BIOCLIMATOLOGY

Bioclimatology (biometeorology) is the study of the relationships between climate (weather) and living organisms. The field is vast and brings together scientists from many disciplines. Bioclimatology is frequently divided into human, plant (agricultural and forest), and animal bioclimatology. Other subdivisions include aerobiology (the behavior of airborne living material), phenology, urban bioclimatology, air pollution bioclimatology, tourism and recreation bioclimatology, mountain bioclimatology, electromagnetic and ionization bioclimatology, and bioclimatological rhythms. However, no single classification system has been adopted universally. The American Meteorological Society, for example, has several committees with bioclimatological involvements: Agricultural and Forest Meteorology, Applied Climatology, Biometeorology and Aerobiology, and Meteorological Aspects of Air Pollution. The time intervals studied range from the daily cycle to geological times.

Bioclimatology is an interesting research field that has many important practical applications for human comfort, agricultural yields, regional land-use planning, forest management, building research, and so forth. A focus for bioclimatological studies is provided by the International Society of Biometeorology, which sponsors the *International Journal of Biometeorology* (Springer-Verlag Publishers, Heidelberg, Germany). However, research results appear in a wide range of journals.

Bioclimatologists customarily refer to an environmental stress that causes a biological response. The word stress does not necessarily imply a harmful effect; a brisk walk on a cold day may be considered invigorating by many people, for example. Over the centuries, humans have been increasing their ability to reduce unwanted environmental stresses through use of clothing, heated and air-conditioned buildings, irrigation, flood-control systems, fertilizers, and pesticides. By the year 1960 expectation was widespread that humans soon would have total control of their environment. However, beginning in the 1960s this utopian view began to be challenged, and since the 1980s it is generally believed that environmental stresses are necessary to retain the resilience of humans and supporting ecosystems. By using technology to shield living things from the rigors of the elements, the chances increase that the capacity to withstand extremes may become seriously impaired. For example, a severe ice storm in January 1998 in eastern Canada and northeastern United States caused serious damage to the power supply infrastructure, which led to electricity blackouts for several days (Higuchi et al., 2000). Communities in those regions that depended heavily on modern technology suffered more than those that were accustomed to power outages and had their own back-up alternatives. Bioclimatologists have a full agenda for the next few decades elaborating these issues, particularly in the face of global environmental change (see article in this Encyclopedia on Global Environmental Change: Impacts, by the same authors).

The field of bioclimatology is too broad to cover here; therefore, the approach taken is to discuss a few topics in sufficient detail to give the reader an idea of the flavor of bioclimatology. A list of further reading is added with respect to subjects not mentioned in the text.

Bioclimatological methods

Methods used in bioclimatological research are of three main types:

1. Statistical

Multivariate regressions or other statistical methods, in which a response characteristic is correlated with an array of possible indicators of stress. Although a significance test may indicate an association, it does not imply the existence of a cause– effect relationship.

2. Experimental

Controlled *laboratory studies* using human volunteers or greenhouses/phytotrons/biotrons in the case of plants, animals and whole ecosystems. An ethical problem with studies involving human volunteers is that the stress produced might be harmful (e.g. causing an asthma attack) for a few of the more sensitive people participating. Yet these individuals provide data for that part of the stress–response curve of most interest.

Field studies of stress–response relations, preferably under given sets of conditions, e.g. using only data when skies are clear, or when gradient winds are light.

3. Models

Mathematical statements synthesizing current understanding of stress–response relationships. For large systems, e.g. those used in integrated pest management, models can interconnect various kinds of information. Models can also be used to test the utility of various proposed management strategies.

Data sets selected for study

Biological data sets used by bioclimatologists are of four main types: (1) general biological data sets that happen to be available, e.g. census information, crop yields, insect populations; (2) data sets relating to biological indicators that are specific to conditions of extreme environmental stresses, e.g. studies of organisms existing at high elevations, studies of health effects during heat waves, cold waves, or air pollution episodes; (3) data sets relating to cycles, e.g. diurnal, annual, or life cycles; and (4) data sets that are model-dependent. In the initial stages of an investigation, e.g. with respect to electromagnetic effects, the stress–response mechanism may be obscure and only a time-series analysis will be possible.

Epidemiological (large-population) statistical regressions may suggest laboratory or field studies that should be undertaken, and models that should be tested. In the latter case the data sets must be selected with care, or new data must be collected, the specific goal being model-performance testing.

Meteorological data sets include hourly, daily and monthly records of variables such as temperature, humidity, precipitation, etc.

Some problems with bioclimatological studies

Bioclimatological studies are difficult to design for several reasons:

Lack of reproducibility

Even under controlled laboratory conditions the response of a living organism to environmental stress may vary greatly from time to time. The response depends on the time of day (most organisms display a circadian rhythm of about 24 hours) and the frequency with which the response is imposed. Sometimes *acclimatization* (short-term physiological adjustment) may take place and may lead to long-term *adaptation.*

Variation in population responses

The response of populations to an environmental stress can vary greatly. For example, not everyone suffers from hay fever, no matter how high the concentration of pollen. The World Health Organization makes a useful distinction between an *effect* (a biological reaction) and a *response* (the percentage of exposed organisms/people who react with a specific effect.)

Existence of time lags

An environmental stress may produce an almost immediate response (e.g. exposure to H_2S causes an instantaneously detected bad smell), or the response may be lagged by days, weeks, years, or decades (e.g. up to a 20-year latency period may be required before asbestos exposure causes lung cancer; or for UV-B radiation to cause skin cancer). In the meantime the population being studied may have changed its life-style, making it impossible to disentangle stress–response relationships.

Multiple stresses

Living organisms frequently are subjected to several stresses at the same time. For example, during heat waves, air quality becomes poor, but it is not possible to determine whether the resulting effects on health are due to high temperatures, poor air quality or both.

Estimation of exposures

Most living things move about, and it is not easy to characterize their exposure. Many people spend most of their time indoors where the environment may be quite different from that measured outdoors at weather-observing and air-quality stations. For this reason, studies of human exposure to air pollutants often use human volunteers who wear portable pollution samplers to obtain their daily exposures (see, e.g., Silverman et al., 1992).

Failure of standard statistical methods

Many responses are curvilinear, making standard statistical methods inappropriate. Furthermore, most data sets contain time correlations rather than being random samples, causing correlation coefficients between two variables to be inflated. For more information on biometeorological methods, see Munn (1970), Houghton (1985), and Kates et al. (1985).

Human bioclimatology

Atmospheric variables that may affect humans include heat, cold, wind, humidity, solar radiation (especially UV-B radiation), air pollution, pressure, negative ions, electromagnetism, and biorhythms. In the case of the first six factors the existence of stress–response relationships has been clearly demonstrated. However, with respect to the last four factors the results obtained are still controversial, even though studies began more than a hundred years ago, particularly at the great European health spas, where people went to seek relief from arthritis, respiratory ailments, and allergies.

Heat stress and cold stress continue to demonstrate the most obvious effects of weather and climate on people, and will be discussed in the following paragraphs as good examples of the state of the art in bioclimatology.

Warm-blooded mammals must keep their inner body temperature within a very narrow range (around 37°C) or irreparable harm ensues. The body gains heat by its own metabolism; gains (or loses) heat from (or to) its surroundings by radiation, conduction, and convection; and loses heat by evaporation (breathing and sweating). There are two types of metabolic heat stress: *basal metabolic heat* (released when the body is at rest) and *muscular metabolic heat* (released, in addition to basal metabolic heat, during periods of work or body exercise).

Basic heat transfer models can predict the heat balances of simple volumes such as spheres or cylinders. However, the human body has a complex shape and some parts of the body – such as nose, cheeks and earlobes – are fully exposed whereas other parts are covered with clothing. Therefore, the study of heat and cold stress is not a straightforward problem in thermodynamics. Recently, more advanced heat transfer models have been developed and are being tested for use in a wide range of environmental conditions (see, for example, Fiala et al., 2001; Huizenga et al., 2001; Tanabe et al., 2002; and the International Society of Biometeorology: http://www.biometeorology.org/).

Heat stress is associated with various combinations of the following conditions: (1) high muscular activity; (2) high solar radiation, particularly in the tropics at high elevations; (3) high infrared radiation, e.g. near a blast furnace in a steel mill; (4) air temperatures greater than body temperature (37°C), producing a net gain in body heat from convection; (5) high humidity, reducing the rate of evaporational cooling from the body; and (6) strong winds in combination with (4) and (5), increasing the convective heat gains of the body.

The *physiological* (involuntary) mechanisms used to cope with heat stress are (1) dilating of blood vessels near the surface of the skin, increasing the flow of blood near the skin and increasing the heat exchange from the body to its surroundings; (2) increased sweating, resulting in evaporational cooling; and (3) increased respiration (equivalent to panting of dogs). The *voluntary* mechanisms are (1) avoiding strenuous activity; (2) avoiding direct sunlight and strong infrared sources; (3) switching to lightweight clothing; (4) changing diet to reduce basal metabolic heat production; and (5) remaining in air-conditioned buildings.

An indicator of heat stress is *effective temperature*, the temperature at which motionless saturated air would induce the same degree of comfort/discomfort as that associated with ambient conditions of temperature, humidity, and wind. Although the words “comfort” and “discomfort” are subjective terms, some consensus on their meaning has been achieved through physiological studies of volunteers walking on treadmills in controlled conditions. During each experiment, measurements are made of skin temperature, sweat rate, and body weight, and the volunteers are asked about their degree of discomfort. In other kinds of studies the learning rates of students or work outputs of office employees are examined in relation to room temperature and humidity. The results of these types of studies have been summarized in tables of discomfort.

Table B3 Humidex from dry-bulb temperature and relative humidity readings

	RH (%)																
Temp (°C)	100	95	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20
43													56	54	51	49	47
42												56	54	52	50	48	46
41											56	54	52	50	48	46	44
40										57	54	52	51	49	47	44	43
39									56	54	53	51	49	47	45	43	41
38							57	56	54	52	51	49	47	46	43	42	40
37					58	57	55	53	51	50	49	47	45	43	42	40	
36			58	57	56	54	53	51	50	48	47	45	43	42	40	38	
35		58	57	56	54	52	51	49	48	47	45	43	42	41	38	37	
34	58	57	55	53	52	51	49	48	47	45	43	42	41	39	37	36	
33	55	54	52	51	50	48	47	46	44	43	42	40	38	37	36	34	
32	52	51	50	49	47	46	45	43	42	41	39	38	37	36	34	33	
31	50	49	48	46	45	44	43	41	40	39	38	36	35	34	33	31	
30	48	47	46	44	43	42	41	40	38	37	36	35	34	33	31	31	
29	46	45	44	43	42	41	39	38	37	36	34	33	32	31	30		
28	43	42	41	41	39	38	37	36	35	34	33	32	31	29	28		
27	41	40	39	38	37	36	35	34	33	32	31	30	29	28	28		
26	39	38	37	36	35	34	33	32	31	31	29	28	28	27			
25	37	36	35	34	33	33	32	31	30	29	28	27	27	26			
24	35	34	33	33	32	31	30	29	28	28	27	26	26	25			
23	33	32	32	31	30	29	28	27	27	26	25	24	23				
22	31	29	29	28	28	27	26	26	24	24	23	23					
21	29	29	28	27	27	26	26	24	24	23	23	22					

Source: Data obtained from the Meteorological Service of Canada, Downsview, Ontario.

Table B4 Relation of Humidex with comfort

Humidex	Degree of discomfort
20–29	Comfortable
30–39	Varying degrees of discomfort
40–45	Almost everyone uncomfortable
46 and over	Many types of labor must be restricted

Source: Data obtained from the Meteorological Service of Canada, Downsview, Ontario.

An example of a simple empirical discomfort index (*Humidex*), used by the Meteorological Service of Canada, is shown in Table B3, and the associated discomfort ranges are given in Table B4. Humidex is derived from air temperature and humidity (Masterton and Richardson, 1979). For example, air temperature of 30°C and relative humidity of 90%, giving a Humidex value of 46, are an extremely uncomfortable combination.

Cold stress occurs during exposure to low temperature, strong winds, and thin or wet clothing. It is not always realized that severe cold stress can occur at temperatures well above freezing if clothing becomes saturated with moisture (see, for example, Pugh, 1966).

The *physiological* (involuntary) mechanisms activated to cope with cold are (1) contracting of blood vessels near the surface of the skin; and (2) shivering. The *voluntary* mechanisms are (1) switching to warmer and drier clothing; (2) moving indoors or to locations sheltered from wind and rain; (3) exercising; and (4) changing diet to increase basal metabolic heat production.

A widely used method of expressing cold stress is by calculating *wind chill*. One of the early empirical methods was derived from 89 sets of measurements made in Antarctica by Siple and Passel (1945), who recorded temperature, wind speed, and the time required to freeze a plastic cylinder of water. However, this method was found to exaggerate the effect of cold due to certain assumptions that do not apply for the human face (Bluestein and Zecher, 1999; Osczevski, 2000; Tikuisis and Osczevski, 2002). More complex but also more realistic approaches for calculating wind chill, as well as the full range of thermal stress, are based on heat budget models of the whole body (see, for example, Steadman, 1984; Hoeppe, 1999; Fiala et al., 2001; Huizenga et al., 2001; Laschewski and Jendritzky, 2002; Tanabe et al., 2002). However, these models have not yet been widely tested or used, and a coordinated international effort is currently under way to develop a universal thermal climate index (see International Society of Biometeorology: http://www.biometeorology.org/). A simpler approach has recently been developed and implemented in Canada and the United States, based on the cooling effect of wind on the human face, and was validated on a group of healthy volunteers (see Meteorological Service of Canada: http://www.msc-smc.ec.gc.ca/education/windchill/index.cfm). The data are shown in Table B5, together with explanatory notes concerning the risk of frostbite. The table is developed for the dry human face in the shade and may not represent the discomfort of a warmly dressed person, a person exposed to sunshine or a person with wet skin.

The thermal insulation of clothing is expressed in *clo* units, where 1 clo is the insulation that maintains comfort in a resting person indoors at an air temperature of 21°C with relative humidity of less than 50%. Experimentally, 1 clo has been estimated to be equal to 0.18°C m^2 h/kcal. The insulating efficiency of clothing can be measured, and the results can be used

Table B5 Wind chill, where T_{air} = Air temperature in °C, and V_{10} = Observed wind speed at 10-m elevation, in km/h

	T_{air}											
V_{10}	5	0	−5	−10	−15	−20	−25	−30	−35	−40	−45	−50
5	4	−2	−7	−13	−19	−24	−30	−36	−41	−47	−53	−58
10	3	−3	−9	−15	−21	−27	−33	−39	−45	−51	−57	**−63**
15	2	−4	−11	−17	−23	−29	−35	−41	−48	−54	**−60**	**−66**
20	1	−5	−12	−18	−24	−31	−37	−43	−49	−56	**−62**	**−68**
25	1	−6	−12	−19	−25	−32	−38	−45	−51	−57	**−64**	**−70**
30	0	−7	−13	−20	−26	−33	−39	−46	−52	−59	**−65**	**−72**
35	0	−7	−14	−20	−27	−33	−40	−47	−53	**−60**	**−66**	**−73**
40	−1	−7	−14	−21	−27	−34	−41	−48	−54	**−61**	**−68**	**−74**
45	−1	−8	−15	−21	−28	−35	−42	−48	−55	**−62**	**−69**	**−75**
50	−1	−8	−15	−22	−29	−35	−42	−49	−56	**−63**	**−70**	**−76**
55	−2	−9	−15	−22	−29	−36	−43	−50	−57	**−63**	**−70**	**−77**
60	−2	−9	−16	−23	−30	−37	−43	−50	−57	**−64**	**−71**	**−78**
65	−2	−9	−16	−23	−30	−37	−44	−51	−58	**−65**	**−72**	**−79**
70	−2	−9	−16	−23	−30	−37	−44	−51	−59	**−66**	**−73**	**−80**
75	−3	−10	−17	−24	−31	−38	−45	−52	−59	**−66**	**−73**	**−80**
80	−3	−10	−17	−24	−31	−38	−45	−52	**−60**	**−67**	**−74**	**−81**

***Approximate thresholds*:**

Risk of frostbite in prolonged exposure: wind chill below	**−25**	
Frostbite possible in 10 minutes at	**−35**	Warm skin, suddenly exposed. Shorter time if skin is cool at the start.
Frostbite possible in less than 2 minutes at	**−60**	Warm skin, suddenly exposed. Shorter time if skin is cool at the start.

Note: Other factors such as wet skin (causing increased cold stress) or direct sunshine (causing warming) become important and are not accounted for in the table. (*Source:* Meteorological Service of Canada, Downsview, Ontario.)

in conjunction with joint climatological frequency distributions of temperature and wind speed to produce clo climatologies. For example, at Yellowknife in the Canadian Northwest Territories in January, the numbers of clos required to maintain comfort outdoors are 5.2, 4.1, 2.7, and 1.2 for metabolic rates of 80, 100, 150 and 300 kcal $m^{-2} h^{-1}$, respectively (Auliciems et al., 1973).

That heat stress and cold stress indeed cause increases in morbidity and mortality has been amply demonstrated. See Macfarlane (1977, 1978) for reviews of relevant epidemiological studies on mortality. In one particularly interesting investigation, Clarke and Bach (1971) found that the number of deaths caused by heat in St Louis, Missouri, in July of 1966 could be fitted by a straight line when plotted against average temperature of the previous day; no deaths at 32°C (assumed to be the critical level) rising to 73 cases at 35°C. A more recent heat wave during 12–15 July of 1995 caused over 500 excess deaths in Chicago, Illinois (WMO, 1999; Klinenberg, 2002). The average daily maximum and minimum temperatures during the 4-day heat wave exceeded 38°C and 26°C, respectively, coupled with very high dewpoint temperatures during day and night (Kunkel et al., 1996). The high number of deaths was blamed on several factors, including an inadequate heat-wave warning system, power failure, inadequate health-care and air-conditioned facilities, an aging population, and poor home ventilation due to poverty or fear of crime (Changnon et al., 1996). A much more dramatic heat wave in Western Europe in August 2003 caused between 22,000 and 35,000 excess deaths (Schär and Jendritzky, 2004), over 14,000 of them in France alone (Allen and Lord, 2004).

This review of human bioclimatology admittedly is incomplete. However, the following list will lead the reader into the literature on specific topics:

Further reading

For a general overview, see Landsberg (1969), Jendritzky (1991), multi-author reviews published in *Experientia* (Birkhauser Verlag, Basel) in 1993, Hoeppe (1997), and WMO (1999).

For infectious diseases, see "Under the Weather: Climate, Ecosystems, and Infectious Disease," by the Committee on Climate, Ecosystems, Infectious Disease, and Human Health (CEIDH). Washington DC: National Academy Press, 2001.

For thermal insulating properties of clothing, see Cena and Clark (1978), Kaufman et al. (1982), Havenith (1999), and Chen et al. (2003).

For negative ions, see First (1980), Bissell et al. (1981), Yost and Moore (1981), Watanabe et al. (1997), and Nakane et al. (2002).

For electromagnetic effects, see Malin and Srivastava (1979), and NRC (1997).

For quantifying population exposures to air pollution, see WHO (1982, 1999).

For biorythms, see Wever (1979, 1986, 1989), and Min (2003).

For UV-B impacts, see UNEP (1998).

Plant bioclimatology (agricultural and forest)

Humans have been managing (or in some cases mismanaging) renewable resources for many centuries. The goal is to increase crop and timber yields without causing long-term degradation of soils and forests. Climate has a direct effect on plants; it provides the primary source of energy; it governs the temperature of plant organs; and it controls water loss by transpiration. The main climatological stresses that adversely affect vegetation are drought, flood, hail, strong winds, and frost. However, atmospheric processes are indirectly important in seed dispersal, pest outbreaks, air pollution concentration (including acidic rains), soil erosion, and soil moisture. Because many cash crops are grown outside their normal climatological ranges, they must be irrigated and protected from frost and strong winds. The bioclimatologist assists in this latter regard, either by modifying the landscape (e.g. with shelterbelts) or by providing advice on how to optimize the use of terrain irregularities (*topoclimatology*). For example, a forest clearing can create a frost pocket, making it difficult for young seedlings to survive. The forest industry therefore has a need to evaluate topoclimatological features in order to assure regeneration of clear-cut areas.

A single example, apple-growing in Britain, will illustrate some of the factors considered in a bioclimatological study (Landsberg, 1980). First, the life cycle of apple trees must be described: from seedlings to mature orchards and from bud production (late summer and early fall) through blossoming (spring) to fruiting (late summer). Next, the sensitivity of an orchard to environmental stresses must be evaluated with respect to each phenological stage of development of the tree and of the fruit. The main stresses are drought, unseasonably mild winters, spring frost, wet and cold summers, and weather-sensitive pest outbreaks. These several stresses have an effect on both quantity and quality of the harvest. Landsberg reviews the work that has been done to understand the effects of weather on the apple orchards of Britain. He asserts that part of the problem has been solved: the annual total dry matter produced by apple trees can be estimated satisfactorily, given the daily weather throughout the year being studied. But orchards are grown for their fruit, not for their biomass. An empirical relationship has therefore been developed that relates dry matter production to quantity and quality of apples.

Agricultural and forest bioclimatology has become increasingly significant in the recent climate change debate. Agricultural lands and forests sequester large amounts of carbon; therefore improved management practices are needed to partially offset the rising levels of atmospheric CO_2. Climate change may also alter the pattern of food and timber production, either for the better in some regions, or for the worse in others. Plant bioclimatology will therefore continue to play a major role in understanding the impacts of climate change, and in formulating mitigation and adaptation measures (see Global Environmental Change, in this volume).

For more information on agricultural and forest bioclimatology, consult the following references. For crop-weather relations, see Baier et al. (1976), Skjelvag (1980), Burt et al. (1981), Parry (1985), and Parry et al. (1986); for topoclimatology, see Skaar (1980), and Utaaker (1980); for shelterbelts, see Rosenberg (1975); for UV radiation, see Grant (1997); for ozone effects, see Krupa et al. (2001); for effects of nitrogen compounds, see a series of articles in *Environmental Pollution* (2002), vol. 118, issue no. 2, pp. 165–283. In general, see the journal *Agricultural and Forest Meteorology*, published by Elsevier Publishing Company, Amsterdam, and the book *Forest Microclimatology* (Lee, 1978).

Animal bioclimatology

Bioclimatologists seek to quantify the direct and indirect impacts of climate on animals, particularly domestic ones. In the case of farm animals the objective is to improve the quality and quantity of meats and dairy products, as well as to increase the work output of "beasts of burden". Direct effects involve heat exchanges between the animal and its environment, which are linked to air temperature, humidity, wind speed, and thermal radiation. These linkages affect animal health, growth, milk and wool production, reproduction, and performance in general. For example, heat and cold stress can have marked effects on milk yield of lactating cows, depending on breed, feed intake and degree of acclimatization. Conception rates of dairy cows are also sensitive to seasonal fluctuations. Climatic extremes such as droughts, floods, violent winds, heat waves, and severe winter storms can result in injury and death of vulnerable animals. Indirect effects include climatic influences on quantity and quality of feedstuffs such as pastures, forages, and grains, as well as the severity and distribution of livestock diseases and parasites.

Bioclimatologists also undertake studies on wild animals to determine the effects of atmospheric stresses such as acidic deposition, long-range transport of toxic chemicals, weather disasters, and more recently UV-B radiation and climate change. Ecologists need this information to help understand population changes, species diversity and ecosystem health. Biodiversity has become a fast-growing field of study linked in many ways to bioclimatology.

Animal bioclimatology is a vast field and only a few references are listed here. For general information, see Tromp (1980), and Johnson (1997). For heat transfer from animals, see Cena and Monteith (1975), and Tracy (1977); for bioclimatology of domestic animals, see Bianca (1976), Dragovich (1981), Christianson et al. (1982), Igono and Aliu (1982), and Starr (1983); for bioclimatology of wild animals, see Shkolnik (1971), and Picton (1979).

Phenology

Blooming wildflowers, falling leaves, migrating birds and insects, spawning fish, hibernating animals, freezing ponds and rivers, and the like, are all influenced primarily by climatic conditions. Bioclimatologists undertake phenological studies to understand the role of climate variables in the dynamics of plant and animal natural cycles. The relationships between climate variables and the timing of these phenophases provide useful information to farmers, gardeners, horticulturists, and beekeepers, e.g. first growth and flower dates, last frost of spring or first frost of fall, planting and harvesting dates, and appearance of insect or weed pest species. Wildlife managers also need information on bird and animal migration dates, growth stage dates of various plant and animal species, dates of critical lake and soil temperatures, and breeding activities and nesting/denning dates (see, e.g., Lieth and Schwartz, 1997).

Phenological studies have become increasingly valuable in recent years, because trends in phenology may serve as natural indicators of global climate change (IPCC, 2001; Lechowicz, 2001; Van Noordwijk, 2003).

Aerobiology

Airborne living material is transported by the wind, sometimes for thousands of kilometers. Field naturalists are interested in bird and insect migrations, and in large-scale movements associated with the life cycles of pollen, rusts, and spores, which are of economic and health significance. For example, pollen and other allergy-causing materials may be transported from countryside to city, or from state to state, causing health problems at considerable distances from the source regions. (A question often asked is how large an area surrounding a city should be cleared of ragweed in order to provide effective relief to hay fever sufferers?) Other examples include the potato blight, wheat rust, locusts, the gypsy moth, and spruce budworms. A final example is that many viruses and other substances that harm animals and/or people can also be transmitted by the wind, e.g. foot-and-mouth disease, rinderpest, influenza viruses, etc. In 2001 a severe outbreak of foot-and-mouth disease spread in the UK, leading authorities to destroy several million livestock. Computerized models are often used to predict the dispersion, movement and deposition of viruses and other biological agents.

Aerobiology contributes to understanding the atmospheric part of the life cycles of the pests mentioned above, and to an activity called *integrated pest management*. A good example is the study by Fleming et al. (1982), who examined the effect of field geometry on the spread of crop disease. Using reaction–diffusion models, rectangles of various dimensions were studied. The models suggest that the greater the perimeter-to-area ratio, the slower the increase of disease within a field. Assuming that a constant proportion of a region is allotted to a particular crop, the models also indicate that decreasing field size and elongating fields in the cross-wind direction will reduce disease losses.

There are, of course, many other types of aerobiological studies (see, e.g., Edmonds, 1979; Pedgley, 1982; and Isard and Gage, 2001).

Climatic adaptation

Finally, mention should be made of climatic adaptation. Because the time scale involved is of the order of centuries or longer, it is difficult to demonstrate stress–response relationships. Yet the presumption of climatic adaptation seems to be justified in many cases. For example, the shape of the Arctic igloo is optimal for minimizing heat losses. Similarly, small insects often have spherical or cylindrical bodies to reduce heat loss on cold nights. As another example, vegetation has "learned" to survive along the coastline of the Arctic Ocean at a site (the Smoking Hills) where SO_2 concentrations and soil pH values should be lethal; in this case the cliff has been burning naturally for at least several centuries (Havas and Hutchinson, 1983). Some of the species have been successfully transplanted on mine tailings near the Sudbury copper smelter.

Other examples of adaptation include desert plants and animals, which have minimized their water consumption and water losses through physiological mechanisms (Smith, 1978), and bird, insect, and animal migrations, which depend on the regularity of annual climatic cycles. Black people in the tropics have skin pigments that protect them from sunburn and skin cancer, while native people in the Arctic have adjusted diet and body fat to cope successfully with the long northern winters.

On the global scale, the *Gaia* theory of Lovelock (1979) asserts that the biosphere played an essential role in the evolution of the Earth over a geological time-scale. Once established, the primitive vegetation cover was able to control the oxygen and CO_2 concentrations of the atmosphere, the temperature of atmosphere and oceans, and the salinity and pH of oceans.

For a recent discussion of the *Gaia* theory, see a collection of papers in *Climatic Change* (2002), vol. 52, issue no. 4, pp. 383–509. See also the exchange of views between J. Lovelock and T. Volk in *Climatic Change* (2003), vol. 57, pp. 1–7.

Conclusion

Although the bioclimatologist has been studying stress–response relations for more than a century, nature unlocks its secrets slowly. Nevertheless, future prospects for meaningful research are good. The main problem to be overcome is the difficulty that specialists encounter when working with specialists in other fields. For example, medical doctors and climatologists have traditionally not communicated with one another except at the non-specialist level. It is hoped that interdisciplinary educational and research programs will be encouraged in all parts of the world.

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