperature for
14 sorghum vegetative growth is 26°C to 34°C, and for reproductive growth is 25°C to 28°C
15 (Maiti, 1996). Maximum dry matter production and grain yield occur at 27/22°C, as
16 opposed to temperatures 3°C or 6°C lower or 3°C or 6°C warmer (Downs, 1972). Grain
17 filling duration is reduced as temperature increases over a wide range (Chowdury and
18 Wardlaw, 1978; Prasad et al., 2006a). Nevertheless, as temperature increased above
19 36/26°C to 40/30°C (diurnal max/min), panicle emergence was delayed by 20 days, and
20 no panicles were formed at 44/34°C (Prasad et al., 2006a). Prasad et al. (2006a) found
21 that grain yield, HI, pollen viability, and percent seed-set were highest at 32/22°C and
22 progressively reduced as temperature increased, falling to zero at 40/30°C. Vegetative
23 biomass was highest at 40/30°C and photosynthesis was high up to 44/34°C. Seed size
24 was reduced above 36/26°C. Rice and sorghum have exactly the same sensitivity of grain
25 yield, seed HI, pollen viability, and success in grain formation (Prasad et al., 2006a). In
26 addition, we suspect that maize, a related warm-season cereal, may have the same
27 temperature sensitivity. Basing the yield response of sorghum only on shortening of
28 filling period (Chowdury and Wardlaw, 1978), yield would decline 7.8 percent per 1°C
29 temperature rise from 18.5°C to 27.5°C (a 6.2 percent yield reduction for 0.8°C increase).
30 However, if site temperature is cooler than optimum for biomass/photosynthesis
31 (27/22°C), then yield loss from shorter filling period would be offset by photosynthesis
32 increase. The response from Chowdury and Wardlaw (1978) is supported by the 8.4
33 percent decrease in global mean sorghum yield per 1°C increase in temperature reported
34 for sorghum by Lobell and Field (2007).
35

36 ***Cotton***

37 Cotton is an important crop in the southern United States, and is considered to have
38 adapted to high temperature environments. Despite this perception, reproductive
39 processes of cotton have been shown to be adversely affected by elevated temperature
40 (Reddy et al., 2000; 2005). Being a tropical crop, cotton's rate of leaf appearance has a
41 relatively high base temperature of 14°C and a relatively high optimum temperature of
42 37°C, thus leaf and vegetative growth appear to tolerate elevated temperature (Reddy et
43 al., 1999, 2005). On the other hand, reproductive progression (emergence to square,
44 square to first flower) has a temperature optimum of 28-30°C, along with a high base
45 temperature of about 14°C (Reddy et al. 1997, 1999). Maximum growth rate per boll

1 occurred at 25-26°C, declining at higher temperatures, while boll harvest index was
2 highest at 28°C, declining at higher temperatures, reaching zero boll harvest index at 33-
3 34°C (Reddy et al. 2005). Boll size was largest at temperatures less than 20°C, declining
4 progressively as temperature increased. Initially there was compensation with increased
5 boll number set as temperature increased up to 35/27°C day/night temperature, but, above
6 30°C mean temperature, percent boll set, boll number, boll filling period, rate of boll
7 growth, boll size, and yield all decreased (Reddy et al. 2005). Instantaneous air
8 temperature above 32°C reduces pollen viability, and temperature above 29°C reduces
9 pollen tube elongation (Kakani et al. 2005), thus acting to progressively reduce successful
10 boll formation to the point of zero boll yield at 40/32°C day/night (35°C mean)
11 temperature (Reddy et al. 1992a, 1992b). These failure point temperatures are below
12 those of soybean and peanut, but similar to those of rice and sorghum. There is not a
13 well-defined cotton-yield response to temperature. A quadratic (parabolic) yield response
14 to temperature from the optimum of 25°C to the failure temperature of 35°C was
15 developed, where a 0.8°C increase from 26.7 to 27.5°C would decrease yield by 3.5
16 percent.

17 *Peanut*

18 Peanut is an important crop in the southern United States. The base temperature for
19 peanut-leaf-appearance rate and onset of anthesis are 10°C and 11°C, respectively (Ong,
20 1986). The optimum temperature for leaf appearance rate is above 30°C, while the
21 optimum for rate of vegetative development to anthesis is 29-33°C (Bolhuis and deGroot,
22 1959). Leaf photosynthesis has a fairly high temperature optimum of about 36°C. Cox
23 (1979) observed that 24°C was the optimum temperature for single pod growth rate and
24 pod size, with slower growth rate and smaller pod size at higher temperature. Williams et
25 al. (1975) evaluated temperature effects on peanut by varying elevation and found that
26 peanut yield was highest at a mean temperature of 20°C (27/15°C max/min), a
27 temperature that contributed to a long life cycle and long reproductive period. Prasad et
28 al. (2003) conducted studies in sunlit, controlled-environment chambers, and reported
29 that the optimum mean temperature for pod yield, seed yield, pod harvest index, and seed
30 size occurred at a temperature lower than 26°C; quadratic projections to peak and
31 minimum suggested that the optimum temperature was 23 to 24°C, with a failure point
32 temperature of 40°C for zero yield and zero HI. Pollen viability and percent seed-set in
33 that study began to fail at about 31°C, reaching zero at about 39 to 40°C (44/34°C
34 treatment) (Prasad et al., 2003). For each individual flower, the period sensitive to
35 elevated temperature starts six days prior to opening of a given flower and ends one day
36 after, with greatest sensitivity on the day of flower opening (Prasad et al., 1999; Prasad et
37 al., 2001). Percent fruit-set is first reduced at bud temperature of 33°C, declining linearly
38 to zero fruit-set at 43°C bud temperature (Prasad et al., 2001). Genotypic differences in
39 heat-tolerance of peanut (pollen viability) have been reported (Craufurd et al., 2003). As
40 air temperature in the southern United States already averages 26.7°C during the peanut
41 growing season, any temperature increase will reduce seed yields (4.1 percent per 1°C, or
42 3.3 percent for a 0.8°C rise in range of 26-27°C) using the relationship of Prasad et al.
43 (2003). At higher temperatures, 27.5 to 31°C, peanut yield declines more rapidly (6.9
44 percent per 1°C) based on unpublished data of Boote. A recent trend in peanut production

1 since the collapse of the quota system, has been the move of production from south Texas
2 to west Texas, a cooler location with higher yield potential.

3 *Dry Bean and Cowpea*

4 Red kidney bean is typical of many vegetable crops and is grown in relatively cool
5 regions of the United States. Prasad et al. (2002) found that red kidney bean was quite
6 sensitive to elevated temperature, having highest seed yield at 28/18°C (23°C mean) or
7 lower (lower temperatures were not tested), with linear decline to zero yield as
8 temperature increased to 37/27°C (32°C mean). In that study, pollen production per
9 flower was reduced above 31/21°C, pollen viability was dramatically reduced above
10 34/24°C, and seed size was decreased above 31/21°C. Laing et al. (1984) found highest
11 bean yield at 24°C, with a steep decline at higher temperatures. Gross and Kigel (1994)
12 reported reduced fruit-set when flower buds were exposed to 32/27°C during the six to 12
13 days prior to anthesis and at anthesis, caused by non-viable pollen, failure of anther
14 dehiscence, and reduced pollen tube growth. Heat-induced decreases in seed and fruit set
15 in cowpea have been associated with formation of non-viable pollen (Hall, 1992). Hall
16 (1992) reported genetic differences in heat tolerance of cowpea lines. Screening for
17 temperature-tolerance within bean cultivars has not been done explicitly, but the
18 Mesoamerican lines are more tolerant of warm tropical locations than are the Andean
19 lines, which include the red kidney bean type (Sexton et al., 1994). Taking the initial
20 slope of decline from data of Prasad et al. (2002), bean yield is projected to decrease 7.2
21 percent per 1°C temperature rise, or 5.8 percent for 0.8°C above 23°C.

22 *Tomato*

23 Tomato is an important vegetable crop known to suffer heat stress in mid-summer in
24 southern U.S. locations. The base and optimum temperature is 7° and 22°C for rate of leaf
25 appearance, rate of truss appearance, and rate of progress to anthesis (Adams et al.,
26 2001). Leaf photosynthesis of tomato has a base at 6-8°C (Duchowski and Brazaityte,
27 2001), while its optimum is about 30°C (Bunce, 2000). The rate of fruit development and
28 maturation has a base temperature of 5.7°C and optimum of 26°C and rate of individual
29 fruit growth has its optimum at 22 to 25°C (Adams et al. 2001). Largest fruit size occurs
30 at 17-18°C, and declines at progressively higher temperature (Adams et al. 2001, De
31 Koning, 1996). Rate of fruit addition (fruit-set, from pollination) has an optimum at or
32 lower than 26°C and progressively fails as temperature reaches 32°C (Adams et al.,
33 2001). Peat et al. (1998) observed that number of fruits per plant (or percent fruit-set) at
34 32/26°C day/night (29°C mean) was only 10 percent of that at 28/22°C (25°C mean). The
35 projected failure temperature was about 30°C. Sato et al. (2000) found that only one of
36 five cultivars of tomato successfully set any fruit at chronic exposures to 32/26°C,
37 although fruit-set recovered if the stressful temperature was relieved. Sato et al. (2000)
38 highlighted that pollen release and pollen germination were critical factors affected by
39 heat stress. The anticipated temperature effect on tomato production will depend on the
40 region of production and time of sowing (in the southern United States); however, at
41 optima of 22°C for leaf/truss development, 22-26°C for fruit addition, 22-25°C for fruit
42 growth, and fruit-set failures above 26°C, temperatures exceeding 25°C will reduce
43 tomato production. Depending on region of production, tomato yield is projected to
44 decrease 7.6 percent for 0.8°C rise above 25°C, assuming a parabolic yield response and

1 assuming optimum temperature and failure temperatures for yield of 23.5 and 30°C,
2 respectively.

4 ***Pasturelands***

5 In general, grassland species have received less attention than cropland species in terms
6 of their response to projected changes in temperature, precipitation and atmospheric CO₂
7 concentration associated with climate change (Newman et al. 2001). The response of
8 pasturelands to climate change is complex because, in addition to the major climatic
9 drivers (CO₂ concentration, temperature, and precipitation), other plant and management
10 factors will affect this response (e.g., plant competition, perennial growth habits, seasonal
11 productivity, etc.). Many of the studies presented below, which report on how temperate-
12 climate pasture respond to changes in temperature, precipitation and CO₂ concentrations,
13 originate from regions outside the United States.

15 ***Rangelands***

16 Although responses can be vary considerably among species, in general warming should
17 accelerate plant metabolism and developmental processes, leading to earlier onset of
18 spring green-up, and lengthening of the growing season in rangelands (Badeck et al.
19 2004). The effects of warming are also likely to be seen as changes in the timing of
20 phenological events such as flowering and fruiting. For instance, experimental soil
21 warming of approximately 2°C in a tallgrass prairie (Wan et al. 2005) extended the
22 growing season by three weeks, and shifted timing and duration of reproductive events
23 variably among species; spring blooming species flowered earlier, late blooming species
24 flowered later (Sherry et al. 2007). Extensions and contractions in lengths of the
25 reproductive periods were also observed among the species tested (see also Cleland et al.
26 2006). Different species responses to warming suggest strong selection pressure for
27 altering future rangeland community structure, and for the associated trophic levels that
28 depend on the plants for important stages of their life cycles. Warming also caused both
29 extensions and contractions of the length of the reproductive periods of the study species,
30 which could represent a strong selection pressure on these species and for future
31 community structure of these species and their close associates. Cleland et al. (2006)
32 found similar results in a California grassland, where warming accelerated flowering by
33 two to five days. Periods of drought stress may suppress warming-induced plant activity
34 (Gielen et al. 2005), thereby effectively decreasing plant development time.

36 Like CO₂ enrichment, increasing ambient air and soil temperatures may enhance
37 rangeland NPP, although negative effects of higher temperatures also are possible,
38 especially in dry and hot regions. Temperature directly affects plant physiological
39 processes, but rising ambient temperatures may indirectly affect plant production by
40 extending the length of the growing season, increasing soil nitrogen (N) mineralization
41 and availability, altering soil water content, and shifting plant species composition and
42 community structure (Wan et al. 2005). Rates of biological processes for a given species
43 typically peak at plant temperatures that are intermediate in the range over which a
44 species is active, so direct effects of warming likely will vary within and among years
45 and among plant species. Because of severe cold-temperature restrictions on growth rate
46 and duration, warmer plant temperatures alone should stimulate production in high- and

1 mid-latitude and high-altitude rangelands. Conversely, increasing plant temperature
2 during summer months may reduce NPP. Increasing daily minimum air temperature and
3 mean soil temperature (2.5 cm depth) by 2°C increased aboveground NPP of tallgrass
4 prairie in Oklahoma between zero percent and 19 percent during the first three years of
5 study, largely by increasing NPP of C4 grasses (Wan et al. 2005). Warming stimulated
6 biomass production in spring and autumn, but aboveground biomass in summer declined
7 as soil temperature increased.

8
9 Positive effects of warming on production may be lessened by an accompanying increase
10 in the rate of water loss. Warming reduced the annual mean of soil water content in
11 tallgrass prairie during one year (Wan et al. 2005), but actually increased soil water
12 content in California annual grassland by accelerating plant senescence (Zavaleta et al.
13 2003b).

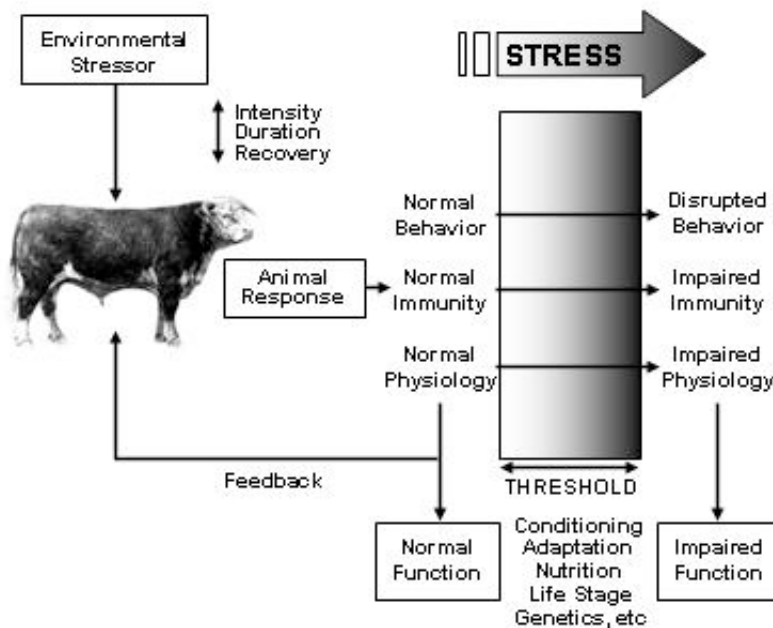
14 **2.4.3 Temperature Response of Animals**

15 *2.4.3.1 Thermal stress*

16
17 The optimal zone (thermoneutral zone) for livestock production is a range of
18 temperatures and other environmental conditions for which the animal does not need to
19 significantly alter behavior or physiological functions to maintain a relatively constant
20 core body temperature. As environmental conditions result in core body temperature
21 approaching and/or moving outside normal diurnal boundaries, the animal must begin to
22 conserve or dissipate heat to maintain homeostasis. This is accomplished through shifts in
23 short-term and long-term behavioral, physiological, and metabolic thermoregulatory
24 processes (Mader et al. 1997b and Davis et al. 2003). The onset of a thermal challenge
25 often results in declines in physical activity and an associated decline in eating and
26 grazing (for ruminants and other herbivores) activity. Hormonal changes, triggered by
27 environmental stress, results in shifts in cardiac output, blood flow to extremities, and
28 passage rate of digesta. Adverse environmental stress can elicit a panting or shivering
29 response, which increases maintenance requirements of the animal and contributes to
30 decreases in productivity. Depending on the domestic species of livestock, longer term
31 adaptive responses include hair coat gain or loss through growth and shedding processes,
32 respectively. In addition, heat stress is directly related to respiration and sweating rate in
33 most domestic animals (Gaughan et al. 1999, 2000, and 2005). Production losses in
34 domestic animals are largely attributed to increases in maintenance requirement
35 associated with maintaining a constant body temperature, and altered feed intake (Mader
36 et al. 2002; Davis et al. 2003; Mader and Davis, 2004). As a survival mechanism,
37 voluntary feed intake (VFI) increases (after a one to two day decline) under cold stress
38 and decreases almost immediately under heat stress (NRC, 1987). Depending on the
39 intensity and duration of the environmental stress, VFI can average as much as 30 percent
40 above normal to as much as 50 percent below normal.

41
42 Domestic livestock are remarkable in their adaptive ability. They can mobilize coping
43 mechanisms when challenged by environmental stressors. However, not all coping
44 capabilities are mobilized at the same time. As a general model for mammals of all
45 species, respiration rate (RR) serves as an early warning of increasing thermal stress, and

1 increases markedly above a threshold as animals try to maintain homeothermy by
 2 dissipating excess heat. At a higher threshold, body temperature (BT) begins to increase
 3 as a result of the animal's inability to adequately dissipate the excess heat load by
 4 increased respiratory vaporization (Brown-Brandl et al. 2003; Davis et al., 2003; Mader
 5 and Kreikemeier, 2006). There is a concomitant decrease in VFI as BT increases, which
 6 ultimately results in reduced performance (production, reproduction), health and well-
 7 being if adverse conditions persist (Hahn et al. 1992; Mader, 2003). Thresholds are
 8 species dependent, and affected by many factors, as noted in Figure 2.7. For shaded *Bos*
 9 *taurus* feeder cattle, Hahn (1999) reported RR as related to air temperature typically
 10 shows increases above a threshold of about 21°C, with the threshold for increasing BT
 11 and decreasing VFI being about 25°C. Recent studies (Brown-Brandl, et al. 2005) clearly
 12 show the influence of animal condition, genotype, respiratory pneumonia, and
 13 temperament on RR of *Bos taurus* heifers.
 14



15

Figure 2.7. Response model for farm animals with thermal environmental challenges (Hahn, 1999).

16

17

18 There is also a time-dependency aspect of responses. For cattle, RR lags behind changes
 19 in ambient temperature, with the highest correlations obtained for a lag of two hours
 20 between RR and ambient temperature. There is also a time delay in acute BT responses
 21 (during the first three to four days of exposure) to a heat challenge, with an increasing
 22 mean and amplitude, along with a phase shift reflecting entrainment by the ambient
 23 conditions (Hahn and Mader, 1997; Hahn, 1999). Even though VFI reduction usually
 24 occurs on the first day of hot conditions, the endogenous metabolic heat load from
 25 existing rumen contents adds to the increased exogenous environmental heat load.
 26 Nighttime recovery also has been shown to be an essential element of survival when
 27 severe heat challenges occur (Hahn and Mader, 1997; Amundson et al. 2006). After three
 28 days, the animal enters the chronic response stage, with mean body temperature declining

1 slightly and VFI reduced in line with heat dissipation capabilities. Diurnal body
 2 temperature amplitude and phase remain altered. These typical thermoregulatory
 3 responses, when left unchecked during a severe heat wave with excessive heat loads, can
 4 lead to a pathological state resulting in impaired performance or death (Hahn and Mader,
 5 1997; Mader, 2003).
 6

7 **2.4.3.2 Methods to identify environmentally stressed animals**
 8

9 Temperature provides a measure of the sensible heat content of air, and represents a
 10 major portion of the driving force for heat exchange between the environment and an
 11 animal. However, latent heat content of the air, as represented by some measure of the
 12 insensible heat content (e.g., dewpoint temperature), thermal radiation (short- and long-
 13 wave), and airflow also impact the total heat exchange. Because of the limitations of air
 14 temperature alone as a measure of the thermal environment, there have been many efforts
 15 to combine the effects of two or more thermal measures representing the influence of
 16 sensible and latent heat exchanges between the organism and its environment. It is
 17 important to recognize that all such efforts produce index values, rather than a true
 18 temperature (even when expressed on a temperature scale). As such, an index value
 19 represents the effect produced by the heat exchange process, which can alter the
 20 biological response that might be associated with changes in temperature alone. In the
 21 case of humans, the useful effect is the sensation of comfort; for animals, the useful effect
 22 is the impact on performance, health, and well-being.
 23
 24
 25

Table 2.7 Heat wave categories

5. severe	very persistent (usually 6-8 days)	40-80/day	3-15/day on 3 or more successive days	very limited: 0-2hr per night
6. extreme Category	very persistent (usually 6-10 ⁺ days)	50-100/day	15-30/day on 3 successive days	nil:#1 for 3 or more successive days
	<u>duration</u>	<u>THI*-hrs</u> ≥79 ⁴	<u>THI-hrs</u> ≥84 ⁴	<u>nighttime recovery</u> (hrs # 72 THI ⁴)
1. slight	limited: 3-4 days	10-25/day	none	good: 5-10hr/night
2. mild	limited: 3-4 days	18-40/day	#5/day	some: 3-8hr/night
3. moderate	more persistent (4-6 days usual)	25-50/day	#6/day	reduced: 1-6hr/night
4. strong	increased persistence (5-7 days)	33-65/day	#6/day	limited: 0-4hr/night
5. severe	very persistent (usually 6-8 days)	40-80/day	3-15/day on 3 or more	very limited: 0-2hr per night

1
2 **Table 2.7** Heat wave categories for *Bos taurus* feedlot cattle exposed to single heat wave events ([Hahn et](#)
3 [al., 1999](#)).⁵ *Temperature Humidity Index (THI).

4
5 Contrary to the focus of human-oriented thermal indices on comfort, the primary
6 emphasis for domestic animals has been on indices to support rational environmental
7 management decisions related to performance, health, and well-being. Hahn and Mader
8 (1997), Hahn et al. (1999), and Hahn et al. (2001) have used retrospective climatological
9 analyses to evaluate the characteristics of prior heat waves causing extensive livestock
10 losses. Although limited by lack of inclusion of wind speed and thermal radiation effects,
11 the Temperature-Humidity Index (THI⁶) has been a particularly useful tool for profiling
12 and classifying heat wave events (Hahn and Mader, 1997, Hahn et al. 1999). In
13 connection with extreme conditions associated with heat waves, the THI has recently
14 been used to evaluate spatial and temporal aspects of their development (Hubbard et al.,
15 1999; Hahn and Mader, 1997). For cattle in feedlots, a THI-based classification scheme
16 has also been developed to assess the potential impact of heat waves (Hahn et al. 1999).
17 The classifications are based on a retrospective analysis of heat waves that have resulted
18 in extensive feedlot cattle deaths, using a THI-hours approach to assess the magnitude
19 (intensity x duration) of the heat wave events which put the animals at risk (Table 2.7).
20 When calculated hourly from records of temperature and humidity, it can be used to
21 compute cumulative daily THI-hrs⁷ at or above the Livestock Weather Safety Index
22 (LWSI) thresholds for the Danger and Emergency categories. The THI-hrs provide a
23 measure of the magnitude of daytime heat load (intensity and duration), while the number
24 of hours below THI thresholds of 74 and 72 indicate the opportunity for nighttime
25 recovery from daytime heat.

26
27 As applied to *Bos taurus* feedlot cattle during the 1995 Nebraska-Iowa (USA), single heat
28 wave event, evaluation of records for several weather stations in the region using the
29 THI-hrs approach reinforced the LWSI thresholds for the Danger and Emergency
30 categories of risk and possible death (Hahn and Mader, 1997). Based on that event,
31 analysis indicated that 15-20 or more THI-hrs per day above a THI base level of 84 for
32 three or more successive days were lethal for vulnerable animals (especially those
33 recently placed in the feedlot, nearing market weight, or sick). The extreme daytime heat
34 in 1995 was exacerbated by limited nighttime relief (only a few hrs with $THI \leq 74$), high
35 solar radiation loads (clear to mostly clear skies), and low to moderate wind speeds in the
36 area of highest risk. For cattle in other locations with 20 or more daily THI-hrs in the
37 Emergency category ($THI \geq 84$) for only one or two days, the heat load was apparently
38 dissipated with minimal or no mortality, although these environmental conditions can
39 markedly depress voluntary feed intake (Hahn, 1999; NRC, 1981) with resultant reduced
40 performance. A similar analysis of an August 1992 single heat wave event further
41 confirmed that 15 or more THI-hrs above a base level of 84 can cause death of vulnerable
42 animals (Hahn et al. 1999). A contributing factor to losses during that event was lack of
43 acclimation to hot weather, as the summer had been relatively cool; in this area, only four
44 years from 1887-1998 had fewer days during the summer when air temperature was \geq
45 32.2°C (High Plains Regional Climate Center, 2000; www.hprcc.unl.edu).

46

1 Modifications to the THI have been proposed to overcome shortcomings related to
 2 airflow and radiation heat loads. Based on recent research, Mader et al. (2006) and
 3 Eigenberg et al. (2005) have proposed corrections to the THI for use with feedlot cattle,
 4 based on measures of windspeed (WS) and solar radiation (SRAD). For a range of
 5 conditions from 25-40°C and 30-50 percent relative humidity (RH), the THI adjustments
 6 as evaluated by Mader et al. (2006) were +0.7 for an increase in SRAD of 100 W/m², and
 7 -2.0 for a WS increase of 1m/s, based on panting scores of observed animals.
 8 Comparatively, the equivalent THI adjustments for the same increases in SRAD and WS,
 9 as determined by Eigenberg et al. (2002) from observations of respiration rate (RR), were
 10 +0.53 and -0.14, respectively, for the same range of conditions. While the proposed
 11 adjustment factor differences are substantial, there were marked differences in the types
 12 and number of animals used in the two studies. Nevertheless, the approach appears to
 13 merit further research to establish acceptable THI corrections, perhaps for a variety of
 14 animal parameters.

15
 16 By using body temperatures, a similar approach was developed to derive an Apparent
 17 Equivalent Temperature (AET) from air temperature and vapor pressure to develop
 18 “thermal comfort zones” for transport of broiler chickens (Mitchell et al. 2001).
 19 Experimental studies to link the AET with increased body temperature during exposure to
 20 hot conditions indicated potential for improved transport practices.

21
 22 Gaughan et al. (2002) developed a Heat Load Index (HLI) as a guide to management of
 23 unshaded *Bos taurus* feedlot cattle during hot weather (>28°C). The HLI was developed
 24 following observation of behavioral responses (respiration rate and panting score) and
 25 changes in dry-matter intake during prevailing thermal conditions. The HLI is based on
 26 humidity, windspeed, and predicted black globe temperature.

27
 28 As a result of its demonstrated broad success, the THI is currently the most widely-
 29 accepted thermal index used for guidance of strategic and tactical decisions in animal
 30 management during moderate to hot conditions. Biologic response functions, when
 31 combined with likelihood of occurrence of the THI for specific locations, provide the
 32 basis for economic evaluation to make cost-benefit comparisons for rational strategic
 33 decisions among alternatives (Hahn, 1981). Developing climatology of summer weather
 34 extremes (in particular, heat waves) for specific locations also provides the livestock
 35 manager with information about how often those extremes (with possible associated
 36 death losses) might occur (Hahn et al. 2001). The THI has also served well for making
 37 tactical decisions about when to apply available practices and techniques (e.g.,
 38 sprinkling) during either normal weather variability or weather extremes, such as heat
 39 waves. Other approaches, such as the Apparent Equivalent Temperature proposed by
 40 Mitchell et al. (2001) for use in poultry transport, also may be appropriate. An enthalpy-
 41 based alternative thermal index has been suggested by Moura et al. (1997) for swine and
 42 poultry.

Table 2.8 Panting scores

Score	Description
1	Elevated respiration
2	Moderate panting and/or presence of drool or a small amount of
0	Normal 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**

1
2
3 **Table 2.8** Panting scores assigned to steers (Mader et al., 2006).

4 Panting score is one observation method used to monitor heat stress in cattle (Table 2.8).
5 As the temperature increases, cattle pant more to increase evaporative cooling.
6 Respiration dynamics change as ambient conditions change, and surroundings surfaces
7 warm. This is a relatively easy method for assessing genotype differences and
8 determining breed acclimatization rates to higher temperatures. In addition, shivering
9 score or indices also have potential for use as thermal indicators of cold stress. However,
10 recent data were not found regarding cold stress indicators for domestic livestock.

11 **2.4.4 Crop Responses to CO₂**

12 **2.4.4.1 Crop Responses**

13
14 Reviews of the early enclosure CO₂ studies indicate that average yield increase over
15 many C3 crops with doubling of CO₂ is 33 percent (Kimball, 1983), at a time when
16 doubling meant increase from 330 to 660 vpm CO₂. The general phenomenon was
17 expressed as increased number of tillers-branches, panicles-pods, and numbers of seeds,
18 with minimal effect on seed size. The C4 species response to doubling of CO₂ was
19 reported by Kimball (1983) to be 10 percent. High temperature stress during reproductive

Crop	Leaf Photosynthesis	Total Biomass	Grain Yield	Stomatal conductance	Canopy T, ET
	----- % change -----				
Corn	3 ^{1*}	4 ^{1, 2, 3, 4}	4 ^{1, 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
Sorghum	9 ^{20, 21*}	3 ^{22*}	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		

20
21 **Table 2.9** Percent response of leaf photosynthesis, total biomass, grain yield, stomatal conductance, and
22 canopy T or ET, to a doubling in CO₂ concentration (usually 350 to 700 ppm, but sometimes 330 to 660
23 ppm). *Responses to increase from ambient to 550 or 570 ppm (FACE) are separately noted.⁸

1
2 development can negate CO₂ beneficial effects on yield even though total biomass
3 accumulation maintains a CO₂ benefit (e.g., for *Phaseolus* bean, Jifon and Wolfe 2000).
4 Unrestricted root growth, optimum fertility, and excellent control of weeds, insects, and
5 disease are also required to maximize CO₂ benefits (Wolfe 1994). Most C3 weeds benefit
6 more than C3 crop species from elevated CO₂ (Ziska 2003).
7

8 In recent years, new field “free-air CO₂ enrichment” (FACE) technology has allowed the
9 evaluation of a few selected crops for their response under field conditions without
10 enclosure-confounding effects. In some cases the results corroborate previous enclosure
11 studies, while results in other cases suggest yield responses are less than previously
12 reported. Although the continuously increasing “ambient” reference concentration is a
13 cause for lesser response, the smaller increment of CO₂ enrichment requires even better
14 replication and sampling in FACE to evaluate the response. Enclosures are not the only
15 concern; single spaced plants or unbordered plants may respond too much, and potted
16 plants that are root bound may not respond well. Additional research, data analysis, and
17 evaluation of a broader range of crops using FACE techniques will be required to sort
18 discrepancies where they exist.
19

20 Effects of doubling of CO₂ on leaf photosynthesis, total biomass, grain or fruit yield,
21 conductance, and canopy T or ET of important non-water-stressed crops are shown in
22 [Table 2.9](#). The CO₂ responses of many species are given in the review paper by Kimball
23 et al. (2002), in addition to specific references cited below.
24

25 Maize, being a C4 species, is less responsive to increased atmospheric CO₂. Single leaf
26 photosynthesis of maize shows no effect of CO₂ on quantum efficiency, but there is a
27 minor increase in leaf rate at light-saturation (3percent for 376 to 542 ppm, Leakey et al.,
28 2006). There is a paucity of data for maize grown to maturity under elevated CO₂
29 conditions. Until 2006, there was only one data set for maize grown to maturity under
30 CO₂ treatments conducted: King and Greer (1986) observed 6.2 percent and 2.6 percent
31 responses to increasing CO₂ from 355 to 625 and 875 vpm, respectively, in a 111-day
32 study. The mean of the two levels gives about 4.4 percent increase to doubling or more of
33 CO₂. Recently, Leakey et al. (2006) conducted a full season study of maize grown to
34 maturity in Free Air CO₂ Enrichment (FACE) and reported no significant response of
35 maize to a 50 percent increase in CO₂ (376 to 542 ppm [target: 370 to 550] ppm. The
36 small biomass sample size used in that FACE study (4 random plant samples per
37 replicate) and the small increment of CO₂ causes concern about whether these
38 experimental measurements were sufficient to detect a statistically significant response,
39 considering the small plot sample size and that a 2-3 percent increase is all that is
40 expected for increase in CO₂ from 370 to 550 ppm. The grain yield response was a non-
41 significant (1 percent). Also, Ziska and Bunce (1997) reported 2.9 percent biomass
42 increase to CO₂ increase from 371 to 674 ppm for a 33-day study in glasshouse and
43 Maroco et al. (1999) reported a 19.4 percent biomass increase to CO₂ increase from 350
44 to 1100 ppm during a 30-day growth period at very high light (supplemented above
45 outdoor

1 ambient) for a short duration study on young plants. Thus, we conclude that maize
2 biomass increase should be about 4 percent (mean of 2 x 0.0, 6.2, 2.6, 2.9, and half of
3 19.4) and grain yield increase should also be about 4 percent (mean of 2 x 1.0, 6.2, and
4 2.6) to increasing CO₂ from 350 to 700 ppm. This is less than the simulated 10 percent
5 increase for C4 species to CO₂ increment from 330 to 660 ppm as parameterized in the
6 CERES-Maize or EPIC models based on sparse data (Tubiello et al., 2007). In summary,
7 the evidence for maize response to CO₂ is sparse and questionable. The expected
8 increment of CO₂ increase over the next 30 years is anticipated to have a negligible effect
9 (1.0 percent, Table 2.10) on maize production, unless there is a water-savings effect in
10 drought years.

11 **Table 2.10 Percent grain yield response to increased temperature**

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13
14
15
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17
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20
21
22
23
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

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Panting score is one observation method used to monitor heat stress in cattle (Table 2.8).
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 26 replication and sampling in FACE to evaluate the response. Enclosures are not the only
 27 concern; single spaced plants or unbordered plants may respond too much, and potted
 28 plants that are root bound may not respond well. Additional research, data analysis, and

1 evaluation of a broader range of crops using FACE techniques will be required to sort
 2 discrepancies where they exist.

3
 4 Effects of doubling of CO₂ on leaf photosynthesis, total biomass, grain or fruit yield,
 5 conductance, and canopy T or ET of important non-water-stressed crops are shown in
 6 **Table 2.9**. The CO₂ responses of many species are given in the review paper by Kimball
 7 et al. (2002), in addition to specific references cited below.

8
 9 Maize, being a C₄ species, is less responsive to increased atmospheric CO₂. Single leaf
 10 photosynthesis of maize shows no effect of CO₂ on quantum efficiency, but there is a
 11 minor increase in leaf rate at light-saturation (3percent for 376 to 542 ppm, Leakey et al.,
 12 2006). There is a paucity of data for maize grown to maturity under elevated CO₂
 13 conditions. Until 2006, there was only one data set for maize grown to maturity under
 14 CO₂ treatments conducted: King and Greer (1986) observed 6.2 percent and 2.6 percent
 15 responses to increasing CO₂ from 355 to 625 and 875 vpm, respectively, in a 111-day
 16 study. The mean of the two levels gives about 4.4 percent increase to doubling or more of
 17 CO₂. Recently, Leakey et al. (2006) conducted a full season study of maize grown to
 18 maturity in Free Air CO₂ Enrichment (FACE) and reported no significant response of
 19 maize to a 50 percent increase in CO₂ (376 to 542 ppm [target: 370 to 550] ppm. The
 20 small biomass sample size used in that FACE study (4 random plant samples per
 21 replicate) and the small increment of CO₂ causes concern about whether these
 22 experimental measurements were sufficient to detect a statistically significant response,
 23 considering the small plot sample size and that a 2-3 percent increase is all that is
 24 expected for increase in CO₂ from 370 to 550 ppm. The grain yield response was a non-
 25 significant (1 percent). Also, Ziska and Bunce (1997) reported 2.9 percent biomass
 26 increase to CO₂ increase from 371 to 674 ppm for a 33-day study in glasshouse and
 27 Maroco et al. (1999) reported a 19.4 percent biomass increase to CO₂ increase from 350
 28 to 1100 ppm during a 30-day growth period at very high light (supplemented above
 29 outdoor
 30 ambient) for a short duration study on young plants. Thus, we conclude that maize
 31 biomass increase should be about 4 percent (mean of 2 x 0.0, 6.2, 2.6, 2.9, and half of
 32 19.4) and grain yield increase should also be about 4 percent (mean of 2 x 1.0, 6.2, and
 33 2.6) to increasing CO₂ from 350 to 700 ppm. This is less than the simulated 10 percent
 34 increase for C₄ species to CO₂ increment from 330 to 660 ppm as parameterized in the
 35 CERES-Maize or EPIC models based on sparse data (Tubiello et al., 2007). In summary,
 36 the evidence for maize response to CO₂ is sparse and questionable. The expected
 37 increment of CO₂ increase over the next 30 years is anticipated to have a negligible effect
 38 (1.0 percent, **Table 2.10**) on maize production, unless there is a water-savings effect in
 39 drought years.

40
 41 **Table 2.10 Percent grain yield response to increased temperature**

42

Crop	Temperature (0.8 °C)	CO ₂ (380 to 440 ppm) ⁹	Temp/CO ₂ Combined Irrigated	Temp on ET of Rainfed	CO ₂ on ET of Rainfed
			% change		
Corn -Midwest	-2.5	+1.0	-1.5	+1.2 ¹¹¹⁰	

(22.5°C)					
Corn - South	-2.5	+1.0	-1.5	+1.2 ¹⁰	
(26.7°C)					
Soybean – Midwest	+1.7	+7.4	+9.1	+1.2 ¹⁰	-2.1
(22.5°C)					
Soybean – South	-2.4	+7.4	+5.0	+1.2 ¹⁰	-2.1
(26.7°C)					
Wheat – Plains	-4.4	+6.8	+2.4	+1.2 ¹⁰	-1.4
(19.5°C)					
Rice – South	-8.0	+6.4	-1.6	+1.2	-1.7
(26.7°C)					
Sorghum	-6.2	+1.0	-5.2	+1.2 ²	-3.9
(full range)					
Cotton – South	-3.5	+9.2	+5.7	+1.2 ²	-1.4
(26.7°C)					
Peanut – South	-3.3	+6.7	+3.4	+1.2 ²	
(26.7°C)					
Bean – relative to	-5.8	+6.1	+0.3	+1.2 ²	
23°C					

Table 2.10 Percent grain yield response to increased temperature (0.8 °C), increased CO₂ (380 to 440 ppm), net effect of temperature and increased CO₂ on irrigated yield assuming additivity, and change in ET of rainfed crops with temperature and CO₂. Current mean air temperature during reproductive growth is shown in parentheses for each crop/region to give starting reference, although yield of all the cereal crops declines with a temperature slope that originates below current mean air temperatures during grain filling.

What are the responses of other important C4 field crop species to doubled CO₂?

Sorghum gave a 9, 34, and 8 percent increases in leaf photosynthesis, biomass, and grain yield with doubling of CO₂ when grown in 1 by 2 m land area sunlit controlled-environment chambers (Prasad et al. 2005a). A CO₂ increase from 368 to 561 ppm for full season on sorghum in FACE studies 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 from 330 to 660 ppm (or 350 to 700 ppm, the authors did not specify range for the doubling) is about 39 percent for light-saturated leaf photosynthesis, 37 percent for biomass accumulation, and 38 percent for grain yield (taking values only for soybean grown in large $\geq 1\text{m}^2$ land area crop stands 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 increase in CO₂ from 330 to 660 ppm. Ainsworth et al. (2002) summarized that leaf conductance was reduced 40 percent (consistent with other C3 and C4 species, Morison, 1987), and seed harvest index was reduced by nine percent. The C3 photosynthetic response to CO₂ enrichment is well-documented and is generally easy to predict using either the Farquhar and von Cammerer (1982) equations or simplifications based on those equations. The leaf photosynthesis equations in the CROPGRO-soybean model (Boote et al. 1998) are based on Farquhar

1 kinetics equations (Boote and Pickering, 1994), and were found by Alagarswamy et al.
2 (2006) to predict single-leaf response to CO₂ with as good of accuracy as the Farquhar
3 equations.

4
5 The CROPGRO-soybean model predicts 29 to 41 percent increase in biomass and 29 to
6 34 percent increase in grain yield with increase in CO₂ from 350 to 700 ppm (Boote et al.
7 1997), values that are comparable to metadata summarized by Ainsworth et al. (2002)
8 and by Allen and Boote (2000). Future projections of response to incremental CO₂
9 increase must consider present day levels as a starting point because the response is
10 asymptotically saturating. In fact, some of the increased yield of crops like soybean
11 currently attributed to technological innovation over the past four to five decades is in
12 fact attributable to the rise in CO₂. Simulations by Boote et al. (2003) suggested that
13 soybean yield in Iowa would have increased 9.1 percent over the period 1958 to 2000,
14 during which time the CO₂ increased from 315 to 370 ppm. Concurrently, the crop ET
15 was predicted to decrease 1.5 percent and water use efficiency (WUE) (on grain basis)
16 increased 10.7 percent, using a version of the model that lacked direct stomatal coupling.
17 Using a model with direct stomatal feedback may have given greater increase in WUE.
18 Using a Michaelis-Menten rectangular hyperbola projection, a CO₂ increase from 380 to
19 440 ppm, is projected to increase in yield by 7.4 percent (Table 2.10) for the dominant
20 soybean growing regions of the Midwestern United States. For the same regions, the
21 expected temperatures are so close to the optimum for soybean yield, and the temperature
22 increment so small (0.8°C) that the net effect of climate change on soybean yield is
23 dominated by the CO₂ increment. To the extent that water-use efficiency increases with
24 CO₂ enrichment and conserves soil water, yield response for rainfed regions will be
25 enhanced by the “net” effect on ET (+1.2 – 2.1 = 0.9 percent increase)

26
27 Other C3 field crop species exhibit similar responses to increasing CO₂. For wheat, a
28 cool-season cereal, doubling of CO₂ (350 to 700 ppm) increased light-saturated leaf
29 photosynthesis by 30-40 percent (Long, 1991) and grain yield by about 31 percent,
30 averaged over many data sets (Amthor, 2001). For rice, doubling CO₂ (330 to 660 ppm)
31 increased canopy assimilation, biomass, and grain yield by about 36, 30, and 30 percent,
32 respectively (Horie et al. 2000). Baker and Allen (1993a) reported 31 percent increase in
33 grain yield, averaged over five experiments, with increase of CO₂ from 330 to 660 ppm.
34 Rice shows photosynthetic acclimation associated with decline in leaf N concentration
35 and a six to 22 percent reduction in leaf rubisco content per unit leaf area (Vu et al.
36 1998). For peanut, a warm-season grain legume, doubling CO₂ increased light-saturated
37 leaf photosynthesis, total biomass and pod yield of peanut by 27, 36 and 30 percent,
38 respectively (Prasad et al. 2003). Doubling CO₂ (350 to 700 ppm) increased light-
39 saturated leaf photosynthesis, biomass, and seed yield of dry bean by 50, 30, and 27
40 percent (Prasad et al., 2002). For cotton, a warm-season non-legume, doubling CO₂ (350
41 to 700 ppm) increased light-saturated leaf photosynthesis, total biomass, and boll yield by
42 33 percent, 36 percent, and 44 percent (K. R. Reddy et al. 1995, 1997), and decreased
43 stomatal conductance by 36 percent (V. R. Reddy et al. 1995). Under well-watered
44 conditions, leaf and canopy photosynthesis of cotton increased about 27 percent with CO₂
45 enrichment, to 550 ppm CO₂ in a FACE experiment in Arizona (Hileman et al. 1994).
46 Mauney et al. (1994) reported 37 percent and 40 percent increases in biomass and boll

1 yield of cotton with CO₂ enrichment to 550 ppm. Even larger increases in yield and
2 biomass of cotton were obtained under the same enrichment for cotton under water-
3 deficit situations (Kimball and Mauney, 1993). An important consideration relative to
4 cotton responses in Arizona is that the large VPD may have given more benefit to
5 elevated CO₂ via water conservation effects. So, the degree of responsiveness in arid
6 region studies may differ from that in humid regions. There were no reported effects of
7 doubled CO₂ on vegetative or reproductive growth stage progression in cotton (Reddy et
8 al. 2005), soybean (Allen and Boote, 2000; Pan, 1996), dry bean (Prasad et al. 2002), and
9 peanut (Prasad et al. 2003).

10 *Interactions of CO₂ increase with temperature increase*

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

19
20 There are no reported beneficial interactions on grain yield caused by CO₂ increase with
21 temperature increase. Main effects of CO₂ are present, and main effects of temperature
22 are present, but no beneficial interactions have been reported for rice (Baker and Allen,
23 1993a, 1993b; Baker et al. 1995; Snyder, 2000), wheat (Mitchell et al. 1993), soybean
24 (Baker et al. 1989; Pan, 1994), dry bean (Prasad et al. 2002), peanut (Prasad et al. 2003),
25 and sorghum (Prasad et al. 2005a). By contrast, there are three reported negative
26 interactions of elevated CO₂ with temperature on fertility (percent seed-set), where
27 elevated CO₂ causes greater sensitivity of fertility (seed-set) to temperature in rice (Kim
28 et al. 1996; Matsui et al. 1997), sorghum (Prasad et al. 2006a), and dry bean (Prasad et al.
29 2002). For rice, the relative enhancement in grain yield with doubled CO₂ decreases and
30 actually goes negative as Tmax increases in the range 32 to 40°C (Kim et al. 1996).
31 Likewise, while the interaction was not significant, the relative CO₂ enhancement of
32 grain yield of soybean (Baker et al. 1989) became less as temperature increased from
33 optimum to super-optimum. In the rice, sorghum, and dry bean cases, failure point
34 temperature for complete reproductive failure is about 1-2°C lower at elevated CO₂ than
35 at ambient. The cause is likely the degree to which the elevated CO₂ causes warming of
36 the foliage, which is typically this order of magnitude (doubled CO₂ canopies of dry bean
37 were 1.5°C warmer, Prasad et al. 2002; doubled CO₂ canopies of soybean were 1-2°C
38 warmer, Allen et al. 2003; doubled CO₂ canopies of sorghum averaged 2°C warmer
39 during daytime period, Prasad et al. 2006a). The higher canopy temperature of rice,
40 sorghum, and dry bean adversely affected fertility and grain-set. Increases in canopy
41 temperature for wheat, rice, sorghum, cotton, poplar, potato, and soybean have been
42 reported in FACE experiments (see figure in Kimball and Bernacchi, 2006).

43
44 In cotton, there was progressively greater photosynthesis and vegetative growth response
45 to CO₂ as temperature increased up to 34°C (V. R. Reddy, 1995), but this response did

1 not carry over to reproductive growth (K. R. Reddy et al. 1995). The reproductive
2 enhancement from doubled CO₂ was largest (45 percent) at the 27°C optimum
3 temperature for boll yield, and there was no beneficial interaction of increased CO₂ on
4 reproductive growth at elevated temperature, reaching zero boll yield at 35°C (K. R.
5 Reddy et al. 1995).

6
7 Mitchell et al. (1993) conducted field studies of wheat grown at ambient and +4°C
8 temperature differential and at elevated versus ambient CO₂ in England. While there were
9 no interactions of CO₂ and temperature on yield, high temperature reduced grain yield at
10 both CO₂ levels such that yields were significantly greater at ambient CO₂ and ambient
11 temperature compared to elevated CO₂ and high temperature. Batts et al. (1997) similarly
12 reported no beneficial interactions of CO₂ and temperature on wheat yield.

13
14 In studies with bean (Jifon and Wolfe, 2005) and potato (Peet and Wolfe, 2000), there
15 was no significant beneficial effect of CO₂ on yield in high temperature treatments that
16 negatively affected reproductive development, although the beneficial effect on
17 vegetative biomass was maintained. These results suggest that in those regions and for
18 those crops where climate change impairs crop reproductive development because of an
19 increase in the frequency of high temperature stress events, the potential beneficial
20 effects of elevated CO₂ on yield may not be fully realized.

21
22 For peanut, there was no interaction of elevated temperature with CO₂ increase, as the
23 extent of temperature-induced decrease in pollination, seed-set, pod yield, seed yield, and
24 seed HI was the same at ambient and elevated CO₂ levels (Prasad et al. 2003). For red
25 kidney bean, Prasad et al. (2002) found no beneficial interaction of elevated temperature
26 with CO₂ increase, as the temperature-induced decrease in pollination, seed-set, pod
27 yield, seed yield, and seed HI was the same or even greater at elevated than at ambient
28 CO₂ levels. The temperature-sensitivity of fertility (grain-set) and yield for sorghum was
29 significantly greater at elevated CO₂ than at ambient CO₂ (Prasad et al., 2006a), thus
30 showing a negative interaction with temperature, associated with fertility and grain-set,
31 but not on photosynthesis.

32 **2.4.4.2 Interactions of CO₂ increase with N fertility**

33

34 For non-legumes like rice, there is clear evidence of an interaction of CO₂ enrichment
35 with N fertility regime. For *japonica* rice, Nakagawa et al. (1994) reported 17, 26, and 30
36 percent responses of biomass to CO₂ enrichment, at N applications of 40, 120, and 200 kg
37 N ha⁻¹, respectively. For *indica* rice, 0, 29, and 39 percent responses of biomass to CO₂
38 enrichment were reported at N applications of 0, 90, and 200 kg N ha⁻¹, respectively
39 (Ziska et al. 1996). For C4 bahiagrass (*Paspalum notatum* L.), Newman et al. (2006)
40 observed no biomass response to doubled CO₂ at low N fertilization rate, but observed
41 seven to 17 percent increases with doubled CO₂ when fertilized with 320 kg N ha⁻¹.
42 Biomass production in that study was determined over four harvests in each of two years
43 (the seven percent response in year one was non-significant, but 17 percent response in
44 year two was significant).

45

1 **2.4.5 Effects of CO₂ Increase on Water Use and Water Use Efficiency**

2 **2.4.5.1 Changes in crop water use due to increasing temperature, CO₂, and O₃**

3

4 Crop water use (i.e. ET) of crop plants is a physical process but mediated by crop
5 physiological and morphological characteristics (e.g., Kimball, 2007). It can be described
6 by the Penman-Monteith equation, whose form was recently standardized (Allen et al.,
7 2005). The equation reveals several mechanisms by which the climate change parameters
8 – temperature, CO₂, and O₃ – can affect water use. These include: (1) direct effects on
9 crop growth and leaf area, (2) alterations in leaf stomatal aperture and consequently their
10 conductance for water vapor loss, and (3) physical changes in the vapor pressure inside
11 leaves.

12

13 When plants are young and widely spaced, increases in leaf area are approximately
14 proportional to the increases in growth, and transpiration increases accordingly.
15 However, as plants shift from vegetative to reproductive growth during their life cycle,
16 proportionately more of the accumulating biomass is partitioned to other organs, such as
17 developing grain. At this point, leaf area and biomass accumulation are no longer
18 proportional. Also, as plants grow, the mutual shading and interference among the leaves
19 within a plant canopy also causes changes in plant transpiration to asymptotically plateau
20 with leaf area index and less coupled to changes in leaf area index (Ritchie, 1972;
21 Villalobos and Fereres, 1990; Sau et al. 2004). Further, considering that a doubling of
22 CO₂ from present-day levels is likely to increase average C3 species growth on the order
23 of 30 percent (e.g. Kimball, 1983, 2007; Kimball et al. 2002, refer back to particular
24 previous section), so projecting out to 2030 with a CO₂ concentration of about 440 ppm
25 suggests increases in C3 plant growth only on the order of 10 percent. Therefore, because
26 changes in growth affect ET mostly only while plants are small after planting and
27 progressively less after canopy closure, the changes in ET rates by 2030 due to leaf area
28 index effects are likely to be minor.

29

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

35

	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

1 Elevated CO₂ causes partial stomatal closure, which decreases their conductance for the
2 loss of water vapor from leaves to the atmosphere. Reviews of the effects of elevated CO₂
3 on stomatal conductance from chamber-based studies have reported that, on average, a
4 doubling of CO₂ reduces stomatal conductance about 34 percent (e.g., Kimball and Idso,
5 1983). Morison (1987) calculated an average reduction of about 40 percent with no
6 difference between C3 and C4 species. More recently, Wand et al. (1999) performed a
7 meta-analysis on observations reported for wild C3 and C4 grass species, and found that
8 with no stresses, elevated CO₂ reduced stomatal conductance by 39 and 29 percent for C3
9 and C4 species, respectively. Ainsworth et al. (2002) found an average reduction of about
10 40 percent in conductance of soybean for a wide range of CO₂ concentrations, with the
11 reduction for a doubling being about 30 percent. A meta-analysis by Ainsworth and Long
12 (2005) of data generated by free-air CO₂ enrichment experiments for which the daytime
13 CO₂

14
15 **Table 2.11** Sensitivity of evapotranspiration (ET; percent change in ET per EC change in temperature or
16 percent change in ET per percent change in variable other than temperature) to changes in weather and
17 plant variables as calculated by Kimball (2007) from the proposed ASCE standardized hourly reference
18 equation for alfalfa (Allen *et al.*, 2005). The weather data were from the AZMET network (Brown, 1987) for
19 Maricopa, AZ, for a clear summer day (21 June 2000) or for the whole 2000 year. Calculations were done
20 hourly and then summed for the clear summer day or whole year.

21
22 concentrations were 550-600 ppm produced an average reduction in stomatal
23 conductance of 20 percent. They did not detect any significant difference between C3 and
24 C4 species. Projecting out 30 years, the atmospheric CO₂ concentration likely will be
25 about 440 ppm (IPCC, 2001). Interpolating from these reviews, it appears likely that an
26 increase in CO₂ concentration from 380 to 440 ppm will cause reductions on the order 10
27 percent in stomatal conductance compared to today's values.

28
29 The water conserving response to high CO₂ at the leaf scale (i.e., conductance change) is
30 modulated by processes at the whole-plant and/or ecosystem scales (e.g., high CO₂ can

1 cause an increase in total leaf (transpirational surface) area). As a result, ET and soil
2 water use are generally less affected by high CO₂ than is conductance at the leaf scale
3 (Field et al. 1995). An increase in ET at elevated compared to current ambient CO₂,
4 although not commonly observed, sometimes occurs (e.g., Hui et al. 2001).

5
6 Less research has been done on the effects of elevated O₃ on stomatal conductance
7 compared to elevated CO₂, but some pertinent work has been published. Barnes et al.
8 (1995) and Balaguer et al. (1995) measured stomatal conductance of wheat exposed to
9 700 μmol mol⁻¹ CO₂, about 75 nmol mol⁻¹ O₃, and CO₂+O₃ in controlled-environment
10 chambers. The ozone treatment reduced conductance by about 20 percent, while both
11 CO₂ and CO₂+O₃ reduced it by 40 percent. Wheat was exposed by Donnelly et al. (2000)
12 to 680 μmol mol⁻¹ CO₂, 50 or 90 nmol mol⁻¹ O₃, and CO₂+O₃ in open-top chambers, and
13 they found all three treatments produced reductions in stomatal conductance of about 50
14 percent with relative order changing with days after sowing and year. Using open-top
15 chambers with potato, both Lawson et al. (2002) and Finnan et al. (2002) report stomatal
16 conductance is reduced about 50 percent by 680 μmol mol⁻¹ CO₂ and a similar amount in
17 combination with elevated O₃, but their results are variable and mutually inconsistent
18 among treatments. In a FACE project with both CO₂ and O₃ treatments, Noormets et al.
19 (2001) measured stomatal conductance of aspen leaves. Their results varied with leaf age
20 and aspen clone, but generally it appears that the conductance had the following
21 treatment rank: Control>O₃>CO₂+O₃>CO₂. Morgan et al. (2003) performed a meta-
22 analysis of 53 prior chamber studies in which O₃ was elevated by 70 ppm above clean air,
23 and they found that stomatal conductance was reduced by 17 percent on average.
24 However, in a recent FACE experiment on soybean in which O₃ was elevated by 50
25 percent above ambient conditions, Bernacchi et al. (2007) detected no significant effect
26 of O₃ on stomatal conductance. Thus, while chamber studies comparing the effects of O₃
27 on stomatal conductance showed that reductions can occur, in the case of field-grown
28 plants exposed to present-day ambient levels of O₃ that are considerably above zero, the
29 effects on conductance of the additional increases in O₃ levels that are likely to occur by
30 2030 will probably be rather small.

31
32 The water vapor pressure (e; kPa) inside leaves is tightly coupled to leaf temperature (T;
33 °C) and can be calculated from the exponential Tetten's equation, $e = 0.61078 \cdot \exp$
34 $(17.269 \cdot T / (T + 237.3))$. Therefore, anything that affects the energy balance and
35 temperature of a crop's leaf canopy will affect the water vapor pressure inside the leaves
36 and ultimately its water consumption. Consequently, increases in air temperature, will
37 thereby likely also increase crop canopy temperature, leaf water vapor pressure, and ET.

38
39 Allen et al. (2005) published a standard version of the Penman-Monteith equation for
40 calculating ET based on short grass or 50-cm-tall alfalfa as reference crops. Focusing on
41 alfalfa for the reference crop, the sensitivity of the equation to individual weather and
42 plant parameters was tested using hourly weather data for the year 2000 from the
43 AZMET station (Brown, 1987) at Maricopa, AZ (33.05 EN latitude, 112.00 EW
44 longitude, 358 m elevation) (Kimball, 2007). The sensitivity results are presented in
45 [Table 2.11](#) adapted from Kimball (2007). Annual reference ET changes about 3.4 percent
46 per EC change in temperature assuming all the other variables, including absolute

1 humidity remain constant. However, with global warming, precipitation is also predicted
2 to increase on average worldwide (IPCC, 2001), although with much uncertainty
3 especially with regard to individual localities. Therefore, it is more likely that relative
4 humidity will remain more constant than will absolute humidity (e.g., Amthor, 1999).
5 When temperature increases but relative humidity is constant, annual ET increases less,
6 about 2.1 percent/EC. If absolute vapor pressure were to change alone, such as with a
7 changing precipitation pattern, then ET would be expected to change -0.2 percent per
8 percent increase in absolute humidity. Although there is no specific mention of projected
9 changes in solar radiation in the IPCC report (IPCC, 2001), projected increases in
10 average global rainfall would seem to imply some increases in cloudiness and consequent
11 decreases in the amount of solar radiation impinging on future crops. If such changes in
12 radiation were to occur, the sensitivity of reference ET is 0.6 and 0.4 percent per percent
13 change in radiation for a clear day and for a whole year, respectively, at Maricopa, AZ.
14 Likewise for wind speed, although projected changes are not mentioned (IPCC, 2001), if
15 they were to occur, ET likely would change about 0.3 and 0.4 percent per percent change
16 in wind speed for a clear day and for a whole year, respectively, at Maricopa, AZ.
17 Stomatal conductance and leaf area have the same relative effect on ET, increasing ET by
18 0.09 and 0.16 percent for a clear summer day and whole year, respectively.

19
20 Reiterating the projections for the next 30 years, average global temperature is likely to
21 have increased by about 0.8 °C (at constant relative humidity) and atmospheric CO₂
22 concentration to about 440 ppm, the latter of which will cause stomatal conductance to
23 decrease about 10 percent. Using the sensitivities in Table 5, ET for an alfalfa reference
24 crop at Maricopa, AZ, can be expected to increase about 1.9 percent and 2.7 percent for a
25 clear summer day and a whole year, respectively. At the same time, a decrease in
26 stomatal conductance of about 10 percent due to elevated CO₂ concentrations of about
27 440 ppm will likely decrease ET by about 0.9 and 1.6 percent respectively. The two
28 effects are about the same size and in opposite directions, so the net changes in ET are
29 likely to be minimal.

30
31 Elevated CO₂ concentrations at about 550 ppm in FACE experiments have reduced water
32 use in FACE experimental plots by about two to 13 percent depending on species (Figure
33 2.8). Interpolating linearly to 440 ppm of CO₂, the corresponding reductions likely would
34 be about one-third of those observed in the FACE experiments (i.e., one to four percent).
35 Because there are fetch considerations in extrapolating FACE plot data to larger areas
36 (see discussion in Triggs et al., 2004), the reductions in crop water requirements due to
37 elevated CO₂ likely will be significant but smaller yet.

38
39 Another aspect to consider is the dynamics of crop water use and the timing of
40 rain/irrigation events. The latent energy associated with ET from soybean is 10 to 60
41 W/m² less in the FACE plots compared to the control plots at ambient CO₂ when the
42 crop had ample water (Figure 2.9 adapted from Bernacchi et al. 2007).

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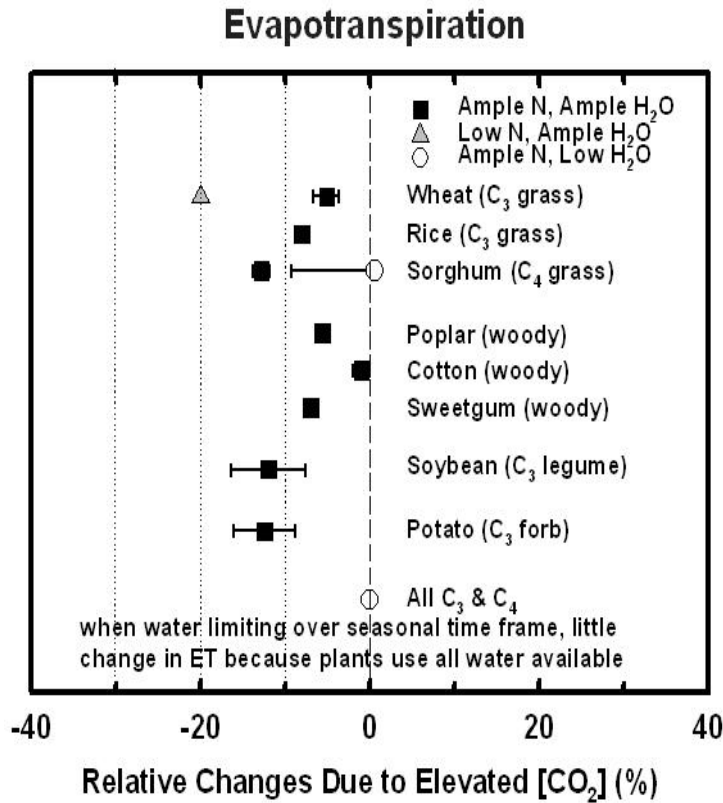


Figure 2.8. Relative changes in evapotranspiration due to elevated CO₂ concentrations in FACE experiments at about 550 ppm. [Wheat and cotton data from Table 2 of Kimball et al. (2002); rice datum from Yoshimoto et al. (2005); sorghum datum from Triggs et al. (2004); poplar datum from Tommasi et al. (2002); sweetgum from Wullschleger and Norby (2001); soybean datum from Bernacchi et al. (2007); and potato datum from Magliulo et al. (2003)].

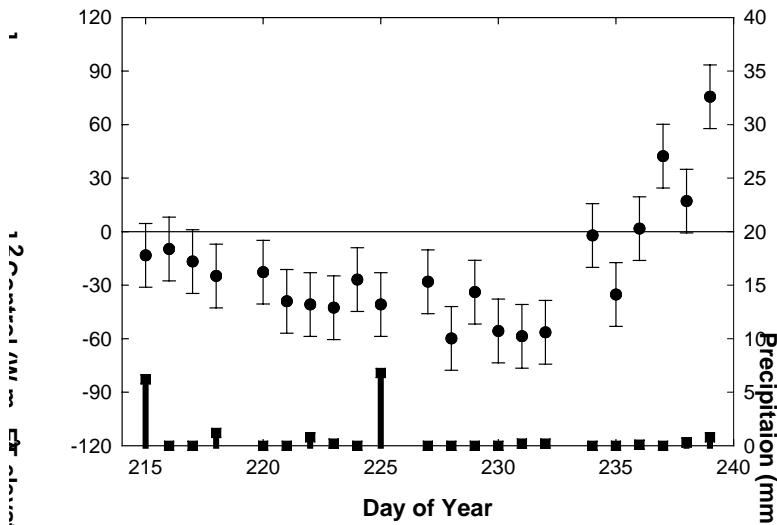


Figure 2.9 Differences in evapotranspiration rate (latent energy, $W m^{-2}$) between soybean plots enriched to 550 ppm from free-air CO_2 enrichment (FACE) and plots at today's ambient CO_2 levels at Urbana, IL, versus day of year (circles, left axis). Corresponding precipitation is also shown (squares, right axis). Adapted from Figure 2.7 of Bernacchi et al.,

However, on about Day-of-Year (DOY) 233, the control plots had exhausted their water supply, and their water use declined. In contrast, the water conservation in the elevated- CO_2 plots enabled them 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, when the FACE had their stomata open while those of the control plots were closed, the FACE plots were able to continue photosynthesizing and growing while the controls were not. In other words, under-rain-fed agriculture, which often experiences periods of drought, elevated concentrations of CO_2 can enable some conservation of soil water, which will sustain crop productivity more days than if it were at today's CO_2 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 from general circulation models (GCMs) and estimates of decreased stomatal conductance due to elevated CO_2 (e.g., Allen et al. 1991; Izaurrealde et al. 2003). The estimate by Izaurrealde et al. (2003) is a comprehensive assessment of climate change impacts on agricultural production and water resources of the conterminous United States. They used a crop growth model (EPIC) 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 CO_2 concentration (28 percent reduction corresponding to $560 \mu mol CO_2 mol^{-1}$), as well as increasing photosynthesis via improved radiation use efficiency. For climate change projections, they used scenarios generated for 2030 (and 2095, but these are not presented here) by the Hadley Centre (HadCM2J) GCM, which was selected because its climate sensitivity is in the midrange of most of the GCMs and radiatively active gas emission scenarios. For corn, Izaurrealde

1 et al. (2003) calculated that by 2030 irrigation requirements will change from -1 (Lower
2 Colorado Basin) to +451 percent (Lower Mississippi Basin). Given the variation in the
3 sizes and baseline irrigation requirements of the basins, a representative figure for the
4 overall U.S. increase is 64 percent if stomatal effects are ignored, or 35 percent if they are
5 included. They made similar calculations for alfalfa whose overall irrigation requirements
6 are predicted to increase 50 and 29 percent in the next 30 years for the cases of ignoring
7 and including stomatal effects, respectively.

8
9 The prior sections have suggested that increasing temperatures are likely to increase ET.
10 At the same time, increasing CO₂ will decrease stomatal conductance, which will
11 decrease ET by about same amount that temperature would increase it, resulting in little
12 net effect. In contrast to this expectation, continental river runoff records around the
13 globe have increased through the 20th century (Gedney et al. 2006). Gedney et al. (2006)
14 examined several climatic forcing factors, and they concluded that the increase in
15 streamflow is mostly likely due to elevated CO₂, causing partial stomatal closure and
16 consequent reductions in ET.

17
18 Pan evaporation rates have declined in the United States and elsewhere, which some
19 thought must imply that actual ET rates must be increasing (e.g., Hobbins et al. 2004), in
20 contrast to the continental streamflow data. To explain the mechanisms causing the
21 observed trend in pan evaporation, Hobbins et al. (2004) plotted trends in mean annual
22 solar radiation, illustrating declines across almost all of the United States. They also
23 plotted trends in vapor pressure deficit, finding declines in the Eastern United States, but
24 heterogeneity in the West. They also estimated ET from several river basins across the
25 country as precipitation minus streamflow. These data indicated that about half these U.S.
26 basins had increasing ET rates, and the other half had declining ET rates. However, the
27 combined solar, vapor pressure deficit, and actual ET estimates confirmed that declines in
28 pan evaporation were a manifestation of the complementarity between potential and
29 actual ET.

30
31 While the main foci are on the increasing CO₂ concentration and increasing temperatures
32 associated with global warming, at the same time other variables that affect ET and
33 consequently plant water relations are also changing and will impact crop production and
34 quality.

35 ***2.4.5.2 Implications for irrigation and water deficit***

36
37 Stomatal conductance is reduced about 40 percent for doubling of CO₂ for both C3 and
38 C4 species (Morison, 1987), thus causing water conservation effects and potentially less
39 water deficit. However, the actual reduction in crop transpiration and ET will not be as
40 much as the reduction in stomatal conductance because warming of the foliage to solve
41 the energy balance will increase both latent heat loss (transpiration) and sensible heat
42 loss. Allen et al. (2003) concluded that both increased foliage temperature (solving the
43 energy balance) and increased LAI associated with CO₂ enrichment, were responsible for
44 the compensatory effects on ET (small to non-existent reductions). Jones et al. (1985)
45 reported 12 percent reduction in season-long transpiration and 51 percent increase in

1 WUE measured for canopies of soybean crops grown in ambient and doubled CO₂ in
2 sunlit, controlled-environment chambers. In experimental studies in the same chambers,
3 foliage temperatures measured by infrared sensors have typically been increased 1 to 2°C
4 (soybean) 1.5°C (dry bean) and 2°C (sorghum) in response to doubled CO₂ (Pan, 1996;
5 Prasad et al., 2002; Prasad et al., 2006a). Allen et al. (2003) reported that soybean foliage
6 at doubled CO₂ averaged 1.3°C warmer at mid-day. Andre and du Cloux (1993) reported
7 8 percent decrease in transpiration of wheat in response to doubled CO₂, which compares
8 well to a 5 percent reduction in ET of wheat for a 200 ppm CO₂ increase in FACE studies
9 (Hunsaker et al., 1997). Reddy et al. (2000, Figure 2.?), using similar chambers, found an
10 8 percent reduction in transpiration of cotton canopies at doubled CO₂ averaged over five
11 temperature treatments, while Kimball et al. (1983) found a 4 percent reduction in
12 seasonal water use of cotton at ambient versus 650 ppm CO₂ in lysimeter experiments in
13 Arizona. Soybean canopies grown at 550 compared to 375 ppm in FACE experiments in
14 Illinois, had 9 to 16 percent decreases in ET depending on season (Bernacchi et al. 2007).
15 The slope in Bernacchi Figure 2.4 (p. 4?) shows a 12 percent reduction over three years.
16 Allen et al. (2003) observed 9 percent reduction in ET of soybean with doubling of CO₂
17 in the sunlit, controlled-environment chambers for a 28/18°C treatment (about the same
18 mean temperature as the Illinois site), but they observed no reduction in ET for a high
19 temperature treatment 40/30°C. The extent of CO₂-related reduction in ET appears to be
20 dependent on temperature. In their review, Horie et al. (2000) reported the same
21 phenomenon in rice, where doubling CO₂ caused 15 percent reduction in ET at 26°C, but
22 resulted in increased ET at higher temperature (29.5°C). At 24-26°C, WUE of rice was
23 increased by 50 percent with doubled CO₂, but the CO₂ enrichment effect declined as
24 temperature increased. At higher temperature, the CO₂-induced reduction in conductance
25 was less.

26
27 Using observed sensitivity of soybean stomatal conductance to CO₂ in a crop climate
28 model, Allen (1990) showed that CO₂ enrichment from 330 to 800 ppm should cause an
29 increase in foliage temperature of about 1°C when air VPD is low, but an increase of
30 about 2.5 and 4°C with air VPD of 1.5 and 3 kPa, respectively. At the higher VPD values,
31 the foliage temperatures simulated with this crop climate model (Allen, 1990) exceeded
32 the differential observed under larger VPD in the sunlit controlled-environment chambers
33 (Prasad et al. 2002; Allen et al., 2003; Prasad et al., 2006a). Allen et al. (2003) found that
34 soybean canopies increased their conductance (lower resistance) at progressively larger
35 VPD (associated with higher temperature), such that foliage temperature did not increase
36 as much as supposed by the crop-climate-model. Concurrently, the anticipated degree of
37 reduction in ET with doubling of CO₂, while being 9 percent less at cool temperature
38 (28/18°C), became progressively less and was non-existent (no difference) at very high
39 temperatures (40/30°C and 44/34°C). In other words, the CO₂-induced reduction in
40 conductance became less as temperature increased.

41
42 Boote et al. (1997, see Table 2.10-11) used a version of the CROPGRO-Soybean model
43 with hourly energy balance and feedback of stomatal conductance on transpiration and
44 leaf temperature (Pickering et al., 1995), to study simulated effects of 350 versus 700
45 ppm CO₂ for field weather from Ohio and Florida. The simulated transpiration was
46 reduced 11 to 16 percent for irrigated sites and 7 percent for a rainfed site in Florida,

1 while the ET was reduced 6 to 8 percent for irrigated sites and 4 percent for the rainfed
2 site. Simulated water use efficiency was increased 53 to 61 percent, which matches the 50
3 to 60 percent increase in soybean WUE reported by Allen et al. (2003) for doubling of
4 CO₂. The smaller reduction in transpiration and ET for the rainfed site was associated
5 with more effective prolonged use of the soil water, also giving a larger yield response
6 (44 percent) for rainfed crop than for irrigated (32 percent). The model simulated
7 reductions in transpiration were close (11 to 16 percent) to those measured (12 percent)
8 by Jones et al. (1985), and the reduction was much less than the reduction in leaf
9 conductance. The model simulations also produced a 1°C higher foliage temperature at
10 mid-day under doubled CO₂.

11
12 Interactions of CO₂ enrichment with climatic factors of water supply and evaporative
13 demand will be especially evident under water deficit conditions. The reduction in
14 stomatal conductance with elevated CO₂ will cause soil water conservation and
15 potentially less water stress, especially for crops grown with periodic soil water deficit or
16 under high evaporative demand. This reduction in water stress effects on photosynthesis,
17 growth, and yield has been documented for both C3 wheat (Wall et al. 2006) and C4
18 sorghum (Ottman et al. 2001; Wall et al. 2001; Triggs et al. 2004). Sorghum grown in the
19 Arizona FACE site showed significant CO₂-induced enhancement of biomass and grain
20 yield for water deficit treatments but no significant enhancement for sorghum grown with
21 full-irrigation (Ottman et al. 2001). In the sorghum FACE studies, the stomatal
22 conductance was reduced 32-37 percent (Wall et al. 2001), while ET was reduced 13
23 percent (Triggs et al. 2004).

25 **2.4.6 Crop Response to Tropospheric Ozone**

26
27 Ozone at the land surface has risen in rural areas of the United States, particularly over
28 the past 50 years, and is forecast to continue increasing over the next 50 years. The
29 Midwest and Eastern United States have some of the highest rural ozone levels on the
30 globe. Average ozone concentrations rise toward the east and south, such that average
31 levels in Illinois are higher than in Nebraska, Minnesota, and Iowa. Only Western Europe
32 and Eastern China have similarly high levels. Argentina and Brazil, like most areas of the
33 Southern Hemisphere, have much lower levels of ozone, and are forecast to see little
34 increase over the next 50 years. Increasing ozone tolerance will therefore be important to
35 the competitiveness of U.S. growers. Numerous models for future changes in global
36 ozone concentrations have emerged that are linked to IPCC scenarios, so the impacts of
37 ozone can be considered in the context of wider global change. For example, a modeled
38 prediction that incorporates expected economic development and planned emission
39 controls in individual countries predict increases in annual mean surface ozone
40 concentrations in all major agricultural areas of the northern hemisphere (Dentener et al.
41 2005).

42
43 Ozone is a secondary pollutant resulting from the interaction of nitrogen oxides with
44 sunlight and hydrocarbons. Nitrogen oxides are produced in the high temperature
45 combustion of any fuel. They are stable and can be transported thousands of miles in the

1 atmosphere. In the presence of sunlight, ozone is formed from these nitrogen oxides, and,
2 in contrast to most pollutants, higher levels are observed in rural than urban areas. This
3 occurs because rural areas have more hours of sunshine and less haze, and city air
4 includes short-lived pollutants that react with and remove ozone. These short-lived
5 pollutants are largely absent from rural areas allowing formation of high ozone
6 concentrations. Levels of ozone during the day in much of the Midwest now reach an
7 average of 60 parts of ozone per billion parts of air (ppb), compared to less than 10 ppb
8 100 years ago. While control measures on emissions of NO_x and volatile organic carbons
9 (VOCs) in North America and western Europe are reducing peak ozone levels, global
10 background tropospheric ozone concentrations are on the rise (Ashmore, 2005). Ozone is
11 toxic to many plants, but studies in greenhouses and small chambers have shown
12 soybean, wheat, peanut, and cotton are the most sensitive of our major crops (Ashmore,
13 2002; <http://www.ars.usda.gov/Main/docs.htm?docid=8453&page=1>).

14
15 Ozone effects have been most extensively studied and best analyzed in soybean. Soybean
16 is the most widely planted dicotyledonous crop and is our best model of C₃ annual crops.
17 The response of soybean to ozone can be influenced by the ozone profile and dynamics,
18 nutrient and moisture conditions, atmospheric CO₂ concentration, even the cultivar
19 investigated, which has created a very complex literature to interpret. Meta-analytic
20 methods are useful to quantitatively summarize treatment effects across multiple studies
21 and thereby identify commonalities. A meta-analysis of more than fifty studies of
22 soybean, grown in controlled environment chambers at chronic levels of ozone, show
23 convincingly that ozone exposure results in decreased photosynthesis, dry matter, and
24 yield (Morgan et al. 2003). Even mild chronic exposure (40-60 ppb) produces such losses
25 and these losses increase linearly with ozone concentration (Morgan et al. 2003) as
26 anticipated from the exposure/response relationship shown by Mills et al. (2000). The
27 meta-analytic summary further reveals that chronic ozone lowers the capacity of carbon
28 uptake in soybean by reducing photosynthetic capacity and leaf area. Soybean plants
29 exposed to chronic ozone levels were shorter with less dry mass and set fewer pods
30 containing fewer smaller seeds. Averaged across all studies, biomass was decreased 34
31 percent, seed yield was 24 percent lower, but photosynthesis was depressed by only 20
32 percent. Ozone damage increased with the age of the soybean consistent with the
33 suggestion that ozone effects accumulate over time (Adams et al. 1996, Miller et al.
34 1998) and may additionally reflect greater sensitivity of reproductive developmental
35 stages particularly seed filling (Tingey et al., 2002). The meta-analysis did not reveal any
36 interactions with other stresses, even stresses expected to lower stomatal conductance and
37 therefore ozone entry into the leaf (Medlyn et al. 2001). However, all of the ozone effects
38 on soybean mentioned above were less under elevated CO₂ a response generally
39 attributed to lower stomatal conductance (Heagle et al. 1989).

40
41 Plant growth in chambers can be different compared to the open field (Long et al. 2006),
42 and therefore the outcomes of the chamber experiments have been questioned as a sole
43 basis for projecting yield losses due to ozone (Elagoz & Manning, 2005). FACE
44 experiments in which soybean was exposed to a 20 percent elevation above ambient
45 ozone levels indicate that ozone-induced yield losses were at least as large under open air
46 treatment. In 2003, the background ozone level in central Illinois was unusually low over

1 the growing season, averaging 45 ppb. Elevation of ozone by 20 percent in this year
2 raised the ozone concentration to the average of the previous 10 years. In the plots with
3 elevated ozone in 2003, yields were reduced approximately 25 percent (Morgan et al.
4 2006). This suggests that under open-air field conditions the yield loss, in a typical year
5 due to ozone is even greater than predictions from greenhouse experiments (Ashmore,
6 2002). Analysis in the soybean FACE results showed a significant decrease in leaf area
7 (Dermody et al. 2006), a loss of photosynthetic capacity during grain filling, and earlier
8 senescence of leaves (Morgan et al. 2004). This may explain why the yield loss is largely
9 due to decreased seed size rather than decreased seed number (Morgan et al. 2006). On
10 average, yield losses in Illinois soybean FACE experiments between 2002 and 2005 were
11 0.5 percent per ppb increase over the 30 ppb threshold, which is twice the ozone
12 sensitivity as determined in growth chamber studies (Ashmore, 2002). These results
13 suggest that during an average year, ozone is currently causing soybean yield losses of 10
14 to 25 percent in the Midwest, with even greater losses in some years. The IPCC forecasts
15 that ozone levels will continue to rise in the rural Midwest by about 0.5 ppb per year
16 suggesting that soybean yields may continue to decline by one percent every two to four
17 years. IPCC also forecasts that ozone, which is low in South America, will remain low in
18 that region over the next 50 years.

19
20 Meta-analysis has not been conducted for the effects of ozone on any crops other than
21 soybean or across different crops. Nevertheless, there is little doubt that current
22 tropospheric ozone levels are limiting yield in many crops (e.g., Heagle, 1989) and
23 further increases in ozone will reduce yield in sensitive species further. The effect of
24 exposure to ozone on yield and yield parameters from studies conducted prior to 2000 are
25 compiled in Table 4 of Black et al. (2000), which reveals that, in addition to soybean, the
26 yield of the C3 crops wheat, oats, French and snap bean, pepper, rape, and various
27 cucurbits are highly sensitive to chronic ozone exposure. Yield of woody perennial cotton
28 is also highly sensitive to ozone (e.g., Temple, 1990; Heagle et al. 1996). While there are
29 isolated reports that maize yield is reduced by ozone (e.g., Rudorff et al. 1996), C4 crops
30 are generally much less sensitive to ozone. A recent study by Booker et al., (2007) and
31 Burkey et al. (2007) on peanuts evaluated the effect of ozone under CO₂ levels from 375
32 to 730 ppm, and ozone levels of 22 to 75 ppb showed that CO₂ increases offset the effects
33 of ozone. Increasing CO₂ levels overcame the effect of ozone on peanut yield; however,
34 in none of the treatments was there a change in seed quality, or protein or oil content of
35 the seed (Burkey et al. 2007).

36 **2.4.7 Pastureland**

37 An early comprehensive greenhouse study examined the photosynthetic response of 13
38 pasture species (Table 2.12) to elevated CO₂ (350 and 700 ppm) and temperature (12/7,
39 18/13, and 28/23 °C for daytime / nighttime temperatures, respectively) (Greer et al.
40 1995). On average, photosynthetic rates increased by 40 percent under elevated CO₂ in
41 C3 species while those for C4 species remained largely unaffected. The response of C3
42 species to elevated CO₂ decreased as temperatures increased from 12 to 28°C. However,
43 the temperatures at which the maximum rates of photosynthesis occurred varied with
44 species and level of CO₂ exposure. At 350 ppm, four species (*L. multiflorum*, *A.*
45 *capillaris*, *C. intybus*, and *P. dilatatum*) showed maximum rates of photosynthesis at

1 18°C while, for the rest, the maximum occurred at 28 °C. At 700 ppm, rates shifted
 2 upwards from 18 to 28°C in *A. capillaries*, and downwards from 28 to 18 °C in *L.*
 3 *perenne*, *F. arundinacea*, *B. wildenowii*, and *T. subterraneum*. However, little if any
 4 correlation existed between the temperature response of photosynthesis and climatic
 5 adaptations of the pasture species.

6
 7
 8

Table 2.12 Names, photosynthetic pathway, and growth characteristics

Species	Common name	Photosynthetic pathway	Growth characteristics
<i>Lolium multiflorum</i>	Italian ryegrass	C3	Cool season annual grass
<i>Bromus wildenowii</i>		C3	Cool season perennial grass
<i>Lolium perenne</i>	Ryegrass	C3	Cool season perennial grass
<i>Phalaris aquatica</i>		C3	Cool season perennial grass
<i>Trifolium dubium</i>		C3	Cool season annual broadleaf
<i>Trifolium subterraneum</i>	Subterranean clover	C3	Cool season annual broadleaf
<i>Agrostis capillaris</i>		C3	Warm season perennial grass
<i>Dactylis glomerata</i>	Orchardgrass	C3	Warm season perennial grass
<i>Festuca arundinacea</i>	Tall fescue	C3	Warm season perennial grass
<i>Cichorium intybus</i>		C3	Warm season perennial broadleaf
<i>Trifolium repens</i>	White clover	C3	Warm season perennial broadleaf
<i>Digitaria sanguinalis</i>	Crabgrass	C4	Warm season annual grass
<i>Paspalum dilatatum</i>	Dallisgrass	C4	Warm season perennial grass

9 **Table 2.12** Names, photosynthetic pathway, and growth characteristics of 13 pasture species. Adapted from
 10 Greer et al. (1995).

11
 12
 13
 14
 15
 16
 17

In Florida, a 3-yr study examined the effects of elevated atmospheric CO₂ (360 and 700 ppm) and temperature (ambient temperature or baseline [B], B+1.5, B+3.0, 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 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

1 responses to elevated CO₂ obtained in many other studies, where C4 plants show a
2 reduced response to CO₂ because bundle sheath cells allow them to maintain a higher
3 CO₂, thereby reducing the external-internal CO₂ gradient.

4

5 The response of forage species to elevated CO₂ may be affected by grazing and
6 aboveground/belowground interactions (Wilsey, 2001). In a phytotron study, Kentucky
7 bluegrass and timothy (*Phleum pratense* L.) – one plant of each species – were grown
8 together in pots during 12 weeks under ambient (360 ppm) and elevated CO₂ (650 ppm),
9 with and without aboveground defoliation, and with and without the presence of
10 *Pratylenchus penetrans*, a root-feeding nematode commonly found in old fields and
11 pastures. Timothy was the only species that responded to elevated CO₂ with an increase
12 in shoot biomass leading to its predominance in the pots. This suggests that Kentucky
13 bluegrass might be at the lower end of the range in the responsiveness of C3 grasses to
14 elevated CO₂, especially under low nutrient conditions. Defoliation increased
15 productivity only under ambient CO₂; thus, the largest response to elevated CO₂ was
16 observed in non-defoliated plants. Timothy was the only species that showed an increase
17 in root biomass under elevated CO₂. Defoliation reduced root biomass. Elevated CO₂
18 interacted with the presence of nematodes in reducing root biomass. In contrast,
19 defoliation alleviated the effect of root biomass reduction caused by the presence of
20 nematodes. This study demonstrates the importance of using aboveground/belowground
21 approaches when investigating the environmental impacts of climate change (Wardle et
22 al. 2004).

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

34 The rising of CO₂ together with the projected changes in temperature and precipitation
35 may significantly change the growth and chemical composition of plant species.
36 However, it is not clear how the various forage species that harbor mutualistic
37 relationships with other organisms would respond to elevated CO₂. Newman et al. (2003)
38 studied the effects of endophyte infection, N fertilization, and elevated CO₂ on growth
39 parameters and chemical composition of tall fescue. Fescue plants, with and without
40 endophyte infection (*Neotyphodium coenophialum*), were transplanted to open chambers
41 and exposed to ambient (350 ppm) and elevated (700 ppm) levels of CO₂. All chambers
42 were fertilized with uniform rates of P and K. Nitrogen fertilizer was applied at rates of
43 6.7 and 67.3 g N m⁻². The results revealed complex interactions of the effects of elevated
44 CO₂ on the mutualistic relationship between a fungus and its host, tall fescue. After 12
45 weeks of growth, plants grown under elevated CO₂ exhibited apparent photosynthetic

1 rates 15 percent higher than under ambient conditions. The presence of the endophyte
2 fungus in combination with N fertilization enhanced the CO₂ fertilization effect. Elevated
3 CO₂ accelerated the rate of tiller appearance and increased dry matter production by at
4 least 53 percent (under the low N treatment). Contrary to previous findings, Newman et
5 al. (2003) found that elevated CO₂ decreased lignin concentrations by 14 percent.
6 Reduced lignin concentration would favor the diet of grazing animals but hinder the
7 stabilization of carbon in soil organic matter (Six et al. 2002).

8
9 Climate change may cause reduction in precipitation and, in turn, induce soil moisture
10 limitations in pasturelands. An experiment in New Zealand examined the interaction of
11 elevated CO₂ and soil moisture limitations on the growth of temperate pastures (Newton
12 et al. 1996). Intact turves (plural of turf) composed primarily of perennial ryegrass and
13 dallisgrass (*Paspalum dilatatum* Poir.) were grown for 324 days under two levels of CO₂
14 (350 and 700 ppm) with air temperatures and photoperiod designed to emulate the
15 monthly climate of the region. After this equilibration period, half the turves in each CO₂
16 treatment underwent soil moisture deficit for 42 days. Turves under elevated CO₂
17 continued to exchange CO₂ with the atmosphere while turves under ambient CO₂ did not.
18 Root density measurements indicated that roots acted as sinks for the carbon (C) fixed
19 during the soil moisture deficit period. Upon rewatering, turves under ambient CO₂ had a
20 vigorous rebound in growth while those under elevated CO₂ did not exhibit additional
21 growth suggesting that plants may exhibit a different strategy in response to soil moisture
22 deficit depending on the CO₂ concentration.
23

24 **2.4.8 Rangeland**

25
26 Most forage species on rangelands have either the C3 or the C4 photosynthetic pathway.
27 Photosynthesis of C3 plants, including most woody species and herbaceous broad-leaf
28 species (forbs), is not CO₂-saturated at the present atmospheric concentration, so carbon
29 gain and productivity usually are very sensitive to CO₂ in these species (Drake et al.,
30 1997). Conversely, photosynthesis of C4 plants, including many of the perennial grass
31 species of rangelands, is nearly CO₂-saturated at the current atmospheric CO₂
32 concentration of ~380 ppm when soil water is plentiful, although the C4 metabolism does
33 not preclude photosynthetic and growth responses to CO₂ (Polley et al. 2003). In
34 addition, CO₂ effects on rates of water loss (transpiration) and plant WUE (i.e. biomass
35 produced per unit of transpiration) are at least as important as photosynthetic response to
36 CO₂ for rangeland productivity. Stomata of most herbaceous plants partially close as CO₂
37 concentration increases, thus reducing plant transpiration. Reduced water loss improves
38 plant and soil water relations, increases plant production under water limitation, and may
39 lengthen the growing season for water-limited vegetation (Morgan et al. 2004b).

40
41 CO₂ enrichment will stimulate NPP on most rangelands, with the amount of increase
42 dependent on precipitation and soil water availability. Indeed, there is evidence that the
43 historical increase in CO₂ of about 35 percent already has enhanced rangeland NPP.
44 Increasing CO₂ from pre-industrial levels to today's elevated concentrations (from 250 to
45 550 ppm) increased aboveground NPP of mesic grassland in central Texas by between 42

1 percent and 69 percent (Polley et al. 2003). Biomass increased by similar amounts at pre-
2 industrial to current, and current to elevated concentrations. Comparisons between CO₂-
3 induced production responses of semi-arid Colorado shortgrass steppe with the sub-
4 humid Kansas tall grass prairie suggest that Great Plains rangelands respond more to CO₂
5 enrichment during dry than wet years, and that the potential for CO₂-induced production
6 enhancements are greater in drier rangelands (Figure 2.12). However, in the still-drier
7 Mojave Desert, CO₂ enrichment enhanced shrub growth most consistently during
8 relatively wet years (Smith et al. 2000). CO₂ enrichment stimulated total biomass
9 (aboveground + belowground) production in one study on annual grassland in California
10 (Field et al. 1997), but elicited no production response in a second experiment (Shaw et
11 al. 2002).

12 *2.5 Episodes of Extreme Events*

13 **2.5.1 Elevated temperature or rainfall deficit**

14
15 Episodic increases in temperature would have their greatest effect if they occur just prior
16 to or during critical crop pollination phases. Crop sensitivity and ability to compensate
17 during later, improved weather will depend on the synchrony of anthesis in each crop;
18 maize for example has a highly compressed phase of anthesis, while spikelets on rice and
19 sorghum may achieve anthesis over a period of a week or more. Soybean, peanut, and
20 cotton will have several weeks over which to spread the success of reproductive
21 structures. For peanut (and presumably other legumes) the sensitivity to elevated
22 temperature for a given flower, extends from six days prior to opening (pollen cell
23 division and formation) up through the day of anthesis (Prasad et al. 2001). Therefore,
24 several days of elevated temperature may affect fertility of many flowers, whether still in
25 their formative 6-day phase or just achieving anthesis today. In addition, the first six
26 hours of the day were more critical during pollen dehiscence, pollen tube growth and
27 fertilization occur.

28
29 For rice, the reproductive processes that occur within one to three hours after anthesis
30 (dehiscence of the anther, shedding of pollen, germination of pollen grains on stigma, and
31 elongation of pollen tubes) are disrupted by daytime air temperatures above 33°C (Satake
32 and Yoshida, 1978). Since anthesis occurs between about 9 to 11am in rice (Prasad et al.
33 2006), exceeding such air temperature may be already be common and may become more
34 prevalent in the future. Pollination processes in other cereals, maize, and sorghum may
35 have a similar sensitivity to elevated daytime temperature as rice. Rice and sorghum have
36 the same sensitivity of grain yield, seed HI, pollen viability, and success in grain
37 formation in which pollen viability and percent fertility is first reduced at instantaneous
38 hourly air temperature above 33°C and reaches zero at 40°C (Kim et al. 1996; Prasad et
39 al., 2006a, 2006b). Diurnal max/min day/night temperatures of 40/30°C (35°C mean)
40 cause zero yield for those two species. We believe the same would apply to maize.

41

42 **2.5.2 Intense rainfall events**

43

1 Historical data for many parts of the United States indicate an increase in the frequency
2 of high-precipitation events (e.g. > 5 cm in 48 hours), and this trend is projected to
3 continue for many regions. One economic consequence of excessive rainfall is delayed
4 spring planting, which jeopardizes profits for farmers paid a premium for early season
5 production of high value horticultural crops such as melon, sweet corn, and tomatoes.
6 Field flooding during the growing season causes crop losses associated with anoxia,
7 increases susceptibility to root diseases, increases soil compaction (due to use of heavy
8 farm equipment on wet soils), and causes more runoff and leaching of nutrients and
9 agricultural chemicals into ground- and surface-waters. More rainfall concentrated into
10 high precipitation events will increase the likelihood of water deficiencies at other times
11 because of the changes in rainfall frequency (Hatfield and Prueger, 2004). Heavy rainfall
12 is often accompanied by wind gusts in storm events, which increases the potential for
13 lodging of crops. Wetter conditions at harvest time could increase the potential for
14 decreasing quality of many crops.
15

16 *2.6 Possible Future Changes and Impacts*

17 **2.6.1 Projections Based on Increment of Temperature and CO₂ for crops**

18
19 What is the expected effect of a further rise in CO₂ of 380 to 440 ppm along with a 0.8°C
20 rise in temperature over the next 30 years for representative crops? The crop
21 responsiveness of grain yield to temperature comes from [Table 2.13](#) with linear
22 interpolation, but dependent on current mean temperatures during the reproductive phase
23 in different regions (crops like soybean and maize are dominant in both Midwest and
24 Southern regions, while some like cotton, sorghum, and peanut are only in Southern
25 regions). The crop responsiveness of grain yield to CO₂ is taken from Table 10, with
26 Michaelis-Menten rectangular hyperbola interpolation with value of 1.0 set at 350 ppm,
27 the published enhancement ratio set at 700ppm and with a compensation CO₂
28 concentration at the x-axis consistent with C3 or C4 species at 30C. With this generalized
29 shape, the response for 380 to 440 ppm CO₂ was 1.0 percent for C4 and 6.1 to 7.4 percent
30 for C3 species, except for cotton, which had 9.2 percent response ([Table 2.10](#)). For
31 maize, under water sufficiency conditions in the Midwest, the net yield response is -1.5
32 percent, assuming additivity of the -2.5 percent from 0.8°C rise and +1.0 percent from
33 CO₂ of 380 to 440 ppm ([Table 2.10](#)). The response of maize in the South could be more
34 negative. For soybean under water sufficiency in the Midwest, net yield response is +9.1
35 percent, assuming additivity of the +1.7 percent from 0.8°C rise above current 22.5°C
36 mean and +7.4 percent from CO₂ increase. For soybean under water sufficiency in the
37 South, the temperature effect will be detrimental, -2.4 percent, with 0.8°C temperature
38 increment above 26.7°C, with the same CO₂ effect, giving a net yield response of +5.0
39 percent. For wheat (with no change in water availability), the net yield response would be
40 +2.4 percent coming from -4.4 percent with 0.8°C rise, and +6.8 percent increase from
41 CO₂ increase. For rice in the South, net yield response is -1.6 percent, assuming additivity
42 of the -8.0 percent from 0.8°C rise and +6.4 percent from CO₂ increase. For peanut in the
43 South, the net yield response is +3.4 percent, assuming additivity of the -3.3 percent from
44 0.8°C rise and +6.7 percent from CO₂ increase. For cotton in the South, the net yield

1 response is +5.7 percent, assuming additivity of the -3.5 percent from 0.8°C rise and +9.2
2 percent from CO₂ increase. The sorghum response is less certain, although yield
3 reduction caused by shortening filling period is dominant, giving a net yield decrease of
4 5.2 percent. Bean yield response is less certain, with net effect of +0.3 percent, coming
5 from -5.8 percent response to 0.8°C rise and +6.1 percent from CO₂ increase.

6
7 Projections of crop yield under water deficit should start with the responses to
8 temperature and CO₂ for the water-sufficient cases (Table 2.10). However, yield will
9 likely be further increased to the same extent (percentage) that increased CO₂ causes
10 reduction in ET. Model simulations with CROPGRO-Soybean with energy balance
11 option and stomatal feedback from CO₂ enrichment (350 to 700 ppm, without
12 temperature increase) resulted in a 44 percent yield increase for water-stressed crops
13 compared to fully-irrigated crops (32 percent). The yield increment was nearly
14 proportional to the decrease in simulated transpiration (11 to 16 percent). Based on this
15 assumption, the 380 to 440 ppm CO₂ increment would further increase yield of C3 crops
16 (soybean, rice, wheat, and cotton) by an additional 1.4 to 2.1 percent (incremental
17 reduction in ET from CO₂ in Table 2.10). However, the projected 0.8°C would increase
18 ET by 1.2 percent, thereby partially negating this water-savings effect of CO₂.

20 2.6.2 Projections for weeds

21
22 Many weeds respond more positively to increasing CO₂ than most cash crops,
23 particularly C3 “invasive” weeds that reproduce by vegetative means (roots, stolons, etc.)
24 (Ziska and George 2004; Ziska 2003). Recent research also suggests that glyphosate, the
25 most widely used herbicide in the United States, loses its efficacy on weeds grown at CO₂
26 levels we anticipate will occur in the coming decades (Ziska et al. 1999). While many
27 weed species have the C4 photosynthetic pathway, and therefore show a smaller response
28 to atmospheric CO₂ relative to C3 crops, in most agronomic situations crops are in
29 competition with a mix of both C3 and C4 weeds. In addition, the worst weeds for a
30 given crop are often similar in growth habit or photosynthetic pathway. To date, for all
31 weed/crop competition studies where the photosynthetic pathway is the same, weed
32 growth is favored as CO₂ is increased (Ziska and Runion, 2006).

33
34 The habitable zone of many weed species is largely determined by temperature, and weed
35 scientists have long recognized the potential for northward expansion of weed species’
36 ranges as the climate changes (Patterson et al. 1999). More than 15 years ago, Sasek and
37 Strain (1990) utilized climate model projections of the -20°C minimum winter
38 temperature zone to forecast the northward expansion of kudzu (*Pueraria lobata*, var.
39 *montana*), an aggressive invasive weed that currently infests more than one million
40 hectares in the southeastern U.S. While temperature is not the only factor that could
41 constrain spread of kudzu and other invasive weeds, a more comprehensive assessment of
42 potential weed species migration based on the latest climate projections for the United
43 States seems warranted.

2.6.3 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 the populations of insect species that currently are 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 C:N 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 atmosphere 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.

2.6.4 Predictions of Forage Yields and Nutrient Cycling under Climate Change

Alfalfa production was simulated with the EPIC (Environmental Policy Integrated Climate) agroecosystem model (Williams, 1995), using various climate change projections from the HadCM2 (Hadley Centre Climate Model) (Izaurrealde et al. 2003), BMRC (Australia's Bureau of Meteorology Research Centre), and UIUC (University of Illinois, Urbana-Champaign) GCMs (Thomson et al. 2005). All model runs were driven with CO₂ levels of 365 and 560 μmol mol⁻¹ and non-irrigated conditions. The results give an indication of pastureland crop response to changes in temperature, precipitation, and

1 CO₂ for major regions of the United States (Table 2.12). Of these three factors, variation
 2 in precipitation had the greatest impact on regional alfalfa yield. Under the HadCM2
 3 projected climate, alfalfa yields increase substantially in eastern regions, with declines
 4 through the central part of the country where temperature increases are greater and
 5 precipitation is lower. Slight alfalfa yield increases are predicted for western regions. The
 6 BMRC model projects substantially higher temperatures and consistent declines in
 7 precipitation over the next several decades, leading to a decline nationwide in alfalfa
 8 yields. In contrast, the UIUC model projects more moderate temperature increases along
 9 with higher precipitation, leading to modest increases in alfalfa yields throughout the
 10 central and western regions. While these results illustrate the uncertainty of model
 11 projections of crop yields due to the variation in global climate model projections of the
 12 future, they also underscore the primary importance of future precipitation changes on
 13 crop yield.

14
 15 **Table 2.13 Change in alfalfa yields**

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

17 **Table 2.13.** Change in alfalfa yields in major U.S. regions as a percentage of baseline yield with average
 18 temperature and precipitation change under the selected climate model for early century (2030) climate
 19 change projections.
 20

1 Multiple regression models built from the data in Table 2.13 revealed how alfalfa yield
2 changes (ΔY , %) were affected by CO_2 concentration, temperature change (ΔT , $^\circ\text{C}$), and
3 precipitation change (ΔP , mm). Overall, the major explanatory variable was precipitation
4 change:

5
6
$$\Delta y = 0.23053\Delta P - 0.15657 \quad R^2 = 0.50^{***} \quad (1)$$

7 For the BMRC model, the best equation was:

8
$$\Delta y = 0.21838\Delta P - 2.4412 \quad R^2 = 0.18^* \quad (2)$$

9 For the HadCM2 model, the best equation was:

10
$$\Delta y = 0.227474\Delta P - 7.73302 \quad R^2 = 0.57^{***} \quad (3)$$

11 For the UIUC model, the best equation was:

12
$$\Delta y = 0.21211\Delta P + 28.277\Delta T - 27.22576 \quad R^2 = 0.24, p < 0.056 \quad (4)$$

13
14 All equations suggest that future changes in precipitation will be very important in
15 determining alfalfa yields. Roughly, for every 4 mm increase in annual precipitation, the
16 models predict a one percent increase in dryland alfalfa yields.

17
18 Thornley and Cannell (1997) argued that experiments on elevated CO_2 and temperature
19 effects on photosynthesis and other ecosystem processes might be limited in their
20 usefulness for at least two reasons. Firstly, the authors argue that laboratory or field
21 experiments incorporating sudden changes in temperature or elevated CO_2 are short term
22 in nature and thus, they rarely produce quantitative changes in NPP, ecosystem C or other
23 ecosystem properties that are connected to the long-term responses to gradual climate
24 change. Secondly, the difficulty of incorporating grazing in these experiments prevents a
25 full analysis of the effects of grazing on ecosystem properties such as NPP, LAI,
26 belowground process, and ecosystem C. Thornley and Cannell (1997) used their Hurley
27 Pasture Model to simulate ecosystem responses of ungrazed and grazed pastures to
28 increasing trends in CO_2 concentrations and temperature. The simulations revealed three
29 important results: a) rising CO_2 induces a C sink, b) rising temperatures alone produce a
30 C source, and c) a combination of the two effects is likely to generate a C sink for several
31 decades ($5\text{-}15 \text{ g C m}^{-2} \text{ yr}^{-1}$). Modeling the dynamics of mineral N availability in grazed
32 pastures under elevated CO_2 , Thornley and Cannell (2000) ascertained the role of the
33 mineral N pool and its turnover rate in slowly increasing C content in plants and soils.

34
35 **2.6.5 Implications of Altered Productivity, Nitrogen cycle (forage quality),**
36 **Phenology, and Growing Season on Species Mixes, Fertilizer, and**
37 **Stocking**

1 In general, the response of pasture species to elevated CO₂ deduced from these studies is
2 consistent with the general response of C3 and C4 type vegetation to elevated CO₂,
3 although significant exceptions exist. Pasture species with C3-type metabolism increased
4 their photosynthetic rates by up to 40 percent but not those with a C4 pathway (Greer et
5 al. 1995). Examples of C3 species grown in the United States exhibiting increased
6 photosynthetic rates under elevated CO₂ include Italian ryegrass, orchardgrass, rhizoma
7 peanut, tall fescue, and timothy (Greer et al. 1995; Newman et al. 2001; Wilsey 2001).
8 Kentucky bluegrass has shown low response to elevated CO₂ (Wilsey 2001). Perennial
9 ryegrass has shown a positive response in terms of photosynthetic rate (Greer et al.,
10 1995), but a low or even negative response in terms of plant yield (Suter et al. 2001).
11 Bahiagrass, an important pasture species in Florida, appears marginal in its response to
12 elevated CO₂ (Newman et al. 2001), which, in combination with current and future
13 reductions in their area growth due to the expansion of urban areas, may force producers
14 to use their pastures more intensely (Stewart et al. 2007).

15 The study of Greer et al. (1995) suggests shifts in optimal temperatures for
16 photosynthesis under elevated CO₂, with perennial ryegrass and tall fescue showing a
17 downward shift in their optimal temperature from 28 to 18°C. Unlike croplands, the
18 literature for pasturelands is sparse in providing quantitative information to predict the
19 yield change of pastureland species under a temperature increase of 0.8 °C. The projected
20 increases in temperature and the lengthening of the growing season should be, in
21 principle, beneficial for livestock produced by increasing pasture productivity and
22 reducing the need for forage storage during the winter period.

23 Naturally, changes in CO₂ and temperature will be accompanied by changes in
24 precipitation, with the possibility of more extreme weather causing floods and droughts.
25 Pasture species that grow under elevated CO₂ may respond differently to drought
26 conditions in comparison to those that grow under ambient conditions. Newton et al.
27 (1996) found that turves of perennial ryegrass and dallisgrass under elevated CO₂ grew
28 more than turves under ambient CO₂. When exposed to a prolonged period of drought,
29 turves under elevated CO₂ continue to exchange CO₂, while those under ambient
30 conditions did not. When the water constraint was removed, the reverse occurred; the
31 turves under ambient CO₂ rebounded vigorously while those under elevated CO₂ failed to
32 exhibit any additional growth suggesting different strategies of the turves for responding
33 to soil moisture deficits depending on the CO₂ concentration. Precipitation changes will
34 likely play a major role in determining NPP of pasture species as suggested by the
35 simulated one percent change in yields of dryland alfalfa for every 4-mm change in
36 annual precipitation (Izaurre et al. 2003; Thomson et al. 20052003).

37 Another aspect that emerges from this review is the need for comprehensive studies of
38 the impacts of climate change on the pasture ecosystem including grazing regimes,
39 mutualistic relationships (e.g., plant roots-nematodes; N-fixing organisms), as well as C,
40 nutrient and water balances. Despite their complexities, the studies by Newton et al.
41 (1996) and Wilson (2001) underscore the importance, difficulties, and benefits of
42 conducting multifactor experiments. To augment their value, these studies should include
43 the use of simulation modeling (Thornley and Cannell, 1997) in order to test hypotheses
44 regarding ecosystem processes.

1 **2.6.5.1 *CO₂ Effects on Rangeland Plants***

2
3 Photosynthesis of C3 rangeland plants, including most woody species and herbaceous
4 broad-leaf species (forbs), is not CO₂-saturated at the present atmospheric concentration,
5 so carbon gain and productivity usually are very sensitive to CO₂ in these species (Drake
6 et al. 1997). Conversely, photosynthesis of C4 plants, including many of the perennial
7 grass species of rangelands, is nearly CO₂-saturated at the current atmospheric CO₂
8 concentration of ~380 ppm when soil water is plentiful, although the C4 metabolism does
9 not preclude photosynthetic and growth responses to CO₂ (Polley et al. 2003). In
10 addition, CO₂ effects on rates of water loss (transpiration) and plant WUE are at least as
11 important as photosynthetic response to CO₂ for rangeland productivity. Stomata of most
12 herbaceous plants partially close as CO₂ concentration increases, thus reducing plant
13 transpiration. Reduced water loss improves plant and soil water relations, increases plant
14 production under water limitation, and may lengthen the growing season for water-
15 limited vegetation (Morgan et al. 2004b).

16
17 CO₂ enrichment will stimulate NPP on most rangelands, with the amount of increase
18 dependent on precipitation and soil water availability. Indeed, there is evidence that the
19 historical increase in CO₂ of about 35 percent already has enhanced rangeland NPP.
20 Increasing CO₂ from pre-industrial to elevated concentrations (from 250 to 550 ppm)
21 increased aboveground NPP of mesic grassland in central Texas by between 42 percent
22 and 69 percent (Polley et al. 2003). Biomass increased by similar amounts at pre-
23 industrial to current and current to elevated concentrations. Comparisons between CO₂-
24 induced production responses of semi-arid Colorado shortgrass steppe with the sub-
25 humid Kansas tall grass prairie suggest that Great Plains rangelands respond more to CO₂
26 enrichment during dry than wet years, and that the potential for CO₂-induced production
27 enhancements are greater in drier rangelands (Figure 2.12). However, in the still-drier
28 Mojave Desert, however, CO₂ enrichment enhanced shrub growth most consistently
29 during relatively wet years (Smith et al. 2000). CO₂ enrichment stimulated total biomass
30 (aboveground + belowground) production in one study on annual grassland in California
31 (Field et al., 1997), but elicited no production response in a second experiment (Shaw et
32 al. 2002).

34 **2.6.5.2 *Increases in Temperature on Rangelands***

35
36 Like CO₂ enrichment, increasing ambient air and soil temperatures may enhance
37 rangeland NPP, although negative effects of higher temperatures also are possible,
38 especially in dry and hot regions. Temperature directly affects plant physiological
39 processes, but rising ambient temperatures may indirectly affect plant production by
40 extending the length of the growing season, increasing soil N mineralization and
41 availability, altering soil water content, and shifting plant species composition and
42 community structure (Wan et al. 2005). Rates of biological processes for a given species
43 typically peak at plant temperatures that are intermediate in the range over which a
44 species is active, so direct effects of warming likely will vary within and among years
45 and among plant species. Because of severe cold-temperature restrictions on growth rate

1 and duration, warmer plant temperatures alone should stimulate production in high- and
2 mid-latitude and high-altitude rangelands. Conversely, increasing plant temperature
3 during summer months may reduce NPP. Increasing the daily minimum air temperature
4 and mean soil temperature (2.5 cm depth) by 2°C increased aboveground NPP of tallgrass
5 prairie in Oklahoma between 0 percent and 19 percent during the first three years of
6 study, largely by increasing NPP of C4 grasses (Wan et al. 2005). Warming stimulated
7 biomass production in spring and autumn, but aboveground biomass in summer declined
8 as soil temperature increased.

9
10 Positive effects of warming on production may be lessened by an accompanying increase
11 in the rate of water loss. Warming reduced the annual mean of soil water content in
12 tallgrass prairie during one year (Wan et al. 2005), but actually increased soil water
13 content in California annual grassland by accelerating plant senescence (Zavaleta et al.
14 2003b).

16 *2.6.5.3 Altered Precipitation Effects on Rangeland*

17
18 Historic changes in climatic patterns have always been accompanied by changes in
19 grassland vegetation because grasslands display an optimal combination of production
20 potential and variability in precipitation (Knapp & Smith 2001). In contrast, aboveground
21 net primary productivity (ANPP) variability in forest systems appears to be limited by
22 invariant rainfall patterns, while production potential more strongly limits desert and
23 arctic/alpine systems.

24
25 Increased rainfall variability caused by altered rainfall timing (no change in rainfall
26 amount) led to lower and more variable soil water content (0-30 cm depth), an
27 approximate 10 percent reduction in ANPP, which was species-specific, and increased
28 root to shoot ratios in a native tallgrass prairie ecosystem in northeastern Kansas (Fay et
29 al. 2003). In general, vegetation responses to rainfall timing (no change in amount) were
30 at least equal to changes caused by rainfall quantity (30 percent reduction, no change in
31 timing). Reduced ANPP most likely resulted from direct effects of soil moisture deficits
32 on root activity, plant water status, and photosynthesis. Projected increases in rainfall
33 variability may alter key carbon cycling processes as well as plant community
34 composition, independent of changes in total precipitation (Knapp et al. 2002). Thus,
35 altered rainfall regimes are likely to elicit important changes in several aspects of
36 rangeland ecology, and interactions of those response with other climate change elements
37 remains a significant challenge for predicting ecosystem responses to climate change.

38
39 On most rangelands where total annual precipitation is sufficiently low that soil water
40 limits productivity more than other soil resources, seasonality of precipitation plays an
41 important role in regulating NPP. For example, herbaceous plants in the Great Basin are
42 physiologically adapted to winter/early spring precipitation patterns, where reliable soil
43 water recharge occurs prior to the growing season. A change in climate that shifts
44 precipitation away from a winter precipitation pattern to a spring/early summer pattern
45 would likely reduce productivity, cover, and reproduction of native herbaceous plant

1 species (Svejcar et al. 2003), and could lead to the eventual loss of species most affected.
2 Without species replacement, increased bare ground and greater vulnerability to soil
3 erosion would increase likelihood of invasion by noxious weeds. Wildlife, domestic
4 livestock, and other organisms that depend on herbaceous annual and perennial
5 vegetation would likely also be affected.

6
7 Oak savannas of the southwestern United States also experience a strongly seasonal
8 pattern of precipitation, with a primary peak in summer and lesser peak in winter
9 (Weltzin & McPherson 2003). The herbaceous understory species are most responsive to
10 summer precipitation, while oak seedling growth (*Quercus emoryi*.) was not responsive.
11 Here, herbaceous biomass was more sensitive to summer precipitation than to winter
12 precipitation, but the growth of *Q. emoryi* seedlings was not affected by season of
13 precipitation. If precipitation regimes shift toward wetter winters and drier summers, loss
14 of herbaceous biomass and an increase in woody vegetation in this system would be
15 expected. However, winter precipitation can play an important role where the recharge of
16 soil moisture is required to offset low summer precipitation. Northern Great Plains
17 grasslands are dominated by cool-season plant species that complete most of their growth
18 by late spring to early summer, and ANPP primarily depends on sufficient soil moisture
19 going into the growing season (Heitschmidt and Haferkamp 2003).

21 **2.6.6 Impacts on Species Composition**

22 *2.6.6.1 Environmental controls on species composition*

23
24 At regional scales, the species composition of rangelands is determined mostly by climate
25 and soils, with fire regime, grazing, and other land uses locally important. The primary
26 climatic control on the distribution and abundance of plants is water balance (Stephenson,
27 1990). On rangelands in particular, species composition is highly correlated with both the
28 amount of water plants use and its availability in time and space.

29
30 Each of the global changes considered here, CO₂ enrichment, altered precipitation
31 regimes, and higher temperatures, may change species composition by altering water
32 balance. The importance of water balance to species composition is evident in the strong
33 correlation between current relative abundances of different plant types (C3 grasses, C4
34 grasses, and shrubs) and temperature and precipitation (Paruelo and Lauenroth 1996).
35 Epstein et al. (2002) used climate change projections from GCMs and regression
36 equations, which related current relative abundances of plant types to climatic variables,
37 to predict future abundances of grasses and shrubs on western rangelands. Using GCM
38 predictions of a >4°C increase in mean annual temperature, and 10 percent increase in
39 precipitation within the century, Epstein et al. (2002) predicted that C4 grasses would
40 increase substantially in the western U.S., particularly in currently cool areas like the
41 northern U.S. and southern Canada. Shrub abundance was projected to increase at the
42 expense of grasses in the already shrubby desert ecosystems of the Southwest.

43
44 A warmer climate should be characterized by more rapid evaporation and transpiration,
45 and an increase in frequency of extreme events like heavy rains and droughts. Changes in

1 timing and intensity of rainfall may be especially important on arid rangelands where
2 plant community dynamics are ‘event-driven’ and the seasonality of precipitation
3 determines which plant growth strategies are successful. The timing of precipitation also
4 affects the vertical distribution of soil water, which regulates relative abundances of
5 plants that root at different depths (Ehleringer et al. 1991; Weltzin and McPherson 1997),
6 and influences natural disturbance regimes, which feedback to regulate species
7 composition. For example, grass-dominated rangelands in the eastern Great Plains were
8 historically tree-free due to periodic fire. Fires occurred frequently because the area is
9 subject to summer droughts, desiccating grasses, and providing abundant fuel for
10 wildfires.

11
12 Unless stomatal closure is compensated by atmospheric or other feedbacks, CO₂
13 enrichment also should affect water balance by slowing canopy-level ET (Polley et al.
14 2007), and the rate or extent of soil water depletion (Morgan et al. 2001; Nelson et al.
15 2004). Plants that are less tolerant of water stress than current dominants may be favored
16 (Polley et al. 2000). However, because of their sensitivity to CO₂ rising CO₂ may
17 generally favor C3 grasses, forbs, and woody plants over C4 grasses (Morgan et al. 2005,
18 Polley, 1997). Also, deep-rooted forbs, and shrubs will also be favored under this
19 scenario because of their strong carbon-allocation and nitrogen-use strategies (Polley et
20 al. 2000; Bond and Midgley 2000; Morgan et al. in press).

21
22 However, rising CO₂ may favor plants with greater photosynthetic sensitivity to CO₂,
23 such as C3 grasses and deep-rooted forbs, as compared to C4 grasses, which have a
24 limited direct photosynthetic response to CO₂ (Morgan et al. 2005, Polley, 1997). The
25 final outcome of these competitive responses of species to combined temperature,
26 precipitation, and rising CO₂ will likely vary among in different rangeland ecosystems.

27
28 Observational evidence that global changes are affecting rangelands and other
29 ecosystems is accumulating. During the last century, juniper trees in the arid west grew
30 more than expected because of climatic conditions, implying that the historical increase
31 in atmospheric CO₂ concentration stimulated juniper growth (Knapp et al. 2001). The
32 apparent growth response of juniper to CO₂ was proportionally greater during dry than
33 wet years, consistent with the notion that access to deep soil water, which tends to
34 accumulate under elevated CO₂ (Morgan et al. 2004b), gives a growth advantage to deep-
35 rooted woody vegetation (Polley, 1997, Morgan, in press). Results from many CO₂
36 experiments (Morgan et al. 2004b) suggest that expansion of shrublands over the past
37 couple hundred years has been driven in part by a combination of climate change and
38 increased atmospheric CO₂ concentrations (Polley, 1997, Archer et al. 1995).

39 40 ***2.6.6.2 Local and short-term changes***

41
42 Our ability to predict vegetation changes at local scales and over shorter time periods is
43 more limited because at these scales the response of vegetation to global changes depends
44 on a variety of local processes, including disturbance regimes, and how quickly various
45 species can disperse seeds across sometimes-fragmented landscapes. Nevertheless,

1 patterns of vegetation response are beginning to emerge.

2
3 1) Directional shifts in the composition of vegetation occur most consistently when
4 global change treatments alter water availability (Polley et al. 2000, Morgan et al.
5 2004b).

6
7 2) Effects of CO₂ enrichment on species composition and the rate of species change
8 likely will be greatest in disturbed or early-successional communities where nutrient and
9 light availability are high and species change is influenced largely by growth-related
10 parameters (e.g., Polley et al. 2003).

11
12 3) Weedy and invasive plant species likely will be favored by CO₂ enrichment (Smith et
13 al. 2000) and perhaps by other global changes because these species possess traits (rapid
14 growth rate, prolific seed production) that permit a large growth response to CO₂.

15
16 4) CO₂ enrichment may accelerate the rate of successional change in species composition
17 following overgrazing or other severe disturbances (Polley et al. 2003).

18
19 5) Plants do not respond as predictably to temperature or CO₂ as to changes in water, N,
20 and other soil resources (Chapin et al. 1995). Progress in predicting the response of
21 vegetation to temperature and CO₂ thus may require a better understanding of indirect
22 effects of global change factors on soil resources. At larger scales, effects of atmospheric
23 and climatic change on fire frequency and intensity and on soil water and N availability
24 likely will influence botanical composition to a much greater extent than global change
25 effects on production.

26
27 6) Rangeland vegetation will be influenced more by management practices (land use)
28 than by atmospheric and climatic change. Global change effects will be superimposed on
29 and modify those resulting from land use patterns in ways that are as yet uncertain.

30 31 **2.6.6.3 Nutrient cycle feed-backs**

32
33 Plant production on rangelands often is limited by nitrogen (N). Because most terrestrial
34 N occurs in organic forms that are not readily available to plants, rangeland responses to
35 global changes will depend partly on how quickly N cycles between the organic and
36 inorganic compounds in which it occurs. Plant material that falls to the soil surface or is
37 deposited belowground as the result of root exudation or death is subject to
38 decomposition by soil fauna and micro flora and enters the soil organic matter (SOM)
39 pool (Figure 2.11). During decomposition of SOM, mineral and other plant-available
40 forms of N are released.

41
42 Several of the plant and environmental variables that regulate N-release may be affected
43 by climate change and CO₂ enrichment. Warmer temperatures generally increase SOM
44 decomposition, especially in cold regions (Reich et al. 2006b; Rustad et al. 2001),
45 although warming also may limit microbial activity by drying soil or enhancing plant

1 growth (Wan et al. 2005). Warming stimulated N mineralization during the first year of
2 treatment on Oklahoma tallgrass prairie, but in the second year, caused N immobilization
3 by reducing plant N concentration (An et al. 2005), stimulating plant growth, and
4 increasing allocation of C compounds belowground (Wan et al. 2005). Warming can also
5 affect decomposition processes by extending the growing season, (Wan et al. 2005).
6 However, as water becomes limiting, decomposition becomes more dependant on soil
7 water content and less on temperature (Epstein, Burke and Lauenroth 2002; Wan et al.
8 2005), with lower soil water content leading to reduced decomposition rates. A recent
9 global model of litter decomposition (Parton et al. 2007) indicates that litter N-
10 concentration, along with temperature and water, are the dominant drivers behind N
11 release and immobilization dynamics, although UV-stimulation of decomposition (Austin
12 and Vivanco 2006) is especially important in controlling surface litter decomposition
13 dynamics in arid systems like rangelands.

14
15 Although rising atmospheric CO₂ has no direct affect on soil microbial processes, it can
16 affect soil micro flora and fauna indirectly. The Progressive Nitrogen Limitation (PNL)
17 hypothesis holds that CO₂ enrichment is reducing plant-available N by increasing plant
18 demand for N and enhancing the sequestration of N in long-lived plant biomass and SOM
19 pools (Luo et al. 2004). The greater plant demand for N is driven by CO₂-enhanced plant
20 growth. Accumulation of N in organic compounds at elevated CO₂ may eventually reduce
21 soil N availability and limit plant growth response to CO₂ or other changes (Reich et al.
22 2006a,b; van Groenigen et al. 2006; Parton et al. 2007). Alternatively, greater C input
23 may stimulate N accumulation in soil/plant systems. A number of processes may be
24 involved, including increased biological fixation of N, greater retention of atmospheric N
25 deposition, reduced losses of N in gaseous or liquid forms, and more complete
26 exploration of soil by expanded root systems (Luo et al. 2006). Rangeland plants often
27 compensate for temporary imbalances in C and N availability by maximizing the amount
28 of C retained in the ecosystem per unit of N. Thus, N concentration of leaves or
29 aboveground tissues declined on shortgrass steppe, tallgrass prairie, and mesic grassland
30 at elevated CO₂, and on tallgrass prairie with warming, but total N content of
31 aboveground tissues increased with plant biomass in these ecosystems and on annual
32 grasslands (Owensby et al. 1993, Hungate et al. 1997, King et al. 2004, An et al. 2005,
33 Gill et al. 2006). The degree to which N may respond to rising atmospheric CO₂ is
34 presently unknown, but may vary among ecosystems (Luo et al. 2006), and has important
35 consequences for forage quality and soil C storage, as both depend strongly on the
36 available soil N.

37
38 Nutrient cycling also is sensitive to changes in plant species composition; this may result
39 because species differ in sensitivity to global changes. Soil microorganisms require
40 organic material with relatively fixed proportions of C and N. The ratio of C to N in plant
41 residues thus affects the rate at which N is released during decomposition in soil. Because
42 C:N varies among plant species, shifts in species composition can strongly affect nutrient
43 cycling (Allard et al. 2004; Dijkstra et al. 2006; Gill et al. 2006; King et al. 2004;
44 Schaeffer et al. 2007; Weatherly et al. 2003). CO₂ enrichment may reduce decomposition
45 by reducing the N concentration in leaf litter (Gill et al. 2006), for example, although
46 litter quality may not be the best predictor of tissue decomposition (Norby et al. 2001).

1 Like CO₂, climatic changes may alter litter quality by causing species change (Murphy et
2 al. 2002; Semmartin et al. 2004; Weatherly et al. 2003). Elevated atmospheric CO₂ and/or
3 temperature may also alter the amounts and proportions of micro flora and fauna in the
4 soil microfood web (e.g., Hungate et al. 2000; Sonnemann and Wolters 2005), and/or the
5 activities of soil biota (Billings et al. 2004; Henry et al. 2005; Kandeler et al. 2006).
6 Although changes in microbial communities are bound to have important feedbacks on
7 soil nutrient cycling and C storage, the full impact of global changes on microbes remains
8 unclear (Niklaus et al. 2003; Ayers et al. in review).

9
10 Computer simulation models that incorporate decomposition dynamics and can evaluate
11 incremental global changes agree that combined effects of warming and CO₂ enrichment
12 during the next 100 years will stimulate plant production, but disagree on the impact on
13 soil C and N. The Daycent Model predicts a decrease in soil C stocks, whereas the
14 Generic Decomposition And Yield Model (G'Day) predicts an increase in soil C (Pepper
15 et al. 2005). Measurements of N isotopes from herbarium specimens collected over the
16 past hundred years indicate that rising atmospheric CO₂ has been accompanied by
17 increased N fixation and soil N mineralization, decreased soil N losses, and a decline in
18 shoot N concentration (Penuelas and Estiarte, 1997). Collectively, these results indicate
19 that soil N may constrain the responses of some terrestrial ecosystems to CO₂.

21 **2.6.7 Forage Quality**

22 *2.6.7.1 Plant-animal interface*

23
24 Animal production on rangelands, as in other grazing systems, depends on the quality as
25 well as the quantity of forage. Key quality parameters for rangeland forage include fiber
26 content and concentrations of crude protein, non-structural carbohydrates, minerals, and
27 secondary toxic compounds. Ruminants require forage with at least 7 percent crude
28 protein (as a percentage of dietary dry matter) for maintenance, 10-14 percent protein for
29 growth, and 15 percent protein for lactation. Optimal rumen fermentation also requires a
30 balance between ruminally-available protein and energy. The rate at which digesta passes
31 through the rumen decreases with fiber content, which depends on the fiber content of
32 forage. Increasing fiber content slows passage and reduces animal intake.

33 *2.6.7.2 Climate change effects on forage quality*

34
35 Based on expected vegetation changes and known environmental effects on forage
36 protein, carbohydrate, and fiber contents, both positive and negative changes in forage
37 quality are possible as a result of atmospheric and climatic change (Table 2.14). Although
38 non-structural carbohydrates can increase under elevated CO₂ (Read and Morgan,
39 XXXX), thereby potentially enhancing forage quality, plant N, and crude protein, these
40 typically decline in CO₂-enriched atmosphere. This reduces the positive effects of CO₂
41 enrichment. For example, impacts on crude protein content of forage likely will be
42 negative because plant nitrogen concentration usually declines at elevated CO₂ (Cotrufo
43 et al. 1998, Milchunas et al. 2005). Limited evidence suggests that the decline is greater

1 when soil nitrogen availability is low than high (Bowler and Press, 1996; Wilsey, 1996),
 2 implying that rising CO₂ could reduce the digestibility of forages that are already of poor-
 3 quality for ruminants. Experimental warming also reduces tissue N concentrations (An et
 4 al. 2005), but reduced precipitation typically has the opposite effect. Reductions in forage
 5 quality could have pronounced negative effects on animal growth, reproduction, and
 6 mortality (Milchunas et al. 2005, Owensby et al. 1996), and could render livestock
 7 production unsustainable unless animal diets are supplemented with N (e.g. urea, soybean
 8 meal). On shortgrass steppe, for example, CO₂ enrichment reduced the crude protein
 9 concentration of autumn forage below critical maintenance levels for livestock in three
 10 out of four years and reduced the digestibility of forage by 14 percent in mid-season and
 11 by 10 percent in autumn (Milchunas et al. 2005). Significantly, the grass most favored by
 12 CO₂ enrichment, also had the lowest crude protein concentration. Plant tissues that re-
 13 grow following defoliation generally

14
 15 **Table 2.14 Potential changes in forage quality**
 16

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 C3 grasses relative to C4 grasses at elevated CO ₂ .	Increase in the proportion of C4 grasses relative to C3 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.

17
 18 **Table 2.14** Potential changes in forage quality arising from atmospheric and climatic change.
 19

20 are of higher quality than older tissue, so defoliation could ameliorate negative effects of
 21 CO₂ on forage quality. This however, did not occur on shortgrass steppe (Milchunas et al.

1 2005). Changes in life-forms, species, or functional groups resulting from differential
2 responses to global changes (2.5.5.1) will likely vary among rangelands depending on the
3 present climate and species composition, with mixed consequences for domestic
4 livestock (Table 2.14).
5

6 **2.6.8 Climatic Influences on Livestock**

7
8 Climate changes, as suggested by some GCMs, could impact the economic viability of
9 livestock production systems world-wide. Surrounding environmental conditions directly
10 affect mechanisms and rates of heat gain or loss by all animals (NRC, 1981). Lack of
11 prior conditioning to weather events most often results in catastrophic losses in the
12 domestic livestock industry. In the central U.S. in 1992, 1995, 1997, 1999, 2005, and
13 2006, individual feedlots (intensive cattle feeding operations) lost in excess of 100 head
14 each during severe heat episodes. The heat waves of 1995 and 1999 were particularly
15 severe with documented cattle losses in individual states approaching 5,000 head each
16 year (Hahn and Mader, 1997; Hahn et al. 2001). The magnitude and/or duration of the
17 2005 and 2006 heat waves were just as severe as the 1995 and 1999 heat waves, although
18 the extent of losses could not be adequately documented. The winter of 1996-97 also
19 caused hardship for cattle producers because of greater than normal snowfall and wind
20 velocity with some feedlots reporting losses in excess of 1,000 head. During that winter,
21 up to 50 percent of the newborn calves were lost with over 100,000 head of cattle lost in
22 the Northern Plains of the United States. Additional snowstorm losses were incurred with
23 the collapse of and/or loss of power to buildings that housed confined domestic livestock.
24 Early snowstorms in 1992 and 1997 resulted in the loss of over 30,000 head of feedlot
25 cattle each year in the Southern Plains of the United States (Mader 2003). Economic
26 losses from reduced cattle performance (morbidity) likely exceed those associated with
27 cattle death losses by several-fold (Balling, 1982). In addition to losses in the 1990s, in
28 the winter of 2000-2001, feedlot cattle efficiencies of gain and daily gain decreased
29 approximately five and 10 percent, respectively, from previous years as a result of late
30 autumn and early winter moisture combined with prolonged cold stress conditions
31 (Mader 2003). In addition, the 2006 snowstorms, which occurred in the southern plains
32 around Christmas and New Years, appear to be as devastating as the 1992 and 1997
33 storms. These documented examples of how climate change can impact livestock
34 production illustrate the potential for more drastic consequences of increased variability
35 in weather patterns and extreme events that may be associated with climate change.

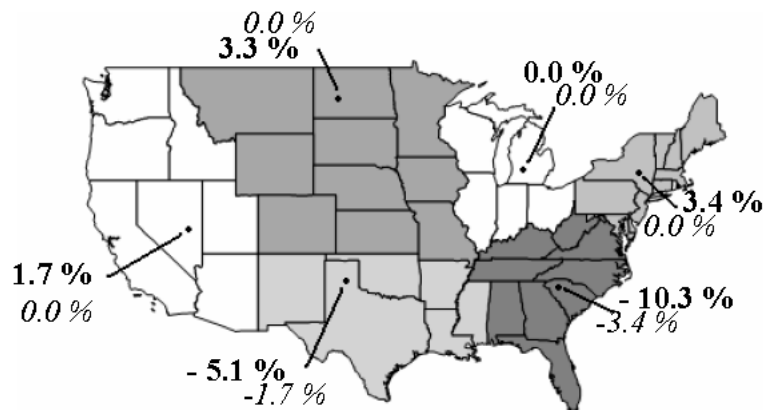
36 **2.6.9 Potential Impact of Climate Change on Livestock**

37
38 The risk potential associated with livestock production systems due to global warming
39 can be characterized by levels of vulnerability as influenced by animal performance and
40 environmental parameters (Simensen, 1984; Hahn, 1995). When performance level and
41 environmental influences combine to create a low level of vulnerability, there is little
42 risk. As performance levels increase, the vulnerability of the animal increases and when
43 coupled with an adverse environment, the animal is at greater risk. Combining an adverse
44 environment with high performance pushes the level of vulnerability and consequent risk

1 to even higher levels. Inherent genetic characteristics or management scenarios that limit
2 the animal's ability to adapt to or cope with the environment also puts the animal at risk.
3 At very high performance levels, any environment other than near-optimal may increase
4 animal vulnerability and risk.

5
6 The potential impacts of climatic change on overall performance of domestic animals can
7 be determined using defined relationships between climatic conditions and VFI,
8 climatological data, and GCM output. Because ingestion of feed is directly related to heat
9 production, any change in VFI and/or energy density of the diet will change the amount
10 of heat produced by the animal (Mader et al. 1999b). Ambient temperature has the
11 greatest influence on VFI. However, animals exposed to the same ambient temperature
12 will not exhibit the same reduction in VFI. Body weight, body condition, and level of
13 production affect the magnitude of VFI and ambient temperature at which changes in VFI
14 begin to be observed. Intake of digestible nutrients is most often the limiting factor in
15 animal production. Animals generally prioritize available nutrients to support
16 maintenance needs first, followed by growth or milk production, and then reproduction.

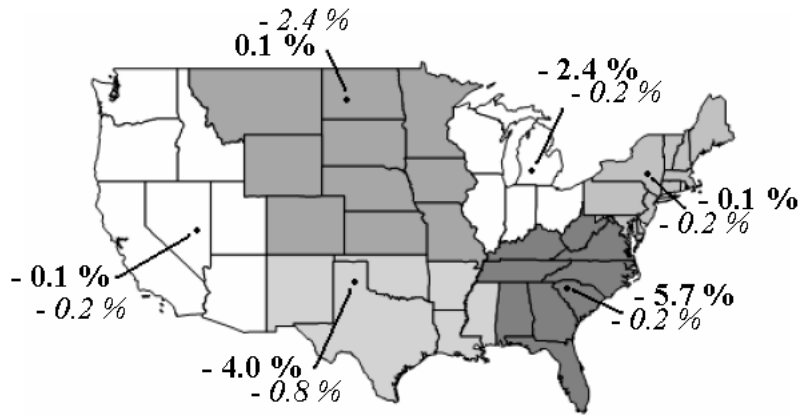
17
18 Based on predicted climate outputs from GCM scenarios, production and response
19 models for growing confined swine and beef cattle, and milk-producing dairy cattle have
20 been developed (Frank et al. 2001). The goal in the development of these models was to
21 utilize climate projections – primarily average daily temperature – to generate an estimate
22 of direct climate-induced changes in daily VFI and subsequent performance, during
23 summer in the central portion of the United States (the dominant livestock producing
24 region of the country) and across the entire country. The production response models
25 were run for one current (pre-1986 as baseline) and two future climate scenarios: a
26 double CO₂ (~2040) and a triple of CO₂ (~2090) levels. This data base employed the
27 output from two GCM, the Canadian Global Coupled Model, Version I, and the United
28 Kingdom Meteorological Office/Hadley Center for Climate Prediction and Research
29 model, for input to the livestock production/response models. Changes in production of
30 swine and beef cattle data were represented by the number of days to reach the target
31 weight under each climate scenario and time period. Dairy production is reported in kg
32 milk produced per cow per season. Details of this analysis are reported by Frank (2001)
33 and Frank et al. (2001).



34
35

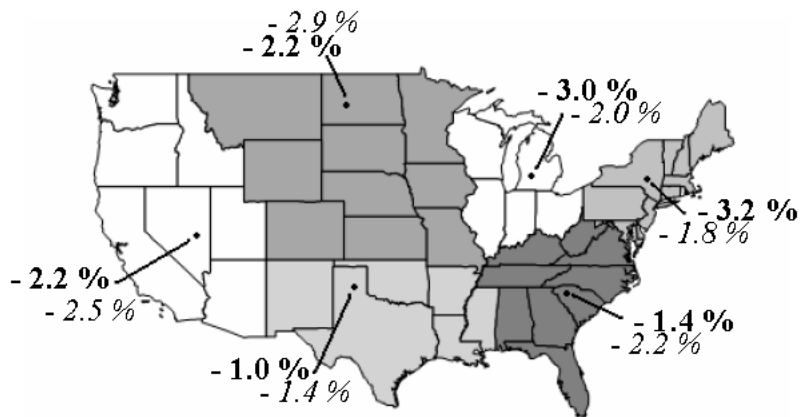
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Figure 2.12 Percent change from baseline to 2040 of days for swine to grow from 50 to 110 kg, beginning June 1 under CGC and Hadley modeled climate (Frank 2001; Frank et al. 2001).



4
5
6
7
8
9

Figure 2.13 Percent change from baseline to 2040 of days for beef cattle to grow from 350 to 550kg, beginning June 1 under CGC and Hadley modeled climate (Frank 2001; Frank et al. 2001).



10
11
12
13

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

14
15
16

17 In the central U.S. (MINK region = Missouri, Iowa, Nebraska, and Kansas), days-to-
18 slaughter weight for swine, associated with the CGC 2040 scenario, increased an average
19 of 3.7 days from the baseline of 61.2 days (Figure 2.12). Potential losses under this
20 scenario averaged six percent and would cost swine producers in the region \$12.4 million
21 annually. Losses associated with the Hadley scenario are less severe. Increased time-to-
22 slaughter weight averaged 1.5 days, or 2.5 percent, and would cost producers \$5 million,
23 annually. For confined beef cattle reared in the central U.S., time-to-slaughter weight
24 associated with the CGC 2040 scenario increased 4.8 days (above the 127-day baseline
25 value) or 3.8 percent, costing producers \$43.9 million annually (Figure 2.13). Climate
26 changes predicted by the Hadley model resulted in a loss 2.8 days of production, or 2.2
27 percent. For dairy, the projected CGC 2040 climate scenario would result in a 2.2 percent

1 (105.7 kg/cow) reduction in milk output and cost producers \$28 million, annually (Figure
2 2.14). Production losses associated with the Hadley scenarios would average 2.9 percent
3 and cost producers \$37 million annually. Across the entire United States, percent increase
4 in days to market for swine and beef, and the percent decrease in dairy milk production
5 for the 2040 scenario averaged 1.2 percent, 2.0 percent, and 2.2 percent, respectively,
6 using the CGC model, and 0.9 percent, 0.7 percent, and 2.1 percent, respectively, using
7 the Hadley model. For the 2090 scenario, respective changes averaged 13.1 percent, 6.9
8 percent, and 6.0 percent using the CGC model, and 4.3 percent, 3.4 percent, and 3.9
9 percent using the Hadley model. Respective changes in production for various U.S.
10 regions for the 2040 scenario are shown in Figs. 2.12, 2.13 and 2.14. In general, greater
11 declines in productivity are found with the CGC model than with the Hadley model.
12 Swine and beef production were affected most in the south-central and southeastern U.S.
13 Dairy production was affected the most in the Midwest and Northeast U.S. regions.
14

15 In earlier research, Hahn et al. (1992) also derived estimates of the effects of climate
16 change of swine growth rate and dairy milk production during summer as well as other
17 periods during the year. In the east-central U.S., per animal milk production was found to
18 decline 388 kg (~4 percent) for a July through April production cycle, and 219 kg (~2.2
19 percent) for an October through July production cycle as a result of global warming.
20 Swine growth rate in this same region was found to decline 26 percent during the summer
21 months, but increased nearly 12 percent during the winter months as a result of global
22 warming. Approximately one-half of these summer domestic livestock production
23 declines are offset by improvements in productivity during the winter. In addition, high
24 producing animals will most likely be affected to a greater extent by global climate
25 change than animals with lower production levels. Although percentage changes in
26 productivity may be similar at all production levels.
27

28 A production area in which global climate change may have negative effects, which are
29 not offset by positive winter effects, are conception rates, particularly in cattle, in which
30 the breeding season primarily occurs in the spring and summer months. Hahn (1995)
31 reported that conception rates in dairy cows were reduced 4.6 percent for each unit
32 change in THI above 70. Amundson et al. (2005) reported a decrease in pregnancy rates
33 of *Bos taurus* cattle of 3.2 percent for each increase in average THI above 70 and a
34 decrease of 3.5 percent for each increase in average temperature above 23.4°C. These
35 data were obtained from beef cows in a range or pasture management system. Amundson
36 et al. (2006) also reported that of the environmental variables studied, minimum
37 temperature had the greatest influence on the percent of cows getting pregnant. Clearly,
38 increases in temperature and/or humidity have the potential to affect conception rates of
39 domestic animals not adapted to those conditions. Summertime conception rates are
40 considerably lower in the Gulf States compared with conception rates in the Northern
41 Plains (Spratt et al. 2001).
42

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

1 have lower levels of productivity, which is likely the mechanism by which they were able
2 to survive as a dominant breed for that region. In addition, climate change and associated
3 variation in weather patterns will likely result in more livestock being managed in or near
4 facilities that have capabilities for imposing microclimate modifications (Mader et al.,
5 1997a and 1999a; Gaughan et al. 2002). Domestic livestock, in general, can cope with or
6 adapt to gradual changes in environmental conditions; however, rapid changes in
7 environmental conditions or extended periods of exposure to extreme conditions
8 drastically reduce productivity and are potentially life threatening.

9
10 Estimates of livestock production efficiency suggest that negative effects of hotter
11 weather in summer outweigh positive effects of warmer winters (Adams et al. 1999). The
12 largest change occurred under a 5°C increase in temperature, when livestock yields fell
13 by 10 percent in cow-calf and dairy operations in Appalachia, southeast, Delta, and
14 southern Plains regions of the United States. The smallest change was one percent under
15 1.5°C warming in the same regions. Livestock production also is affected by changes in
16 temperature and extreme events.

17
18 Another area of concern is the influence of climate change on diseases and parasites that
19 affect domestic animals. Incidences of disease, such as bovine respiratory disease, are
20 known to be increasing (Duff and Gaylean 2007). However, causes for this increase can
21 be attributed to a number of non-environmentally related factors. As for parasites, similar
22 insect migration and over-wintering scenarios observed in cropping systems may be
23 found for some parasites that affect livestock.

24
25 Baylis and Githeko (2006) describe the potential of how climate change could affect
26 parasites and pathogens, disease hosts, and disease vectors for domestic livestock. The
27 potential clearly exists for increased rate of development of pathogens and parasites due
28 to spring arriving earlier and warmer winters that allow for greater proliferation and
29 survivability of these organisms. For example, bluetongue was recently reported in
30 Europe for the first time in 20 years (Baylis and Githeko 2006). Warming and changes in
31 rainfall distribution may lead to changes in spatial or temporal distributions of those
32 diseases sensitive to moisture such as anthrax, blackleg, haemorrhagic septicaemia, and
33 vector-borne diseases. However, these diseases, as shown by climate-driven models
34 designed for Africa, may decline in some areas and spread to others (Baylis and Githeko
35 2006).

36 *2.7 Observing/Monitoring Systems*

37 **2.7.1 Monitoring Relevant to Crops**

38 *2.7.1.1 Environmental stress on crop production*

39
40 Stress symptoms on crop production include warmer canopies associated with increased
41 CO₂ (but the increment maybe too small to detect over 30 years), smaller grain size or
42 lower test weight from heat stress, more failures of pollination associated with heat stress,
43 and greater variability in crop production. Heat stress could potentially be monitored by

1 satellite image processing over the 30-year span, but causal factors for crop foliage
2 temperature need to be properly considered (temporary water deficit from periodic low
3 rainfall periods, effects of elevated CO₂ to increase foliage temperature, direct effects of
4 elevated air temperature, offset by opposite effect from prolonged water extraction
5 associated with CO₂-induced water conservation). Increased variability in crop yield and
6 lower test weight associated with greater weather variability relative to thresholds for
7 increased temperature can be evaluated both at the buying point, and by using annual
8 USDA crop statistics for rainfed crops. However, elevated CO₂ will have a helpful effect
9 via reduced water consumption. An assessment of irrigated crops can be done in the same
10 way, but with less expectation of water deficit as a causal factor for yield loss. The extent
11 of water requirement for irrigated crops could be monitored by water management district
12 records and pumping permits, but the same issue is present for understanding the
13 confounding effects of temperature, radiation, vapor pressure deficit, rainfall, and CO₂
14 effects.

15 ***2.7.1.2 Phenological responses to climate change***

16
17 A recent analysis of over 40 years of spring bloom data from the northeastern U.S., the
18 “lilac phenology network”, which was established by the USDA in the 1960s, provided
19 robust evidence of a significant biological response to climate change in the region
20 during the latter half of the 20th century (Wolfe et al. 2005).

21 ***2.7.1.3 Crop pest range shifts in collaboration with Integrated Pest Management*** 22 ***(IPM) programs***

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

30 **2.7.2 Monitoring Relevant to Pasturelands**

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

2.7.3 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, we have a long way to go in 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). Add to this the management imperative of public land agencies, monitoring of rangelands via remote sensing is already an important research activity (Afinowicz et al. 2005; Booth and Cox 2006; Clark and Hardegree 2005; Everitt et al. 2006; Weber 2006) with limited rancher acceptance (Butterfield and Malmstrom 2006). A variety of platforms are currently being evaluated, from low-flying aerial photography to satellite imagery, for use in evaluating a variety of attributes considered as important indicators of rangeland health, like plant cover and bare ground, presence of important plant functional groups or species, to documenting changes in plant communities, including weeds 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). The expansion of ecological models (e.g., state-and-transition; Bestelmeyer et al. 2004; Briske et al. 2005) to incorporate knowledge of rangeland responses to global change, and integration of those models with existing monitoring efforts and plant developmental data bases like the National Phenology Network (<http://www.uwm.edu/Dept/Geography/npn/>) could provide a cost-effective monitoring strategy for enhancing our 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 (<http://soils.usda.gov/survey/nscd/>) is an especially important baseline of soils information that can be useful for understanding the potential of soils to respond to climate change. However, it 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, our 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 (Penuelas and Estiarte, 1997). As a result, sampling of ecologically important

1 target species in different rangeland ecosystems would be a relatively low-cost measure
2 to monitor biogeochemical response to global change.

3 **2.8 Interactions among Systems**

4 **2.8.1 Climate Change and Sustainability of Pasturelands**

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

18 **2.9 Findings and Conclusions**

19 **2.9.1 Grain and Oilseed Crops**

20
21 Crop yield response to temperature and CO₂ for maize, soybean, wheat, rice, sorghum,
22 cotton, peanut, and dry bean in the United States were assembled from the scientific
23 literature. Cardinal base, optimum, and upper failure-point temperatures for crop
24 development, vegetative, and reproductive growth and slopes-of-yield decline with
25 increase in temperature were reviewed. In general, the optimum temperature for
26 reproductive growth and development is lower than that for vegetative growth.
27 Consequently, life cycle will progress more rapidly, especially giving a shortened grain-
28 filling duration and reduced yield as temperature rises. Furthermore, these crops are
29 characterized by an upper failure-point temperature at which pollination and grain-set
30 processes fail. Considering these aspects, the optimum mean temperature for grain yield
31 is fairly low for the major agronomic crops: 18-22°C for maize, 22-24°C for soybean,
32 15°C for wheat, 23-26°C for rice, 25°C for sorghum, 25-26°C for cotton, 20-26°C for
33 peanut, 23-24°C for dry bean, and 22-25°C for tomato.

34
35 The anticipated 0.8°C rise in temperature over the next 30 years is projected to decrease
36 maize, wheat, sorghum, and dry bean yields by 2.5, 4.4, 6.2, and 6.8 percent,
37 respectively, in their major production regions. For soybean, the 0.8°C temperature rise
38 will increase yield 1.7 percent in the Midwest where temperatures during July, August,
39 September average 22.5°C, but will decrease yield 2.4 percent in the South, where mean
40 temperature during July, August, September averages 26.7°C. Likewise, in the South, that
41 same mean temperature will result in reduced rice, cotton, and peanut yields, which will
42 decrease 8.0, 3.5, and 3.3 percent, respectively. An anticipated CO₂ increase from 380 to

1 440 ppm will increase maize and sorghum yield by only one percent, whereas the listed
2 C3 crops will increase yield by 6.1 to 7.4 percent, except for cotton, which shows a 9.2
3 percent increase. The response to CO₂ was developed from interpolation of extensive
4 literature summarization of response to ambient versus doubled CO₂. The net effect of
5 temperature and CO₂ on yield will be maize (-1.5 percent), soybean (Midwest, +9.1
6 percent; South, +5.0 percent), wheat (+2.4 percent), rice (-1.6 percent), sorghum (-5.2
7 percent), cotton (+5.7 percent), peanut (+3.4 percent), and dry bean (+0.3 percent). The
8 CO₂-induced decrease in measured ET summarized from chamber and FACE studies,
9 from 380 to 440ppm, gives a fairly repeatable reduction in ET of 1.4 to 2.1 percent,
10 although the 0.8°C rise in temperature would increase ET by 1.2 percent, giving a net 0.2
11 to 0.9 percent reduction in ET. This effect could lead to a further small 0.2 to 0.9 percent
12 increase in yield under rainfed production. A similar small reduction in crop water
13 requirement will occur under irrigated production.

14
15 As temperature rises, crops will increasingly begin to experience upper failure point
16 temperatures, especially if climate variability increases and if rainfall lessens or becomes
17 more variable. Under this situation, yield responses to temperature and CO₂ would move
18 more toward the negative side. Despite increased CO₂-responsiveness of
19 photosynthesis/biomass as temperature increases, there were no published beneficial
20 interactions of increased CO₂ upon grain yield as temperature increased because
21 temperature effects on reproductive processes, especially pollination, are so dominant.
22 On the other hand, there are cases of negative interactions on pollination associated with
23 the rise in canopy temperature caused by lower stomatal conductance.

24
25 Maximum CO₂ benefits generally require unrestricted root growth, optimum fertility, and
26 control of weeds, insects, and disease. Many C3 weeds benefit more than C3 crops from
27 elevated CO₂, and some research indicates that glyphosate, the most widely used
28 herbicide in the United States., loses effectiveness at CO₂ levels that are projected to
29 occur later this century. For those regions and crops where climate change impairs
30 reproductive development because of an increase in the frequency of high temperature
31 stress events (e.g., > 35°C), the potential beneficial effects of elevated CO₂ on yield may
32 not be fully realized.

33

34 **2.9.2 Horticultural Crops**

35

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

1 **2.9.3 Weeds**

2
3 The potential habitable zone of many weed species is largely determined by temperature.
4 For example, kudzu (*Pueraria lobata*, var. *montana*) is an aggressive species that has a
5 northern range currently constrained by the -20°C minimum winter temperature isocline.
6 While other factors such as moisture and seed dispersal will affect the spread of invasive
7 weeds such as kudzu, climate change is likely to lead to a northern migration in at least
8 some cases.

9
10 Many weeds respond more positively to increasing CO₂ than most cash crops,
11 particularly C₃ invasive weeds that reproduce by vegetative means (roots, stolons, etc.).
12 Recent research also suggests that glyphosate loses its efficacy on weeds grown at
13 elevated CO₂. While there are many weed species that have the C₄ photosynthetic
14 pathway and therefore show a smaller response to atmospheric CO₂ relative to C₃ crops,
15 in most agronomic situations, crops are in competition with a mix of both C₃ and C₄
16 weeds.

17 18 **2.9.4 Insects and Disease Pests**

19
20 In addition to crops and weeds, beneficial and harmful insects, microbes and other
21 organisms present in agroecosystems will be responding to changes in CO₂ and climate.
22 Numerous studies have already documented changes in spring arrival, over-wintering,
23 and/or geographic range of several insect and animal species due to climate change.
24 Disease pressure from leaf and root pathogens may increase in regions where increases in
25 humidity and frequency of heavy rainfall events are projected, and decrease in regions
26 projected to encounter more frequent drought.

27 **2.9.5 Rangelands**

28
29 The evidence from manipulative experiments, modeling exercises, and long-term
30 observations of rangeland vegetation over the past two centuries provide indisputable
31 evidence that warming, altered precipitation patterns, and rising atmospheric CO₂ can
32 have profound impacts on the ecology and agricultural utility of rangelands. Unlike
33 cropped and intensively-managed pasture systems, the vegetation composition and
34 overall ecology of rangelands develops in response to interactions of the environment and
35 management. While most information on these events comes either from short-term (last
36 five years at most) manipulative experiments, modeling exercises, or long-term
37 observations of rangeland vegetation changes (taken during the past 100+ years), the
38 certainty of recent climate and CO₂ predictions by the 2007 IPCC, along with an
39 increasingly complete understanding of ecosystem responses to climate change provide a
40 stable background upon which to forecast anticipated changes in U.S. rangelands for the
41 next 30 to 50 years.

42
43 By itself, increased atmospheric CO₂ leads to higher rangeland plant productivity through
44 greater photosynthesis rates and WUE. However, soil nutrient limitations may eventually

1 constrain production response. Because of its ability to stimulate both photosynthesis and
 2 WUE, rising CO₂ is leading to enhanced rangeland plant productivity. Furthermore,
 3 rangeland value depends as much – or more – on plant species composition as on
 4 productivity. The sensitivity of different species to CO₂ will also direct shifts in plant
 5 community species composition as CO₂ levels continues to climb. Increasing temperature
 6 will have both positive and negative benefits on plant productivity, depending on the
 7 prevailing climate and the extent to which temperature leads to desiccation. Like CO₂,
 8 temperature will certainly induce species shifts depending on species sensitivity and
 9 adaptability to temperature changes. Modeling exercises suggest generally positive NPP
 10 responses of Great Plains native grasslands to combined rising CO₂ and temperature
 11 (Pepper et al. 2005; Parton et al. 2007). This is also supported by experimental results
 12 suggesting enhanced productivity in shortgrass steppe under warming and elevated CO₂
 13 (Morgan et al. 2004a). An important exception to these findings is with California’s
 14 annual grasslands, where production appears only minimally responsive to increases in
 15 CO₂ or temperature (Dukes et al. 2005). Alterations in precipitation patterns will interact
 16 with rising CO₂ and temperature, although uncertainties about the nature of precipitation
 17 shifts, especially at regional levels, and the lack of multiple global change experiments
 18 that incorporate CO₂, temperature, and precipitation, severely limit our ability to predict
 19 consequences for rangelands. Our lack of knowledge of how these global change factors
 20 and soil nutrient cycling will interact to affect soil N availability also reduces confidence
 21 in accurately predicting what will happen with soil carbon storage in the next 30 years.

22
 23 In terms of species shifts, we expect plants with the C3 photosynthetic pathway – forbs,
 24 woody plants, and possibly legumes – to be favored by rising CO₂, although interactions
 25 of species responses with rising temperature and precipitation patterns may affect these
 26 functional group responses (Morgan 2005, in press). For instance, warmer temperatures
 27 and drier conditions will tend to favor C4 species, which may cancel out the CO₂-
 28 advantage of C3 grasses. There is already some evidence that climate change-induced
 29 species changes are underway in rangelands. The encroachment of woody shrubs into
 30 former grasslands is likely due to a combination of over-grazing, lack of fire, and rising
 31 levels of atmospheric CO₂. Combined effects of climate and land management change
 32 can drive species change that can have a tremendous negative impact on the range
 33 livestock industry (Bond and Midgley 2000; Morgan et al., in press; Polley, 1997).
 34 Spread of the annual grass *Bromus tectorum* (cheatgrass) through the Intermountain
 35 region of western North America appears driven at least in part by species sensitivity to
 36 rising atmospheric CO₂ (Smith et al. 2000; Ziska et al. 2005). In turn, this has altered the
 37 frequency and timing of wildfires by reducing establishment of perennial herbaceous
 38 species by pre-empting soil water early in the growing season (Young 1991). It seems
 39 likely that plant species changes will have as much or more impact on livestock
 40 operations as alterations in plant productivity.

41
 42 **Table 2.15. CO₂ and climate change responses**

Factor	RESPONSES TO RISING CO ₂ AND CLIMATE CHANGE	MANAGEMENT OPTIONS
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Primary production	<p><i>Increase or little change with rising CO₂</i>: Applies to most systems, especially water-limited rangelands. N may limit CO₂ response in some systems.</p> <p><i>Increases or little change with temperature</i>: Applies to most temperate and wet systems.</p> <p><i>Decreases with temperature</i>: Applies to arid and semi-arid systems that experience significantly enhanced evapotranspiration and drought, particularly where precipitation is not expected to increase.</p> <p><i>Variable responses with precipitation</i>: 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. Mowing practices (productive grasslands).</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 favour 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 productive grasslands with ample N, forage quality may increase due to more TNC. In N-limited native systems, CO₂-induced reduction in N and increased fibre may lower quality.</p>	<p>Utilize/interseed legumes where N is limiting and practice is feasible. Fertilize where feasible. Alter supplemental feeding practices.</p>
Animal performance to altered climate	<p><i>Increased temperature, warm regions</i>: Reduced feed intake, feed efficiency, animal gain, milk production and reproduction. Increased disease susceptibility, and death.</p> <p><i>Increased temperature, cold regions</i>: 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>Adjust forage harvesting (above) Alter management (e.g., timing of breeding, calving, weaning) Enterprise change (above)</p>

Table 2.15. CO₂ and climate change responses and management options for grazing land factors.

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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

1 presently available on livestock-plant interactions under climate change severely
2 compromises our ability to predict the consequences of climate change on livestock
3 grazing.

4
5 Another important knowledge gap concerns the responses of rangelands to multiple
6 global changes. To date, only one experiment has examined four global changes: rising
7 CO₂, temperature, precipitation, and N deposition (Dukes et al. 2005; Zavaleta et al.
8 2003a). Although interactions between global change treatments on plant production
9 were rare, strong effects on relative species abundances and functional plant group
10 responses suggest highly complex interactions of species responses to combined global
11 changes that may ultimately impact nutrient cycling with important implications for plant
12 community change and C storage. Such results underscore an emerging
13 acknowledgement that while there is certainty that rangeland ecosystems are responding
14 to global change, our ability to understand and predict responses to future changes are
15 limited.

16
17 Rangelands are used primarily for grazing. For most domestic herbivores, the preferred
18 forage is grass. Other plants – including trees, shrubs, and other broadleaf species – can
19 lessen livestock production and profitability by reducing availability of water and other
20 resources to grasses, making desirable plants unavailable to livestock or physically
21 complicating livestock management, or poisoning grazing animals (Dahl and Sosebee,
22 1991). However, in addition to livestock grazing, rangelands provide many other goods
23 and services, including biodiversity, tourism, and hunting. They are also important as
24 watershed catchments. Carbon stores are increasingly being considered as an economic
25 product (Liebig et al. 2005; Meeting et al. 2001; Moore et al. 2001; Schuman, Herrick
26 and Janzen 2001). However, there is still uncertainty about the greenhouse gas sink
27 capacity of rangelands, how it will be altered by climate change – including rising
28 atmospheric CO₂ – and, ultimately, the economics of rangeland C sequestration
29 (Schlesinger 2006; van Kooten 2006). While we are still unable to predict accurately the
30 consequences of all aspects of climate change for rangelands, a recent list of management
31 options (Morgan 2005) suggests the types of choices ranchers and land managers will
32 need to consider in the face of climate change (Table 2.15).

33
34 A challenge for rangeland scientists, public land managers, ranchers, and others
35 interested in rangelands will be understanding how the dynamics of climate change and
36 land management translate into ecological changes that impact long-term use and
37 sustainability. Perhaps more than most occupations, ranching in the present-day United
38 States is as much a lifestyle choice as it is an economic decision (Bartlett et al. 2002), so
39 economics alone will not likely drive decisions that ranchers make in response to climate
40 change. Nevertheless, ranchers are already looking to unconventional rangeland uses like
41 tourism or C storage. In regions where vegetation changes are especially counter-
42 productive to domestic livestock agriculture, shifts in enterprises will occur. Shifts
43 between rangeland and more intensive agriculture may also occur, depending on the
44 effects of climate-induced environmental changes and influence of economics that favor
45 certain commodities. However, once a native rangeland is disturbed, whether
46 intentionally through intensive agriculture or unintentionally through climate change,

1 restoration can be prohibitively costly, and in some cases, impossible. Therefore,
2 management decisions on the use of private and public rangelands will need to be made
3 with due diligence paid towards their long-term ecological impacts.

4 **2.9.6 Animal Production Systems**

5
6 Increases in air temperature reduce livestock production during the summer season with
7 partial offsets during the winter season. Current management systems usually do not
8 provide as much shelter to buffer the effects of adverse weather for ruminants as for non-
9 ruminants. From that perspective, environmental management for ruminants exposed to
10 global warming needs to consider 1) general increase in temperature levels; 2) increases
11 in nighttime temperatures; and 3) increases in the occurrence of extreme events (e.g.,
12 hotter daily maximum temperature and more/longer heat waves).

13
14 In terms of environmental management needed to address global climate change, the
15 impacts can be reduced by recognizing the adaptive ability of the animals and by
16 proactive application of appropriate counter-measures (sunshades, evaporative cooling by
17 direct wetting or in conjunction with mechanical ventilation, etc.). Specifically, the
18 capabilities of livestock managers to cope with these effects are quite likely to keep up
19 with the projected rates of change in global temperature and related climatic factors.
20 However, coping will entail costs such as application of environmental modification
21 techniques, use of more suitably adapted animals, or even shifting animal populations.

22
23 Climate changes affect certain parasites and pathogens, which could result in adverse
24 effects on host animals. Interactions exist among temperature, humidity, and other
25 environmental factors, which, in turn, influences energy exchange. Indices or measures
26 that reflect these interactions remain ill-defined, but research to improve them is
27 underway. Factors other than thermal (i.e., dust, pathogens, facilities, contact surfaces,
28 technical applications) also need better definition. Duration and intensity of potential
29 stressors are of concern with respect to the coping and/or adaptive capabilities of an
30 animal. Further, exposure to one type of stressor may lead to altered resistance to other
31 types. Other interactions may exist, such that animals stressed by heat or cold may be less
32 able to cope with other stressors (restraint, social mixing, transport, etc). Improved
33 stressor characterization is needed to provide a basis for refinement of sensors providing
34 input to control systems.

35
36 Innovations in electronic system capabilities will undoubtedly continue to be exploited
37 for the betterment of livestock environments with improved economic utilization of
38 environmental measures, and mitigation strategies. There is much potential for
39 application of improved sensors, expert systems, and electronic stockmanship. Continued
40 progress should be closely tied to animal needs based on rational criteria, and must
41 include further recognition of health criteria for animal caretakers as well. The ability of
42 the animal's target tissues to respond to disruptions in normal physiological circadian
43 rhythms may be an important indicator of stress. Also, the importance of obtaining
44 multiple measures of stress is also becoming more apparent. However, inclusion and
45 weighting of multiple factors (e.g. endocrine function, immune function, behavior

1 patterns, performance measures, health status, vocalizations) is not an easy task in
2 developing integrated stress measures. Establishing threshold limits for impaired
3 functions that may result in reduced performance or health are essential. Modeling of
4 physiological systems as our knowledge base expands will help the integration process.
5
6