WEEDS, INSECTS, AND DISEASES

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Abstract. The geographic distribution, vigor, virulence, and agricultural impact of weeds, insects, and plant pathogens will be affected by climatic changes accompanying the global "greenhouse effect." Weed/crop competitive interactions, particularly among species differing in photosynthetic pathway (C_3 v C_4), may be altered, with the C_3 species favored by increasing CO_2. Physiological and biochemical changes induced in host crop plants by rising CO_2 may affect feeding patterns of pest insects. Compilation of climatic thresholds for phenological development of pest insects reveals the potential for shifts in pest behavior induced by global warming and other climatic change. Generation times may be reduced, enabling more rapid population increases to occur. Poleward migration may be accelerated during the crop season. The epidemiology of plant diseases also will be altered. Prediction of disease outbreaks will be more difficult in periods of rapidly changing climate and unstable weather. Environmental instability and increased incidence of extreme weather may reduce the effectiveness of pesticides on targeted pests or result in more injury to non-target organisms. Biological control may be affected either negatively or positively. Overall, the challenge to agriculture from pests probably will increase.

1. Introduction

Weeds, insects, and pathogen-mediated plant diseases will be affected by global climate change. Alterations in the geographic distribution of these crop pests and their vigor in current ranges likely will occur. Existing research has investigated climatic determinants of the range of many pests, and a large body of literature addresses the effects of warmer drier climates on crops and some of their pests. However, the potential for climatically driven changes in crop

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losses due to pests have not been included in most agricultural impact studies (Prestidge and Pottinger, 1990; Stinner et al., 1987; Waggoner, 1983). This review provides a background for evaluating possible impacts of climate change on crop pests and the resulting effects on crop production.

2. Weeds

Worldwide, crop production losses from weed interference are estimated to be about 12%. Losses are highest in primitive agricultural production systems, averaging 25% of crop production (Parker and Fryer, 1975). Extensive efforts are made to control weeds. Most cultivation and tillage practices are for weed control, and over half of the pesticides applied annually to cropland are herbicides for controlling weeds (Furtick, 1978).

Weeds share the same trophic level (primary producer) with crops and compete with crops for the resources essential for plant growth. Unless controlled, weeds are always present at yield-reducing levels in the agroecosystem, because of the reservoir of weed seeds in agricultural soils. Changes in CO_2 concentration, temperature, and water or nutrient availability affect plant growth. Factors that differentially affect crops and weeds are most likely to affect weed/crop competition and other weed/crop interactions.

2.1 THE PHYSIOLOGICAL EFFECTS OF RISING CO_2 ON WEEDS

Weeds will benefit from the "CO_2 fertilization effect" and from improvements in water use efficiency associated with the partial closure of stomates by increasing CO_2 concentrations. Evapotranspiration on a land area basis may not be altered as much as expected from the effects of rising CO_2 on stomatal aperature, because of interactions with other limiting factors (Patterson, 1995). The different patterns of response of C_3 and C_4 plants to CO_2 are of particular significance in weed/crop competition, because most of the world's crops are C_3 plants, while many major weeds are C_4 plants (Patterson and Flint, 1980). For example, 80 of the 86 "plant species commodities" that contribute 90% of per capita food supplies worldwide are C_3 plants (Prescott-Allen and Prescott-Allen, 1990), while 14 of the 18 "world's worst weeds" are C_4 plants (Holm et al., 1977). In the agroecosystem, the growth and competitive interactions of C_3 and C_4 crops and weeds are synchronized by the timing of planting of the crop and by other cultural manipulations and are not temporally separated as they are in most natural ecosystems. Additionally, the agricultural weed flora has been homogenized through dispersal and distribution by man, so that species combinations which never occur in natural ecosystems occur

together and compete in agroecosystems.

Under controlled conditions, CO_2 enrichment stimulates the growth of C_3 weeds and crops more than that of C_4 species, although a considerable range of response has been reported (Table 1). Temperatures during growth also affect responses to elevated CO_2, and responses vary with species (Patterson, 1995). In competition experiments, C_3 species generally benefit from CO_2 enrichment at the expense of C_4 species (Carter and Peterson, 1983; Wray and Strain, 1987; Bazzaz and Garbutt, 1988; Patterson and Flint, 1990). For example, the competitiveness between C_3 soybean and C_4 johnson grass (*Sorghum halepense* (L.) Pers.) was increased when CO_2 was increased from 350 to 675 ppm (Patterson et al.; 1984). Unfortunately, no studies of CO_2 effects on weed/crop competition under field conditions have been reported to date.

Table 1

Biomass responses of C_3 and C_4 plants to CO_2 doubling.

Category	Range of Response
C_3 Crops	1.10 to 2.43 X
C_4 Crops	0.98 to 1.24 X
C_3 Weeds	0.95 to 2.72 X
C_4 Weeds	0.56 to 1.61 X

Summarized from a literature survey by Patterson (1993)

2.2 INDIRECT (CLIMATIC) EFFECTS ON WEED GROWTH AND WEED/CROP COMPETITION

In addition to the direct, physiological effects of rising CO_2, climatic change could have significant effects on weed growth, weed/crop competition, and the geographical distribution of weeds. Temperature and precipitation are the primary variables controlling the distribution of vegetation (Woodward and Williams, 1987). High latitude limits of tropical and warm temperate annual species are primarily set by the accumulated heat sum during the growing season. Low latitude limits of species from cool or cold regions are set by competition, cold tolerance apparently being achieved at the expense of competitive ability (Woodward, 1988). Temperature and precipitation patterns influence the distribution of weeds concurrently with the selection of crops. Choice of growing season, manipulative cultural practices, fertilization, and irrigation ameliorate unfavorable conditions for crops, but weeds often benefit

as well (Harlan, 1975).

Most weeds of warm season crops originated in tropical or warm temperate areas. Growth of such species often is very responsive to small increases in temperature. For example, the growth of three leguminous weeds increased significantly as day/night temperature increased from 23/17 to 26/20 or 29/23°C (Flint et al., 1984). Biomass of C_4 smooth pigweed (*Amaranthus hybridus* L.) grown at 29/20°C was 240% of that grown at 26/17°C (Flint and Patterson, 1983). C_4 grass weeds also respond to small temperature increases in the range of 26/20 to 29/23°C (Patterson, 1993). The stimulation of weed growth by 3 to 5°C increments in this range has significant implications for weed/crop competition, because temperature increases of this magnitude may occur within the next 100 yr.

The range expansion of many weeds into higher latitudes may accelerate with global warming (Patterson, 1993; Rahman and Wardle, 1990). Detailed study of the growth of one such species, itchgrass (*Rottboellia cochinchinensis* Lour.), in 36 day/night temperature regimes ranging from 17/11 to 32/26°C confirmed its responsiveness to simulated global warming (Patterson et al., 1979). A warming of 3 °C from 26/20 to 29/23°C increased itchgrass dry weight by 88% and leaf area by 68%. Based on its responses to temperature, itchgrass in the United States' current climate could achieve 75 to 100% of its maximum growth in the Gulf Coast states, the South Atlantic states, the lower Midwest, and the Southwest. Only 50 to 75% of maximum growth would occur in the Middle Atlantic states, the central Midwest and the Sacramento Valley in California. A 3°C warming of these latter areas would effectively shift the zone of 75 to 100% growth northward to include the zone previously supporting only 50 to 75% of maximum growth. Changes in climatic variables other than temperature could influence this hypothetical northward range expansion by itchgrass.

Global warming also could allow the northward range expansion of other exotic noxious weeds in North America such as cogongrass (*Imperata cylindrica* (L.)Beauv), and witchweed (*Striga asiatica* (L.)Ktze) (Patterson, 1995). However, not all exotic weeds will be favored by climatic warming. When the exotic wild proso millet (*Panicum miliaceum* L.) was grown in competition with its native congener, (*Panicum texanum* Buckl.), the latter was superior at 30/24°C while the former was more competitive at 24/18°C (Patterson et al., 1986). Under current climatic conditions, the southward spread of wild proso millet may be at least partially restricted by competition from grass weeds adapted to warm conditions. Climatic warming might further restrict the southward range expansion of wild proso millet and other weeds currently limited either by warm temperatures or by competitive pressure from warm-adapted weeds. The relative advantage conferred to either weed or crop will depend on the competing species and on other environmental factors in addition to temperature.

2.3 IMPLICATIONS FOR WEED MANAGEMENT

A major obstacle to projecting the future impact of climate change on agriculture is a lack of knowledge of the effects on agricultural pests (Prestidge and Pottinger, 1990; Stinner et al., 1987; Waggoner, 1983). If the increasing CO_2 acts as a fertilizer, the growth of weeds as well as crops will be stimulated. Which will benefit the most depends on the species, their photosynthetic pathways, and the interacting effects of other environmental factors. Field experiments with conventional fertilizers have demonstrated that increased weed competition can occur in response to supplemental nutrients and that weed competition can eliminate the yield-enhancing effects of fertilization (Carlson and Hill, 1985).

In addition to influencing the competitiveness and geographical distribution of weeds, increasing CO_2 and climate change probably will require modification of current weed control technology (Patterson, 1993, 1995). Environmental factors such as temperature, precipitation, wind, soil moisture, and atmospheric humidity influence the application of herbicides and their effectiveness (Hatzios and Penner, 1982; Muzik, 1976). Variations in these environmental factors accompanying global warming may make appropriate application more difficult, and may affect herbicide injury of crops and other non-target organisms.

Temperature and moisture availability affect both the uptake and metabolism of herbicides by crops and target weeds. The antitranspirant effects of higher CO_2 levels could reduce plant uptake of soil-applied herbicides. Changes in leaf anatomy and leaf surface characteristics, induced directly by high CO_2 or caused by climatic factors, could also affect plant uptake of herbicides. High leaf starch concentrations which commonly occur in C_3 plants grown under CO_2 enrichment (Wong, 1990) might interfere with herbicide activity. On the other hand, increased temperatures and increased metabolic activity tend to increase uptake, translocation, and effectiveness of many herbicides. Increased rhizome and tuber growth in perennial C_3 weeds is a likely consequence of the increased photosynthate supply in high CO_2 environments (Oechel and Strain, 1985). This could increase the difficulty of controlling perennial weeds either mechanically or chemically.

The effectiveness of natural and implemented biological control of weeds and other pests depends on climate. Synchrony between the growth, development, and reproduction of biocontrol agents and their targets, essential for effective long term control, might not be maintained in periods of climatic change, particularly if climatic extremes occur more frequently. On the other hand, global warming could facilitate overwintering of insect populations and favor earlier poleward migrations in the spring. This could increase the effectiveness of biological control of weeds in some cases.

3. Insect Activity and Distribution

Increasing global atmospheric CO_2 may affect insect feeding activity through effects on host plant physiology and chemical composition (Patterson, 1993). More importantly, the accompanying climatic changes will affect the distribution and degree of infestation of insect pests through both direct effects on the life cycles of insects and indirectly through climatic effects on hosts, predators, competitors, and insect pathogens. There is some evidence that the risk of crop loss will increase due to poleward expansion of insect ranges. Agricultural systems create modified and unstable habitats favoring migratory insects that have higher reproduction and mortality rates (Southwood and Comins, 1976). The population size of insects associated with unstable environments tends to be dominated by density-dependent characteristics, so human alteration of conditions that affect host plant survival, irrigation for example, will affect phytophagous (leaf-eating) insect populations. When confronted by climate change, agricultural insects must diapause (enter a state of dormancy), migrate, otherwise adapt genetically, or die.

Insect life cycle processes affected by climate and weather include lifespan duration, fecundity, diapause, dispersal, mortality and genetic adaptation. Porter et al. (1991) listed the following effects of temperature on insects: limiting geographical ranges; over-wintering; population growth rates; number of generations per annum; length of growing season; crop-pest synchronization; interspecific interactions; dispersal and migration; and availability of host plants and refugia. The effects of climate and weather on insect life cycles have been documented for a wide variety of insect pests of agriculture, rangelands, and forests (Dobzhansky, 1965; Fye and McAda, 1972; Tauber et al., 1986; Mattson and Haack, 1987; Kingsolver, 1989; Cammell and Knight, 1991; Harrington and Stork, 1995). A summary of the climatic thresholds for the phenological development of agricultural pest insects can be found in Table 2. Many effects involve changes in the severity of outbreaks following extreme weather events (on the order of hours to weeks). Freezing temperatures are a major factor in mortality but *Drosophila* sp. insects that survived relatively colder temperatures were found to be more fecund than cohorts that were not exposed to the low temperatures (Dobzhansky, 1965). Temperatures that exceed critical thresholds frequently have adverse effects on fecundity as in the cases of bollworm, *Helicoverpa zea* (Boddie), tobacco budworm, *Heliothis virescens* (F.), beet armyworm, *Spodoptera exigua* (Hü bner), cabbage looper, *Trichoplusia ni* (Hübner), saltmarsh caterpillar, *Estigmene acrea* (Drury), and pink bollworm, *Pectinophora gossypiella* (Saunders) (Fye and McAda, 1972).

Table 2

Climatic thresholds and responses for the phenological development of agricultural pest insects.

Species	Common	Thresholds	Response Functions
Aculops lycoperici	Tomato russet mite	$T_a < 0.0^oC$	Lethal to all stages for prolonged exposure; 7 days per generation
Aedes aegypti	Salt Marsh mosquito	$T_a = 27.0^oC$	10-14 days per generation
Anabrus simplex	Mormon cricket		60-90 days per generation
Antonina sim-plex	Rhodes grass mealybug	$T_x > 42.0^oC$ and $T_n < -2.0^oC$;	Lethal;
		$0.0^oC < T < 38.0^oC$;	Physiological development occurs:
		$29.0^oC < T < 32.0^oC$	Optimal physiological development rate occurs; Confined to $30^oS - 30^oN$ latitude;
Blissus leucopterus	Chinch bugs		Frequent rain during hatch reduces infestations; Extremely low temperatures and sudden changes of temperature kill adults in winter and spring; Thrive in hot, dry weather
Carpophilus lugubris	Dusky sap beetle	$T_a = 24.0^oC$	Eggs: 2.5 days; Larvae: 14 days; Adults: 14 days
Chlorochroa say	Say stinkbug	$T > 21.0^oC$	Oviposition occurs
Cochilomyia hominivorax	Screwworm	$T_a < 12.0^oC$	Two-month exposure is lethal to pupae in the soil
Coleophora laricella	Larch casebearer	No lower thermal limit	
Dasyneura laricis	Larch gall midge	$T_a = 0.0^oC$	1600 DD per generation
Dendroctonus ponderosae	Mountain pine beetle	$T_a = 16.0-30.0^oC$; $21.0^oC<T<38.0^oC$;	Emergence; Flight initiation;

		$T_n < -18.0^oC$; $T_n < -40.0^oC$	Lethal to eggs; Lethal to larvae; Single generation may require 2 years; Multiple generations may develop in the southern part of the range
Dendroctonus micans	Greater European spruce bark beetle	$T = 20.0 - 23.0^oC$	Flight; Eggs:10-15 days at 20.0^oC; Larvae:50-60 days at 19.0-23.0^oC; Pupae: 4-6 days at 19.0-23.0^oC; Emergence: 44 days at 20.0^oC
Diabrotica undecimpunctata undecimpunctata	Western spotted cucumber beetle	Jan. $T_a < 10.0^oC$	No overwintering
Diprion pini	Pine sawfly	$T_n < 10.0^oC$ or $T_x > 35.0^oC$; $T_n < 0.0^oC$ or $T_x > 35.0^oC$; $12.0^oC < T < 25.0^oC$; $T < -20.0^oC$	Lethal to eggs; Lethal to false caterpillars: False caterpillars develop: Eonymphs in cocoons can survive for at least 1 mo.; Incubation: 40 days at 10.0^oC; 18 days at 18.0^oC; 13-14 days at 20.0^oC; 12 days at 25.0^oC; 7 days at 32.0^oC
Epirrita *Oporinia autumnata*	Autumnal moth	$T_n < -37.0^oC$	Lethal to eggs
Heliciverpa zea	Corn earworm, Cotton bollworm	$T_a = 12.5^oC$; $T_a = 12.6^oC$	185 DD for larval development (on sweet corn); 557 DD per generation (on cotton); Overwintering confined to < 39^oN latitude
Heliothis virescens	Tobacco budworm	$T_a = 12.6^oC$	448 DD per generation (on cotton)
Hyblaea puera	Teak defoliator		Larvae 10-12 days at optimal conditions; 21 days average;

Life cycle 19-36 days

Ips typographis	Spruce bark beetle	$T_x > 47.0^oC$	Lethal
Lymantria monacha	Nun moth	$0.0^oC < T < 45.0^oC$	Vital thermal limits; More frequent outbreaks in low-precipitation sites
Lymantria dispar	Gypsy moth	Precipitation 25-100 cm; $15.0^oC < $ Jul. $T_a < 27.0^oC$; $-18.0^oC < $ Jan. $T_a < -12.0^oC$ $T_a = 20.^oC$	Photoperiod does not control diapuse; Dispersal delayed by precipitation or $T < 7.0^oC$; Larvae: 44-50 days at 20.0^oC
Monochamus alternatus	Japanese pine sawyer	$T_a = 12.5^oC$; $T < 18.0^oC$	625 DD per generation; No feeding or dispersal; Flight Index (FI) is a measure of infestation potential: FI= # days with Tavg > 18.0^oC and Pavg < 10 mm, No infestation for FI < 60 days, Severe infestation for FI > 80 days
Musca domestica	House fly	$T_a = 27.0^oC$	10-12 days per generation
Ostrinia nubilalis	European corn borer	$T_a = 10.0^oC$	726 DD per generation; Eggs 7 days; Larvae 35 days; Diapause of mature larvae induced at photophase LD< 14.75:9.25; Cool, rainy weather in June inhibits oviposition and washes emerging Larvae from plants thus reducing infestations; Dry summers and extremely cold winters increase mortality
Panolis flammea	Pine beauty moth		Obilgatory pupal diapause 120-130 days; Oviposition: T < 6.0^oC none; T = 10.0^oC 50%; T = $15.0-20.0^oC$ maximal; Eggs: 6.3 days at 20.0^oC; 19.7 days at 10.0^oC;

			Larvae: 28 days at 20.0°C; 71 days at 10.0°C; Pupae: susceptible to prolonged water logging, desiccation and min. 1 day exposure to T = -20.0°C
Pectinophora gossypiella	Pink bollworm		25-30 days per generation (midsummer)
Perkinsiella saccharicida	Sugarcane delpacid		Life cycle: 48 days at 25.0°C; 56 days at 22.2°C
Phthorimaea operculella	Potato tuberworm	$T_n < 10.0$°C	No damage occurs to plants
Pissodes strobi	Spruce weevil	$T_a = 7.2$°C	785 DD per generation
Pseudaletia unipuncta	Armyworm		Outbreaks follow cold, wet spring weather
Schizaphis graminum	Greenbug	$T_n > 4.5$°C	
Scolytus ventralis	Fir engraver beetle	$T > 24.0$°C	Flight initiation
Sirex noctilio	Woodwasp	$T > 20.0$°C	Enhanced flight and mating; Outbreaks during drought
Spodoptera exigua	Beet armyworm	$T_a = 12.2$°C	517 DD per generation
Spodoptera frugiperda	Fall armyworm	$T_a = 13.8$°C	340 DD per generation
Trypodendron lineatum	Striped ambrosia beetle	$T > 15.5$°C; 19.0°C$ < T < 26.0$°C; $T = 30.0$°C	Dispersal flight initiated; Optimal for flight; Maximum for flight
Zeiraphera diniana	Larch budmoth	$T_n < -51.3$°C; $T > 7.0$°C	Lethal to eggs; Flight initiation

Abnormally cool, wet conditions were associated with high subsequent infestations of cotton by cotton tipworm, *Crocidosema plebejana* (Zeller) (Hamilton and Gage, 1986). November precipitation and April temperature were the best indicators of mean grasshopper densities in southern Idaho

(Fielding and Brusven, 1990). Drought can affect various physiological processes of plants which may increase the plants' attractiveness and susceptibility to phytophagous insects (Mattson and Haack, 1987). Intense precipitation has been noted as a deterrent to the occurrence and success of oviposition by insects such as the European corn borer, *Ostrinia nubilalis* (Hübner) (Davidson and Lyon, 1987). Abundant precipitation can affect mortality through, for example, drowning of soil-dwelling insects (Watt and Leather, 1986), but is more likely to indirectly affect insects through climatic effects on insect pathogens, predators and parasites as has been shown for *H. zea* pupae especially under persistently saturated soil conditions (Raulston et al., 1992).

While the specific ways in which climate change could affect persistent wind patterns such as nocturnal wind jets in the U.S. and convergence systems such as the Inter-Tropical Convergence Zone (ITCZ) are poorly predicted by GCMs, changes in the strength, timing, and geographical extent of these systems have been hypothesized. Some of the most important insect pests of agriculture currently use these systems to disperse widely from decaying habitats to viable habitats (Pedgley, 1982). Corn earworm, *H. zea*, moths in the U.S. (Westbrook et al., 1985; Scott and Achtemeier, 1987; Lingren *et al.*, 1993), grasshoppers or locusts (*Ailopus simulatrix* Walker), old world bollworm (*Heliothis armigera* (Hübner)) and whitefly (*Bemisia tabaci* (Gennadius)) disperse via atmospheric transport. In the case of the ITCZ and locusts, the winds also contribute ephemeral precipitation for host plants as reviewed by Joyce (1983) and Rainey (1989). Changes in these systems would affect the speed and range of dispersal of these pests.

Many of the documented effects of climate on insects are based on unusual weather events affecting the severity of insect outbreaks within their normal range; the (unintended) introduction of exotic species into new environments; or the extension of (host) crops into new environments (e.g., through irrigation). Human-induced local climate change as has occurred within urban areas provides evidence of how insects can adapt to changes in their environment. Examples of genetic adaptation include: Queensland fruitfly (*Dacus tryoni* Froggatt), lucerne flea (*Sminthurus viridis* L.) and sheep blowfly (*Lucilia cuprina*) (Wied.) in Australia after introduction from Europe and with the expansion of crop areas; the European corn borer, *O. nubilalis* (Hübner) and the European spruce sawfly, *Gilpinia hercyniae* (Hartig) in North America after introduction from Europe; and of *Drosophila serrata* Mallock across latitudes (Birch, 1965). *Drosophila serrata* Mallock also has responded by natural selection to the changed conditions in large cities (Dobzhansky, 1965). Selection to tighten host-insect interaction (such as codling moth, *Cydia pomonella* (L.), in fruit trees) appears to favor the evolution of isolated host races (Pashley and Bush, 1979). Climatic, agronomic, political, and economic factors jointly led to populations of boll weevil, *Anthonomus grandis grandis* Boheman, that adapted differently across cotton areas in the U.S. (Terranova *et*

al., 1990). Although insect populations have been redistributed during periods of major climatic change, a continuous intermixing of beetle species' gene pools in the Rocky Mountains of the U.S. was determined to have prevented speciation (Elias, 1991).

Understanding of physiological development and behavior has allowed development of numerical models that estimate insect growth, movement and mortality in response to potential changes in climate   (Goodenough and McKinion, 1992). Minimum and maximum temperatures, required cumulative degree days, and, where important, the effects of drought or wet conditions, which are the basis for such models, have been established for many common agricultural pests (e.g., Fye and McAda, 1972;   Davidson and Lyon, 1987).Simulation models predict *potential* redistribution of insects under simulated climates.

Specific studies of the likely impacts of climate change were reviewed by Cammel and Knight (1991), Porter *et al.* (1991), Sutherst (1990, 1991) and Sutherst *et al.* (1995). They demonstrate that impacts could be severe in many different environments and involve numerous different species of insect pests. Principal concern is with species that can increase their population size by undergoing an extra generation each year in warmer climates or expand their geographical distributions. For example, Porter *et al.* (1991) found that in Europe *O. nubilalis* would shift 1220 km northward if temperature increased by 3° to 6°C by 2025-2070. For a 3°C temperature increase in Japan, Mochida (1991) predicted expanded ranges for tobacco cut worm (*Spodoptera litura*), southern green stink bug (*Nezera viridula*), rice stink bug (*Lagynotomus eleongatus*), lima-bean pod borer (*Etiella zinckenella*), common green stink bug (*Nezera antennata*), soybean stem gall (*Asphondylia* sp.), rice weevil (*Sitophilus oryzae*), and soybean pod borer (*Legumunuvora glycinivorella*), but a decreased range for rice leaf beetle (*Oulema oryzae*) and rice leaf miner (*Agromyza oryzae*). Vegetation subzones were linked with microclimates to extrapolate spruce weevil hazard zones in British Columbia (Spittlehouse and Sieben, 1994).   Models that match discrete ranges of temperature and precipitation, with the presence of particular species (such as CLIMEX), may be especially appropriate for projecting the effects of climate change on insect redistribution (Worner, 1988; Sutherst *et al.*,1995).

Actual insect distributions under climate change will also depend on host distributions (Rainey, 1989), competition with existing species (DeBach, 1965), adaptability to new conditions, and the presence of natural enemies in the area.   Since climate effects on insect life cycles frequently depend on extreme events (e.g., freezes, intense precipitation) and climatic features such as the persistent winds of the Inter-Tropical Convergence system, the reliability of predicted redistribution of insects depends, in part, on the reliability of predictions of these climatic features.

4. Plant Diseases

The occurrence of plant fungal and bacterial pests depends on temperature, rainfall, humidity, radiation, and dew. Climatic conditions affect the survival, growth and spread of pathogens as well as the resistance of their hosts to infection. Friedrich (1994) summarized the observed relationship between climatic conditions and important plant diseases. Among these, mild winters have been associated with more rapid and stronger outbreaks of powdery mildew (*Erysiphe grammis*), brown leaf rust of barley (*Puccinia hordei*), and strip rust of cereals (*Puccinia striiformis*) (Meier, 1985). Mild winters combined with very warm weather conditions provide optimal growth conditions for cercosporea leaf spot disease (*Cercosporea beticola*), powdery mildew (*Erysiphe betae*), and rizomania disease (*Rizomania*) (Treharne, 1989). Warm, humid conditions lead to earlier and stronger outbreaks of late potato blight (*Phytophthora infestans*) (Löpmeier, 1990; Parry et al., 1990). Dry and hot summers generally reduce infestations of most fungal diseases because plant resistance is increased. Summer dryness, particularly in early summer, also decreases rhynchosporium leaf blotch (*Rhynchosporium secalis*) and septoria leaf spot diseases (*Septoria tritici* and *S. nodorum*) but more frequent summer precipitation, particularly heavy storms, would increase incidences of these diseases because rain and rain-born splash water are the means by which disease spores are spread (Royle et al., 1986). Warmer temperatures would likely also shift the occurrence of these diseases into presently cooler regions (Treharne, 1989).

5. Conclusions

Although weeds will be affected directly by increasing atmospheric CO_2 levels, the most significant effects on pests will result from changes in temperature, precipitation distribution, and wind patterns. Climatic change will alter the geographic range and impact of many crop pests. New pest/crop associations may occur. Some old problems may worsen, but others may become less severe. Efforts to control or manage pests will be affected. Environmental variation and increased incidence of extreme weather may reduce the effectiveness of pesticides on targeted pests or result in more injury to non-target organisms. Natural and managed biological control may be affected either negatively or positively. Overall, the challenge to agriculture from pests probably will increase.

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