

CLIMATE CHANGE AND ENVIRONMENTAL POLLUTION: PHYSICAL AND BIOLOGICAL INTERACTIONS

MICHAEL OPPENHEIMER

Environmental Defense Fund, 257 Park Avenue South, New York, NY 10010, U.S.A.

Abstract. Climatic change projected over the next century may occur in an environment already affected by other stress, including UV-B enhancement, air pollution and increasing nutrient fluxes. Focusing on particular ecosystems, temperate zone forests, freshwater lakes, and estuaries, we have examined the interactions among these several environmental problems. An important chemical outcome of atmospheric change is the increase in oxidant levels throughout the lower atmosphere and the hydrosphere. These oxidants are phytotoxic and contribute directly and indirectly, along with other stresses on ecosystems, to the acceleration of the S, N and C cycles. These changes may lead to the net transfer of nutrients from land to coastal ocean with accompanying forest decline and coastal eutrophication. Some shifts already may be under way locally, but the synergistic nature of the stresses threatens to accelerate these processes over the next few decades. In addition to any direct consequences of climatic change, the aggravation of existing environmental problems is an important indirect consequence.

1. Introduction

Climate change presents more than just another environmental problem. A changed climate creates a new framework for the manifestation of other environmental stresses. Acidification of soils and surface waters, degradation of forests by air pollution, eutrophication of fresh and coastal waters, and soil erosion due to land use changes are some of the regional scale problems currently arising from industrial and agricultural development. Stratospheric ozone depletion, occurring rapidly but episodically on a regional scale in Antarctica, and more slowly on a global scale, is increasing the ultraviolet flux to the earth's surface. Over the next 40–80 years, temperature and precipitation changes due to the enhanced greenhouse effect will exacerbate those environmental problems. In addition to any difficulties which humans or natural resources may experience in adjusting to the direct consequences of climate change, the intensification of certain existing pollution problems is an important indirect consequence of a warmer climate.

The interactions between climate change and other environmental change will occur at many points in the tightly coupled biogeochemical system involving the atmosphere and the earth's surface. Some of these interactions will be synergistic, with climate enhancing and accelerating change due to other stresses. Indeed, some of the effects of a changing climate on natural ecosystems may be noticed first through their interaction with other environmental problems.

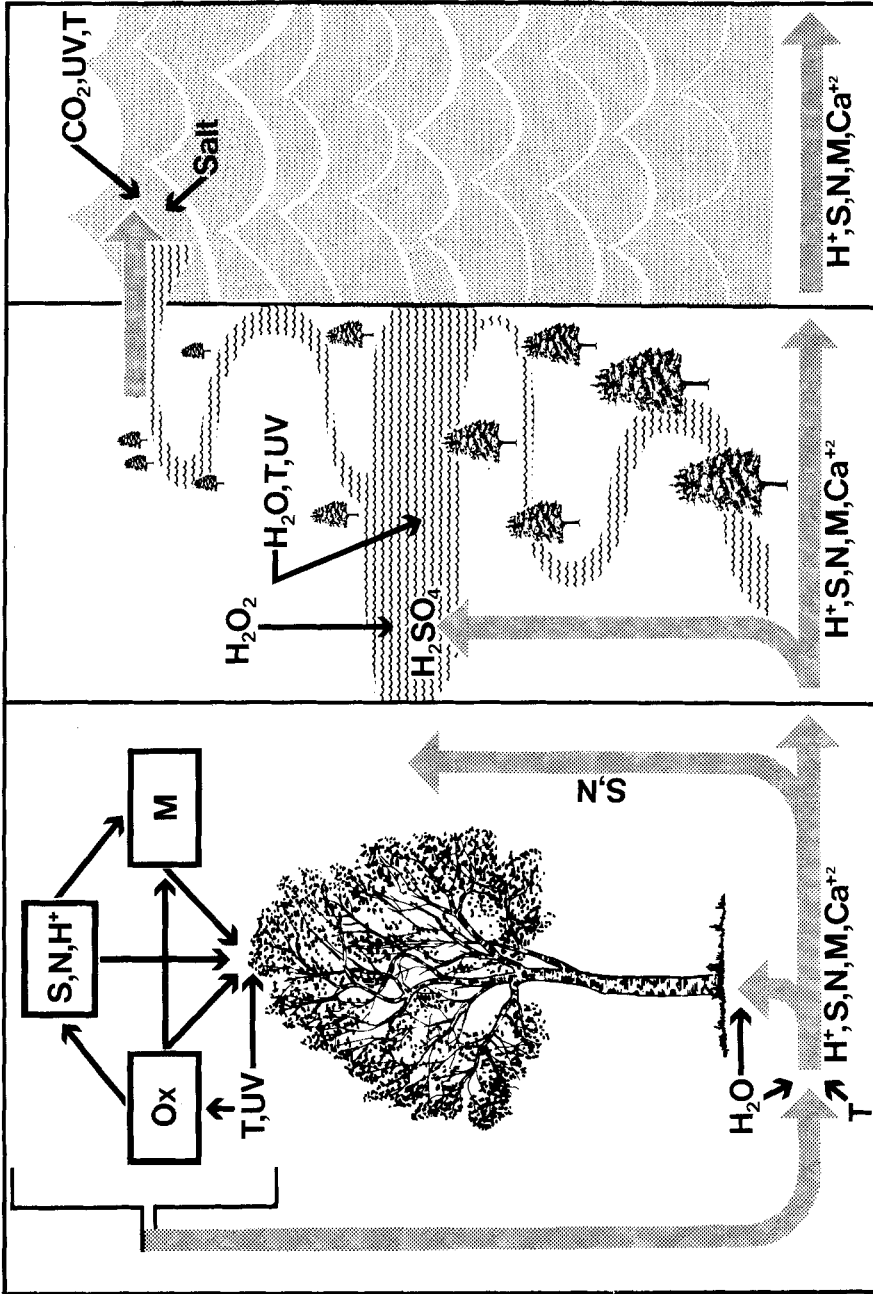


Fig. 1. Interactions among air pollution, climate changes, radiative changes, and three ecosystems, are indicated schematically, left to right, for forests, fresh waters, and estuaries, respectively. The overall direction of pollutant and nutrient flow through ecosystem are indicated by heavy arrows. Points of stress on biological systems or perturbation of chemical systems are indicated by thin arrows. The merging of arrow heads indicates a possible synergism. Ox, M, T, and UV indicate oxidants, metals, temperature, and ultraviolet radiation, respectively. The other chemical symbols have their usual meaning.

In this paper we shall focus on four existing environmental problems: stratospheric ozone depletion, ground level oxidant generation, forest and watershed degradation by acid rain and regional air pollution, and eutrophication of coastal waters. Through an understanding of the mechanisms which lead to these changes, we shall attempt to project the state of the environment in the next century, as these stresses increase regionally, interact with each other, and are accelerated by global climate change.

We make no pretense of an exhaustive analysis; rather a related set of changes are presented as exemplars. The paper is structured from a 'trickle-down' perspective as follows. Atmospheric chlorine will deplete stratospheric ozone, a process which may be enhanced by the increasing global greenhouse effect. Ozone depletion allows increased ultraviolet flux to the surface. Ultraviolet flux increases and climate changes enhance ground level oxidant and acidity levels. Acid deposition and oxidants cause forest and watershed degradation. Forest degradation caused by a changing climate, enhanced ultraviolet radiation and air pollution may lead to increased eutrophication of fresh and coastal waters, as will the direct effects of climate change on these waters. Figure 1 presents a schematic diagram of these interactions. Although these processes will be elaborated in greatest detail for the mid-latitudes, similar changes may be expected at other locations related to increases in air pollution and land use changes in developing countries.

Since several of the pollution problems discussed here originate in anthropogenic emissions to the atmosphere, we shall find it useful to establish emissions estimates for current and future years. Such estimates, and their basis, are given in Table I. Unless otherwise noted, environmental projections refer to a world with a 3 K increase in global annual mean surface temperature, compared to today.

We shall begin this analysis high in the atmosphere and move downward to the biosphere. So our first focus is on the interaction of climate change with stratospheric ozone depletion.

2. Climate Change and Stratospheric Ozone

Trace gas concentrations in the atmosphere are changing rapidly. Atmospheric carbon dioxide concentrations have increased about 25% since the pre-industrial era [1]. Concentrations of methane and nitrous oxide have been increasing recently at the rates of about 1% yr⁻¹ [2], and 0.3% yr⁻¹ [3] respectively. Emissions of chlorofluorocarbons (CFC-11, 12), which have no natural sources, have increased by an order of magnitude over the last 30 years [4] with a leveling since about 1974 and, more recently, a resumption of increasing emissions.

Calculations of stratospheric ozone concentrations using standard gas phase models indicate that growth in trace gases in addition to CFC's affects projected ozone concentrations in two ways [5]: by direct chemical intervention in catalytic production and removal of ozone, and by enhancement of the atmospheric greenhouse effect. In the latter circumstance, the decrease in net upward longwave flux

TABLE I

Physical setting					
World					
	(1850)	1980	2030		
SO ₂ -S	(65)	65	205	ton S	× 10 ⁶ yr ⁻¹
NO _x -N	(30)	20	65	ton N	× 10 ⁶ yr ⁻¹
United States					
SO ₂ -S	(<1)	13	17	ton S	× 10 ⁶ yr ⁻¹
NO _x -N	(<1)	6	9	ton N	× 10 ⁶ yr ⁻¹

SO₂-S and NO_x-N refer to SO₂ emissions (as sulfur) and NO_x emissions (as nitrogen), respectively. SO₂ and NO_x emissions are based on energy scenario projections^a which lead to a 2.4%/yr growth rate for CO₂ emissions. A lower growth rate of 2.1%/yr has been suggested recently.^b

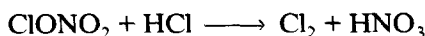
Values under (1850) reflect total natural sources of atmospheric sulfur and nitrogen, not just SO₂ and NO_x. Values for later years reflect anthropogenic SO₂ and NO_x emissions only.

^a R. M. Rotty and G. Marland. Constraints on Carbon Dioxide Production from Fossil Fuel Use, paper presented at Energy/Climate Interactions Workshop, Munster, Germany, March 3-8, 1980.

^b R. M. Rotty and D. B. Reister. Use of Energy Scenarios in Addressing the CO₂ Question. *J.A.P.C.A.* 36, 1111-1115, 1986.

leads to a cooling of the stratosphere, slowing ozone-depleting reactions. In the former case, increasing methane concentrations serve as a net source, while increasing N₂O is a net sink for total ozone. The overall consequence of the consideration of non-CFC trace gases in gas phase models is a reduction in projected ozone depletion. While future total ozone is highly sensitive to assumptions on non-CFC trace gas growth rates, the vertical distribution of ozone is severely altered in all scenarios. This change of distribution will contribute to the alteration of stratospheric temperatures and global climate.

The observation of the 'ozone hole' over Antarctica has revealed the incompleteness of models based on gas phase chemistry alone [6]. Recent observations [7], particularly those of ClO concentrations above values predicted in standard models, indicate that increasing depletion of ozone in springtime would not occur without increasing levels of atmospheric chlorine. The enhanced chemical sink in Antarctica arises from the elimination of ClONO₂ and HCl as important reservoirs of chlorine [8], through surface reactions on polar stratospheric clouds (PSC's) such as



and through condensation of HNO_3 into PSC's which prevents reforming of ClONO_2 . The catalytic removal of ozone appears to be propagated by reaction sequences involving ClO dimerization and reaction of ClO with BrO. The condensation of HNO_3 and the availability of PSC's are consequences of the low temperatures over Antarctica in winter and early spring. Such conditions may also exist to a limited extent in the Arctic.

The increasing greenhouse effect will lower temperatures in the stratosphere [9]. Global circulation models indicate that a global 3K surface temperature increase could be accompanied by a stratospheric temperature decline ranging from 1 K near 18 km to nearly 10 K at 30 km, at tropical latitudes. Projected temperature decreases are slightly smaller at the mid latitudes where current stratospheric temperatures are higher. Critical temperatures for condensation of HNO_3 , aerosol growth and PSC formation occur between 190 K and 200 K, a regime which may become accessible near 20 km over part of the globe as climate changes. Water vapor [10] and sulfur (cf. Section 6) fluxes to the stratosphere, which enhance aerosol production, may also increase. So conditions for rapid ozone loss by surface chemistry may spread beyond the polar regions.

One estimate of the future ozone depletion in a cooler stratosphere can be made by assuming that ClONO_2 is no longer effective as a chlorine sink. Assume CFC emissions stabilize at one-half 1986 levels, reflecting full implementation of the Montreal Protocol On Substances That Deplete The Ozone Layer. Then the predicted year 2030 depletion of O_3 at low to mid latitudes due to this effect would be about 10% below 1960 levels compared to the 1–2% projected by gas phase models [11]. A 2% ozone depletion corresponds to a 4% increase in biologically active UV-B flux at the surface. Substantially greater UV-B increases could occur with a cooled stratosphere. Dispersion of low ozone air from polar regions already appears to be causing global depletion of 2–3% at current CFC concentrations, an effect which would also increase with increasing CFC concentrations [12]. Even if emissions of CFC's are halted shortly, the relatively small current atmospheric chlorine concentrations (~ 3 ppb) would be sufficient to cause an additional ozone depletion of a few percent if surface reactions become effective at non-polar latitudes.

3. Climate Change and Tropospheric Oxidants

The depletion of ozone in the stratosphere, a warmer climate, and increases in anthropogenic gases such as CO, methane, non-methane hydrocarbons (NMHC) and NO_x in the troposphere all have implications for tropospheric concentrations of oxidants, such as ozone and hydrogen peroxide. The ecological consequences of enhanced oxidant concentrations arise from their phytotoxic properties [13]. Oxidants such as ozone and hydrogen peroxide can form in the presence of UV-B in both atmosphere and surface waters, and react rapidly in chemical and biological systems. Oxidant concentrations may increase due to increasing emissions of NO_x

and hydrocarbons, due to increased UV-B, and higher temperatures. The photochemistry is discussed elsewhere [14].

Simulations of future urban [15], rural [16], and remote tropospheric [10] ozone and hydrogen peroxide concentrations have been reported. From these studies and from simulations of the current atmosphere, we can estimate changes in rural ozone concentrations for a world which is 3K warmer, has a UV-B enhancement corresponding to 10% ozone depletion, and has pollutant emissions increases as in Table I. Taking together the NO_x changes projected for the year 2030, with an equivalent NMHC change, we project an increase in rural ozone levels of about a factor of two in the U.S. [10]. In Western Europe, planned new air emission controls may limit oxidant increases. However, in Eastern Europe and in industrial regions in developing countries, emissions growth can be expected to lead to ozone increases in excess of those in the U.S., absent stringent abatement measures.

Model simulations [15] suggest that hydrogen peroxide concentrations (H_2O_2) are more sensitive than ozone to the combined consequences of increased temperature, UV-B, NO_x , and hydrocarbons. Concentrations of this pervasive, highly soluble phytotoxin, currently measured in high concentrations in the gaseous atmosphere, in fog and precipitation, and in surface waters, can be expected to increase markedly in the future in rural areas.

Airborne oxidants, acidic aerosol and other smog components are associated with respiratory and cardiovascular problems in humans. In polluted urban areas, such difficulties will also be exacerbated by the higher temperatures associated with climate change. Smog-related mortality and morbidity rates may be expected to increase.

4. Climate Change and Temperate Forests

The relationship of the atmosphere to the forest is determined by its impact on trees, other vegetation, surface and groundwater, soils, microbes, and even animals. These interactions are so varied and complex that it is difficult to be definitive about the effect of atmospheric changes [17,18]. In general, incremental temperature increases, and perhaps higher carbon dioxide concentration, will increase primary productivity [19,20]. However, forests will come under stress as their appropriate climate zones shift due to temperature and moisture changes. Temperate forests are already under stress from air pollution in both North America and Europe [21, 22, 23]. A variety of symptoms of disturbance are currently observed. How these forests react to an additional climate stress is a complex matter. In fact, some investigators attribute forest decline in certain areas to climatic rather than pollution stress. A recent article [25] argues that climate warming in New England over the last 100 years is already squeezing mid-altitude red spruce out of the lower altitude part of its range. Assigning degree of cause to one or the other agent is not feasible, but some insight on the future interaction of these stresses may be gained by examining forest degradation mechanisms which have been proposed, including:

- (a) gaseous pollutant interaction with foliage;
- (b) acid precipitation or acid fog water surface interaction with foliage;
- (c) acid deposition mobilization of metals in soils and subsequent biotic uptake, and associated soil nutrient impoverishment; and
- (d) toxification of soils by atmospheric deposition of metals.

Visible effects include fine root damage, yellowing or loss of conifer needles, and crown distortion and dieback. Ozone as well as sulfur and nitrogen oxides are known to be phytotoxic and may produce such visible symptoms (but only at the higher end of the ambient concentration spectrum for SO_2 and NO_x). Very acidic fog or rain may visibly damage foliage [24]. In addition, both ozone and SO_2 may inhibit photosynthesis in the absence of short-term visible damage [26, 27], which may explain the broad growth reductions inferred from tree ring data [26]. The final mechanism is quite speculative, so let us examine the first three in detail.

Gaseous pollutants are phytotoxic at levels observed near urban areas [24]. Controlled experiments indicate that ozone, sulfur dioxide, and nitrogen oxides in combination are capable of causing visible damage to conifers [24, 29]. It is uncertain as to whether any one of these pollutants alone is capable of damaging trees at levels observed in rural areas but combinations of these gases at low levels may act synergistically.

As a result of anticipated atmospheric changes (Table I), damage from gaseous pollutants could increase substantially, and the result may be non-additive should SO_2 , O_3 , and NO_x increase simultaneously. In particular, the vulnerability of vegetation to climate extremes may be enhanced by high pollutant concentrations [27].

Also of concern is the potential for damage from H_2O_2 . Phytotoxic action of this chemical in droplets has been reported [30], and its high solubility suggests that it may be easily absorbed by foliage. H_2O_2 is pervasive in atmospheric droplets and its gaseous abundance may increase several fold if temperature, UV-B and atmospheric pollutants increase (see Section 3).

Acid precipitation or acid fog may affect foliage, either synergistically with O_3 (or H_2O_2) or separately by leaching nutrients and destroying the protective coating on conifer needles [24, 30]. Higher temperatures and UV-B changes can affect this mechanism in two ways. First, atmospheric droplets and droplets on foliage are photochemical 'factories' due to internal reactions. Temperature and UV-B increases will enhance droplet acidity by increasing photochemical activity inside and outside these droplets (followed by absorption). In addition, changes in precipitation frequency will alter the surface concentration of dry deposited acids on foliage. Where dry intervals lengthen, the acid stress to leaves will increase. However, drier conditions may also result in lower surface mobilization of pollutants.

In some areas, the effect of acid deposition on soil chemistry will lead to increases in metal mobility in soil solution. Where soils are already acidic and where climate change also reduces runoff, vegetation will absorb less water with lower pH and higher metal concentrations. Long-term soil nutrient impoverishment may slow where runoff decreases. However, increases in SO_2 or NO_x emissions coinci-

dent with runoff decreases could increase both nutrient loss and metal concentrations. Soil impoverishment due to acidification has already been noted in Europe, but only the most sensitive soils are seriously affected on decadal timescales [31].

Temperature increases due to climate change can also enhance soil water acidification [32]. High soil temperatures lead to rapid mineralization of humus. Nitrate deposition of as much as 100 kg/ha-yr already competes as a source with internally cycled nitrogen in some temperate forests. Increasing temperatures and nitrate deposition will lead to acidic discharge of nitrates into soil solution. The associated metal mobilization may damage vegetation. Sporadic soil water acidification during warm episodes may trigger region-wide forest decline in combination with pre-existing stresses. A synergism between acid deposition and climate may result if vegetation absorbs a progressively smaller fraction of available nitrogen as deposition increases. Most important, the increasing occurrence of excessively hot summers as climate changes could exacerbate forest decline indirectly by soil acidification even when there is only a slight change in annual mean temperature.

The discussion above notes two particularly interesting pathways for interactions among stresses on forest ecosystems: enhanced oxidant abundances interacting both chemically and biologically with other air pollutants; and increased temperature interacting with enhanced soil acid loads to leach cations and mobilize soil metals. The large increases which may occur for H_2O_2 merit special attention since investigations of the phytotoxic characteristics of this oxidant are just beginning, and synergistic responses with other pollutants seem likely. H_2O_2 and other oxidants also will accelerate the production of acids in leaf droplets. It has been suggested that doubled CO_2 levels may increase stomatal resistance by as much as 40%, reducing damage from gaseous pollutants [33]. It is unclear whether such an argument pertains to highly soluble gases like H_2O_2 . Further, ozone and perhaps H_2O_2 could affect plants synergistically with acid deposited on foliage.

Increasing UV-B itself represents a significant stress on vegetation. Inhibition of photosynthesis, mutagenesis, changes in patterns of competition, and yield reductions have been observed in plants at the molecular or community levels [33, 34]. The interaction of these changes with climate or pollutant stresses are unknown, although it is known that increased fertilization and water stress decrease sensitivity to UV-B [35]. On the other hand, foliage damaged by air pollution or acid rain may be more vulnerable to UV-B.

Water availability stress in conjunction with air pollution stress has been cited as a possible cause of temperate forest decline [32]. Climate change offers the potential for such joint interaction in areas where soil moisture is decreasing. Models of forest shifts in response to moisture and temperature changes should consider pollution stressed forests as a base case, at least for the mid-latitudes.

The foregoing discussion has identified ways in which temperature, soil moisture, nitrogen and sulfur deposition, and increased UV-B interact synergistically to stress forests. The confluence of these stresses may be expected to accelerate

change and biomass reduction already observed in temperate zone forests in industrial regions, in spite of the fact that nitrogen – frequently a limiting nutrient in forests – is increasing in deposition.

Mechanisms involving oxidants and nitrogen are of particular concern. Projected increases in nitrogen emissions will in turn increase nitrogen deposition and atmospheric ozone concentrations, just as temperature and UV-B changes stimulate tropospheric ozone production. Climate warming and related forest disturbance may enhance mineralization of nitrogen and may accelerate acidification and increase nitrogen leaching. Some drainage basins in the United States already discharge a large fraction of deposited nitrogen, and degradation of these systems has important downstream consequences [36].

On the other hand, some feedbacks will be negative. Decay and nitrification may be slowed by acidic or drier conditions, and CO₂ increases may reduce pollutant interaction with foliage. Furthermore, the direct consequences of climate change may include biomass increases in boreal forests.

5. Climate Change, Freshwater Systems, and Acidification

For freshwaters in general, alterations in flow will be a major stress as climate changes, but other, more subtle changes will occur. The upstream forest degradation described in the previous section may enhance nitrogen and phosphorus fluxes, increasing eutrophication. In this section, we shall focus on another pollution problem, the acidification of sensitive freshwaters.

Freshwater systems in watersheds with non-calcareous soils are subject to acidification in industrialized regions due to enhanced sulfate and nitrate deposition, known as acid rain. This deposition is partly neutralized by weathered alkalinity and cations leached from soils. Climate change will alter precipitation rates and soil moisture content. It is unlikely that acid anion concentrations in precipitation will change sharply with moisture availability since long term concentrations of sulfate in precipitation are not strongly dependent on precipitation rate or volume [37]. Similarly, concentration of alkalinity in surface waters is not sensitive to flow (and hence precipitation rate) under a variety of low to moderate flow conditions.

In contrast, soil cation exchange is highly sensitive to evapotranspiration rate. Simulations suggest that at a fixed concentration of acid in precipitation, soil solution pH varies seasonally by up to 0.5 units due to changes in evapotranspiration which alter acid anion concentrations in soil solution [38]. Therefore, it can be expected that climate change will accelerate soil and surface water acidification, even at constant concentration of acid in precipitation, in areas where runoff decreases. With increases in sulfur dioxide and nitrogen oxide emissions, this effect is enhanced. This interaction is synergistic in the sense that evapotranspiration changes in absence of mineral acids will have little effect on soil solution pH. We note that a preliminary analysis of this interaction by Tirpak [39] reached a dif-

ferent conclusion. Direct increases in surface water acidity due to atmospheric CO_2 changes may also occur, according to the dependence of weathering on carbonic acid concentration.

A temperature-dependent soil acidification mechanism due to increased nitrification was discussed in Section 4. Such a mechanism indirectly affects surface waters. Acidification of lake waters may also increase due to alterations in the chemical oxidation rate in the lakewater column above sediments. The anaerobic reduction of sulfate appears to be an important source of alkalinity in many soft-water lakes, sometimes contributing on the order of $\frac{1}{2}$ the alkalinity [40]. The resulting Fe-S- H_2S system is highly coupled. Intervention by increasing oxidant concentrations will enhance oxidation in bioturbated sediments, as well as in the overlying water column, resulting in increases in both sediment and H_2S oxidation from reduced form to sulfate [41].

These transformations effectively reduce alkalinity as follows. Increased oxidation removes Fe^{+2} from the water column, making it unavailable for pyrite formation. In addition, at H_2O_2 concentrations above 10^{-5} M, reaction with H_2S enhances sulfate concentrations. Such values, occurring in some freshwaters now, will be more common under the future atmosphere discussed in Section 3. Enhanced in situ oxidant formation may be important in waters high in organic carbon [42] while dissolution of oxidants from the atmosphere may be an important source in other waters.

The net effect of such changes would be a *decrease* in freshwater alkalinity. Sulfate additions to waters are partly counteracted by *increases* in sulfate reduction rates [40], but rapidly increasing oxidant levels would have a countervailing effect.

The combined effects of atmospheric change on freshwater acidification are summarized in Figure 1. Increased sulfur and nitrogen emissions and deposition will obviously accelerate acidification of sensitive waters. For the United States, increases may be 30–50% beyond 2010 if no further control actions are taken [43]. In Europe, projected emissions control actions may reduce numbers of acidified waters, but this improvement will be counteracted by sulfur cycle changes due to enhanced oxidant levels. Much larger increases will occur in the developing countries with sensitive waters (cf., Table I). In addition, soil moisture reductions associated with climate change will decrease pH in soil water. Enhanced atmospheric oxidants due to NO_x and hydrocarbon emission increases and higher UV-B levels will accelerate atmospheric photochemistry and freshwater and sediment chemistry, increasing acidity and decreasing production of alkalinity.

A crude estimate based on current surface water alkalinity distributions suggests [44] that sulfur and nitrogen deposition changes alone would increase by a factor of two the number of acidified lakes in the United States. The other simultaneous changes will substantially aggravate this situation. The synergistic interactions noted above, oxidant-interference with the alkalinity production, temperature enhanced nitrification, and increased soil acidity with decreased flow, all occurring while acid deposition is increasing, may cause this value to be a significant under-

estimate. On the other hand, pH-dependent negative feedbacks in the N-cycle could slow acidification [45].

6. Coastal Areas

Coastal wetlands, estuaries, and the coastal ocean will bear the brunt of the combined effects of atmospheric deposition, climate change, and enhanced UV-B. The entire physical setting in which these systems exist may change as sea level rises and erosion and salinity increase. In the long run, this process may simply eliminate many wetlands as physical systems. However, even the wetlands which survive will suffer substantial alterations in system biogeochemistry due directly or indirectly to the UV-B increase and changes in air pollutant deposition. Estuaries will be affected by wetland alteration and by a combination of radiative and chemical changes.

From the perspective of chemical inputs, the largest effects on coastal areas may arise from nitrogen loading. Nitrogen is a limiting nutrient in some estuaries and shallow ocean areas [46]. Atmospheric deposition, agricultural runoff and sewage outfalls are major external contributors to the nitrogen budgets of these waters. In the Baltic Sea, for instance, atmospheric deposition may account for one-half or more of total external nitrogen sources, since nitrogen in river runoff originates partly in the atmosphere [47]. A large external nitrogen source from the atmosphere also characterizes the Chesapeake Bay and presumably other East Coast estuaries [48]. Changes in primary productivity will occur as temperature and CO₂, and nitrogen flux from the atmosphere, sewage, and agricultural runoff increase. These changes may result in accelerated eutrophication with algal blooms, anoxic conditions, and large-scale biotic shifts in estuaries and shallow ocean areas. Increased biomass and large relative changes in populations of algae due to differential nutrient uptake by different species already have been noted in the North Sea [49].

Coastal waters lie at the end of a chain that begins in forested ecosystems [50]. The upstream changes in temperate forests described previously may also increase nitrogen, sulfur, carbon, and phosphorous flows to these waters, encouraging eutrophication and sedimentation. Terrestrial systems respond to disturbance by increasing respiration relative to net primary production, and often by increasing nitrogen leaching [51]. Such changes have been monitored in detail in response to clear cutting and may be expected to occur in response to the continuous disturbance of climate change. In temperate forests, biomass decreases are projected from a changed climate [17]; in addition, migration rates may be slower than climate change rates, leading to enhanced nutrient loss. Continuous disturbance by either air pollution, climate, or other factors (such as land use changes in tropical areas) may be expected to accelerate nitrogen mineralization and flux (and perhaps phosphorous flux) from terrestrial systems [52, 53]. Of course, such releases are self-limiting, either by loss of the terrestrial nitrogen pool or by forest recovery, if any, should disturbance cease.

Increases in UV-B may to some extent counteract eutrophication, as UV-B is known to inhibit at least surface productivity. An important change will be the shift in plankton communities due to selective UV-B and nutrient effects. Increasing UV-B also brings along photochemical changes. Most important may be the increase in hydrogen peroxide concentration in these waters. This molecule, and the associated HO_2^- -radical ion, are important determinants of estuarine chemistry, including sulfur utilization and metals mobility.

7. Overview

Climate change will occur in a pre-stressed world. Stratospheric ozone depletion, tropospheric oxidant concentrations, forest degradation, eutrophication, acidification, and nutrient cycling will be enhanced by climate change. How these changes will affect temperate forests, fresh and coastal waters has been described and one conclusion stands out. In addition to difficulties which the direct effects of climate change may hold for human beings and natural ecosystems, the intensification of some existing pollutant problems will be an important indirect consequence of a warmer climate.

Because this paper is concerned with the interaction of climate stress with pollution, the emphasis has been on changes, such as biomass decreases in midlatitude terrestrial systems, which are generally considered to be undesirable. A few instances where climate-pollution interaction could reduce the effects of pollution are noted. Some of the potential direct consequences of slow temperature and precipitation changes also could be considered beneficial, e.g., biomass increases in boreal regions. However, the rates of change may well be rapid when compared to terrestrial ecosystem response times, so local outcomes of climate change which might be considered beneficial may never materialize [54].

Changes in climate-radiative and pollutant characteristics of the atmosphere may substantially alter ecosystems and biogeochemical cycles by the middle of the next century. With regard to biogeochemical cycles, changes in temperature and oxidant levels will generally accelerate the loss of carbon, sulfur, and nitrogen from terrestrial reservoirs, particularly at the midlatitudes. A prominent concern is the effect of increased levels of atmospheric oxidants. Increased oxidants will:

- (a) interfere in the sulfur cycle, increasing freshwater acidification;
- (b) increase solubilization and mobilization of some metals;
- (c) act as a phytotoxin;
- (d) indirectly enhance nitrogen mineralization and loss from forests due to the degrading consequences of phytotoxicity;
- (e) enhance carbon and nitrogen respiration from soils by accelerating decomposition;
- (f) enhance sediment oxidation, as is the case with increased nitrates and sulfates as well.

Ecosystem disturbance from climate change, air pollution, and land use changes

will also increase soil carbon respiration. Respiration may exceed net production due to the long equilibration time for terrestrial systems. It is likely that nitrogen loss will increase with respiration due to continuous climate and air pollution disturbance, since nitrate fluxes can increase under some conditions in temporarily disturbed forests [51, 55]. Mineralization will accelerate in the warmer, wetter soils brought about by forest decline and, in some areas, directly by climate change.

On the other hand, coastal ocean phyto-plankton experiencing a nitrogen surge from these changes and from atmospheric deposition equilibrate rapidly. They may respond to these changes with increased productivity, leading to local coastal eutrophication as productivity shifts from land to sea, particularly near industrial regions. Biota on land which serve as a carbon reservoir may experience a net decline in the short term.

To some extent, these changes occur synergistically and several specific mechanisms have been proposed to illustrate these synergisms. (Some inhibitory interactions may also occur, and these may ease current stress in a few circumstances.) Climate change fits into a pattern of pre-existing disturbances, the effects of which will be accelerated. The existence of synergisms present the possibility for surprising behavior by ecosystems. Near midlatitude industrial regions, interactive changes may move nutrients from land to coastal waters, increasing productivity along the coast, but sharply decreasing biomass on land.

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