Phyton (Austria) Special issue: "Global change"	**Vol. 42**	Fasc. 3	(171)-(182)	1.10.2002

Impact of Air Pollutants on Agriculture

By

J. ROGASIK[1),©)], S. SCHROETTER[1)] & E. SCHNUG[1)]

Key words: Air pollution, CO_2, temperature, ozone, sulfur, N deposition, ammonia.

Summary

ROGASIK J., SCHROETTER S. & SCHNUG E. 2002. Impact of air pollutants on agriculture. - Phyton (Horn, Austria) 42 (3): (171)-(182).

Air pollutants change plant metabolism, yield, crop quality, soil fertility, temperature regimes and hydrology. Type of air pollutants, deposition rate and structure of ecosystem bias the effects on agriculture. Increased CO_2 concentrations generally cause positive effects through increased root mass, litter and crop residues thereby increasing soil organic matter and plant growth. Accelerated CO_2 concentrations are associated with higher temperatures entailing negative effects on soils. The reduction of SO_2 emissions has a major effect on the productivity of agricultural crops (yield losses, reduced natural resistance, increased non point N losses, increase of surface ozone concentration). N depositions contribute indirectly to N_2O emission through an increased amount of N in the nutrient balance. Deposition of ammonia compounds is a primary cause of soil acidification. Ammonia contributes to transboundary air pollution and nitrogen enrichment of nutrient-poor soils. Air pollutants affect agriculture and may endanger a sustainable crop production. That is inconsistent with the requirement to protect the natural resources soil, water, atmosphere, and energy.

Introduction

The bio-geochemical cycling of nutrients among microorganisms, soils, plants and atmosphere is crucial for functioning of ecosystems. Cycling involves transformation processes, which are responsive to environmental conditions and will therefore be most likely affected by changes in climate and land use (WHEATLEY 1996). Changes in management practices, nutrient deposition, in-

[1)] Institute of Plant Nutrition and Soil Science, Federal Agricultural Research Centre Braunschweig-Völkenrode, Bundesallee 50, D-38116 Braunschweig, Germany.

[©)] Paper presented at the Sino-German Workhop on N_2O Emission from Agroecosystems, October 8-11, 2001, Shenyang, China creasing temperature and CO_2 concentration due to global climate change will consequently affect cycling processes and this again may result in increased air pollution (BULLOCK & al. 1996, DÄMMGEN & ROGASIK 1996, REILLY & al. 1996, SCHNUG 1998). Most of the observed air pollution during the past 50 years can be attributed to human activities. The impact of pollutants on agriculture can be divided into (i) potentially phytotoxic substances (heavy metals, protons, organic compounds, SO_2, NO_2, NH_3, O_3) and (ii) potentially nutritional substances (sulfur- and nitrogen compounds, CO_2) (DÄMMGEN & GRÜNHAGE 1994).

Potentially phytotoxic substances should be taken into account within ecosystems of large surface roughness (forests), because of the expected larger deposition rates. The deposition of acids from the atmosphere increases the risk of mobilization of accumulated heavy metals and will be a serious problem on arable land if liming does not compensate it. For the evaluation of organic compounds on the plant metabolism existing databases are too small. There is no direct phytotoxicity of SO_2 and NO_2 on arable land. The relevance of NH_3 for agriculture is its contribution to eutrophication and acidification of soils and water bodies (DÄMMGEN & GRÜNHAGE 1994).

Potentially nutritional substances of air pollutants will basically change plant metabolism, yield, crop quality, soil fertility, temperature regimes and hydrology. CO_2, sulfur and nitrogen are the best-known man - made pollutants with a fertilizing effect.

Increased CO_2 concentrations generally cause positive effects through increased root mass, litter and crop residues and thus increasing soil organic matter and plant growth. Accelerated CO_2 concentrations are associated with higher temperatures entailing a negative effect on soils (e.g. higher evaporation rates, decreased soil water content, higher risk of erosion and higher compaction risk due to losses of soil organic matter).

Increasing sulfur demands of crops due to higher yields a long time coincided with the increased supply from the atmosphere. The desulfurization of emissions within the last 2 decades led to a drastic decrease of atmospheric S deposition from about 40 to less than 10 kg ha^{-1} S. Consequently the reduction of SO_2 emissions had a major effect on the productivity of agricultural crops (yield losses, reduced natural resistance, increased non point N losses, increase of surface ozone concentration) (SCHNUG 1998).

The atmospheric N input is not relevant for nutrient balances in highly fertilized systems. In legumes and oligotrophic ecosystems, however, nitrogen should be considered as an important nutrient source. In regions with large livestock units the differences between actual deposition rates and critical loads are extraordinary.

This brief overview of some general impacts of air pollution on agriculture will be supplemented with selected experimental results in this contribution. In addition to results from literature the study used long-term fertilizer experiments in Braunschweig (52°18'N; 10°27'E) and Müncheberg (52° 30' N; 14° 8' E) to investigate the impact of air pollutants on agriculture (experimental details see ROGASIK & al. 1996, 2001).

Long-term field experiments were established in 1952 (Braunschweig) and 1963 (Müncheberg) to investigate main and interactive effects of mineral and organic fertilizer applications on soil fertility and stability of yields. Recently more emphasis was put on the integration of economic and ecological needs in food production, in particular by tracing the fates of carbon, nitrogen or sulfur compounds in the plant/soil system. In addition, the effects of a potential climate change on production levels and the sink or source properties of soils were studied. Besides long-term field tests, results from open-top chamber experiments (for experimental design see WEIGEL & JÄGER 1988, WEIGEL & al. 1992, GRÜTERS & al. 1997) were evaluated.

Effect of Air Pollutants on Soil Organic Matter and Biological Activity

A steady state of soil organic matter (SOM) is achieved only after 100 to 1000 years. However, as the rate of change is fastest at the beginning, potential increases or decreases of easily decomposable components in SOM can be determined earlier, usually within decades. Steady state values depend on physical and chemical climate, nitrogen depositions, soil type, management and soil water regime.

Anthropogenic input can affect carbon flows and the driving variables in the soil system. The global aspects are summarized in the following synopsis:

<table>
<tr><th>Feature</th><th>Elevated CO_2</th><th>Increasing temperature</th><th>N- and S-deposition</th></tr>
<tr><td>Biological activity:</td><td>Increased activity of microbiota due to higher amount of litter and root residues</td><td>Stimulation of soil microbiota, faster turnover processes with loss of carbon</td><td rowspan="2">Dose dependent, may be positive in case of nutrient deficiency</td></tr>
<tr><td>Soil organic matter:</td><td>Higher content of organic carbon, but changes in humus quality</td><td>Less litter production due to decline of yield, loss of C*</td></tr>
<tr><td colspan="4">* The soil/ plant system changes from a CO_2 sink to a CO_2 source when the rate of soil organic matter respiration exceeds the rate of humus accumulation and vice versa.</td></tr>
</table>

The soil / plant system is able to react to site-specific conditions but also to change in the general basic conditions. Global change may cause modifications of temperature, precipitation, CO_2 or N and S deposition. The transfer into a new steady state depends on the kinetics of the internal transformations and the rate of inputs. Next, selected results are demonstrated.

Table 1. Effect of mean temperature on date of harvest for winter wheat and winter rye in long-term field experiments at the Müncheberg site (40 years′ average, April to June, 1952 to 1992).

Crop	Temperature (°C)					Shift of harvest date
	< 11.5	11.5-12	12-12.5	12.5-13	13	($d\ K^{-1}$)
	date of harvest in Julian days					
Winter wheat	224	218	213	209	209	-7
Winter rye	221	217	210	206	204	-8

Table 2. Calculation of CO_2 emissions in dependence on climatic factors (data base: long-term field experiments, Müncheberg).

Soil moisture (0-12 cm) (Vol. %)	Air temperature (°C)	CO_2 emission (kg ha^{-1} CO_2-C)
4	18	4621
18	16	7493
8	14	5144
16	4	2440

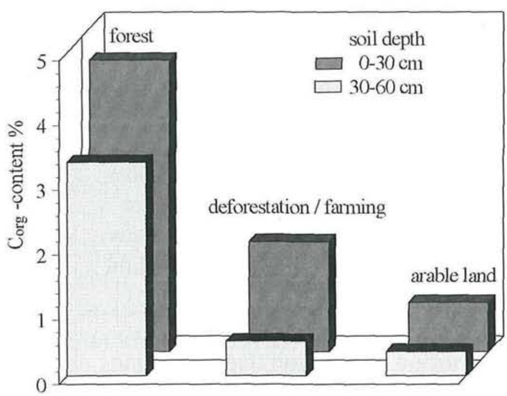

Fig. 1. Changes of soil organic matter caused by land use.

An increase of mean temperatures by 1 K causes a reduction of about 8 days of the growth period for cereals in the temperate zone (Table 1). This reduces grain yield by about 5 %, vegetative biomass and root residues by about 3 %. Consequently the C input is reduced by equal amounts (BRADBURY & POWLSON 1993, ROGASIK & al. 1994).

Duration of management, intensity of soil tillage and type of land use affect the decomposition of soil organic matter. Enhanced C mineralization as a result of intensive soil tillage, more favorable climatic conditions (Table 2) and the availability of readily decomposable carbon substances is linked with an additional CO_2 loading of the atmosphere.

Investigations at the experimental site in Braunschweig showed that 50 years after deforestation followed by farming the organic carbon content of the topsoil decreased by 40 %. The C_{org} content of long-term arable land was reduced by 80 % during the same period (Fig. 1).

Effect of Air Pollutants on Soil Structure, Infiltration Rate and Erosion Risk

The complex, integrated influences of different vegetation and land use, changing hydrological cycle and soil fertility level on soil physical conditions can only be a rough, qualitative estimation (VARALLYAY 1990). The impact of air pollutants on soil structure and erosion risk is a process with numerous indirect pathways. More detailed studies are required for a quantitative characterization. Some general estimations of the possible influence of air pollutants and increasing temperature on soil structure, soil water and erosion risk are listed below:

<table>
<tr><th>Feature</th><th>Elevated CO_2</th><th>Increasing temperature</th><th>N- and S-deposition</th></tr>
<tr><td>Soil structure:</td><td>Greater density of stable biopores, workability may be improved</td><td>Higher compaction risk due to losses of soil organic matter</td><td rowspan="3">Indirectly positive: fertilizing effect with higher amount of plant residues, more stable biopores
Unfavorable: acid rain causes a depletion of soils with basic plant nutrients resulting in degradation of soil structure and higher erosion risk</td></tr>
<tr><td>Soil water:</td><td>Improved water use efficiency</td><td>Unproductive evaporation, deterioration of water dynamics, decreasing soil water storage</td></tr>
<tr><td>Erosion/ infiltration:</td><td>Less runoff and erosion due to higher biomass production and better soil coverage</td><td>Earlier warming and loss of SOM lead to more runoff and reduced infiltration rates</td></tr>
</table>

Effect of Air Pollutatns on Soil Nutrient Status, pH and Soil Acidification

Nitrogen is essential for plant growth and required in sufficient amounts in order to achieve optimum crop yield. N emissions are valuable N losses and increase the risk of air pollution. Type of air pollutants, deposition rate and structure of ecosystem bias the effects on agriculture. Possible general impacts on the element balance are:

<table>
<tr><th>Feature</th><th>Elevated CO_2</th><th>Increasing temperature</th><th>N- and S-deposition</th></tr>
<tr><td>Soil nutrient status:</td><td>Higher nutrient mobilization, but nutrients may be limited due to increased growth</td><td rowspan="2">Reduction of buffering capacity and redox-potential due to decrease of SOM</td><td rowspan="3">Fertilizing effect, but unfavorable acid rain causes a depletion of soils with basic plant nutrients

Higher risk of acidification, and mobilization of heavy metals</td></tr>
<tr><td>PH/ acidification:</td><td>Higher sorption capacity, due to higher SOM content</td></tr>
<tr><td>Leaching:</td><td>Reduced nutrient losses</td><td>Warmer winters accelerate soil N mineralization and N losses</td></tr>
<tr><td>Salinization:</td><td>Reduced risk</td><td>Increased risk</td><td>No effect</td></tr>
</table>

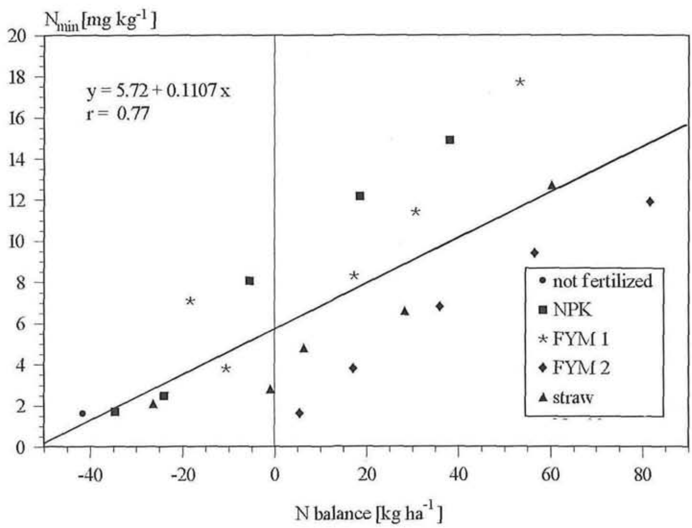

Fig. 2. Relationships between N balance and plant available nitrogen (0-50 cm soil depth) in Müncheberg (FYM = farmyard manure).

In particular, N depositions contribute indirectly to N_2O emissions through an increased amount of N in the nutrient balance. Surplus nitrogen increases the mineral nitrogen content in soil (Fig. 2) and thus the potential risk of nitrogen losses, which may cause environmental pollution when discharged to water bodies.

Anthropogenic emissions of N_2O are highest in agricultural systems with a high N input. The estimates of N_2O emissions cover a wide range and vary widely in different studies (THORNTON & VALENTE 1996).

Deposition of ammonia compounds, following reaction with acidic compounds in the atmosphere, is a primary cause of acidification of soils. This can affect the availability of elements both essential and toxic to plant growth. In addition, ammonia contributes to transboundary air pollution and nitrogen enrichment of nutrient-poor soils (Table 3), which results in major environmentally harmful effects. High ammonia emissions may also directly affect trees or vegetation by damaging foliage and retarding growth, respectively.

Numerous studies showed the impact of acidic rain on the mobilization of heavy metals. Increasing concentrations of heavy metals in soils and plants caused a dysfunction of physiological processes, yield decrease, visible symptoms (chlorosis, necrosis), stunted growth and ultimately plant death.

Table 3. Critical nitrogen loads for different ecosystems (NILSSON & GRENNFELT 1988).

Ecosystem	Critical load (kg ha^{-1} a^{-1} N)
Deciduous forest	5 – 20
Coniferous forest	3 – 15
Rough grassland	3 – 10
Fen/moor	3 – 15
Heather	7 – 30

Effect of Air Pollution on Crop Productivity and Root Development

It is well known that temperature and soil moisture or humidity have a major effect on the dry matter production of plants (Table 4).

Most arable crops belong to the plant group with a C_3 photosynthetic pathway. With view to the CO_2 supply, the gaseous composition of the atmosphere is sub-optimum for the carbon assimilation of those plants (PATTERSON & FLINT 1990). Under elevated atmospheric CO_2 concentration during the vegetation period C_3 plants can enlarge their productivity, both above ground plant parts and roots. The photosynthetic potential of C_3 plants will be stimulated and can result in an increase of plant growth and at least higher yields, if all other growth factors are sufficiently supplied. This includes among others temperature, light, soil fertility, plant available water, nutrient supply and plant health.

The evaluation of long-term experiments confirmed the sensibility of crops (mainly root crops) to changes in climatic conditions (Fig. 3). Increasing temperatures in combination with decreasing rainfall result in obvious yield reduction.

Table 4. Variation of winter wheat yield due to changes in temperature and rainfall (PARRY 1990).

Rainfall (mm)	Temperature (decrease / increase) (K)				
(decrease / increase)	-1.0	-0.5	0.0	+0.5	+1.0
			Variation of yield (%)		
-40	79	79	76	76	76
-20	92	92	89	90	89
0	104	103	100	100	99
+20	115	114	109	109	108
+40	125	124	118	118	117

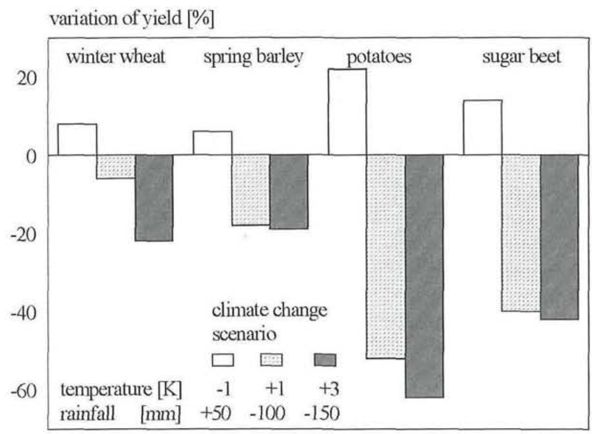

Fig. 3. Calculation of yield variation depending on climate change (data base: long-term experiment, Müncheberg, 1978-1990).

Gas experiments with cereals carried out in open-top chambers show that spring wheat under optimal nitrogen fertilization use a higher CO_2 supply for producing more total biomass. The root dry matter increases because the soil rooting intensity is higher (Fig. 4).

The growth promoting CO_2 effect interacts with different air pollutants, for example ozone. Positive effects of increased CO_2 levels can be reduced by damages of air pollutants such as ozone (Fig. 5). The potential damage of ozone depends on climatic conditions during the vegetative period. The investigation of grassland plant species shows similar results. Perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.), typical representatives of plant communities of intensive used grassland, have an increased root development under elevated CO_2 (Table 5).

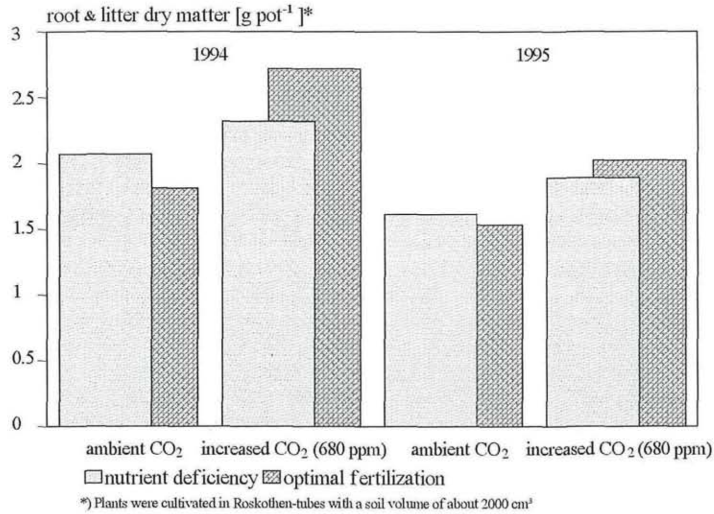

Fig. 4. Effect of atmospheric CO_2 concentration on root growth and litter production of spring wheat under different nutrient regimes (open-top chamber experiment, Braunschweig).

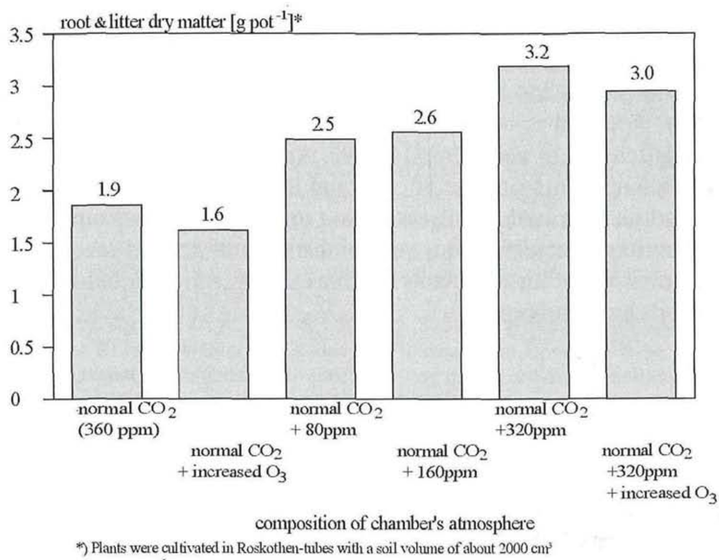

Fig. 5. Influence of atmospheric compounds on root growth of spring wheat (open-top chamber experiment, Braunschweig).

In agroecosystems plants and soil represent an inseparable unit with interactive effects. Agricultural plants serve as temporary carbon sinks. During the growth period plants metabolize atmospheric CO_2 by photosynthesis into glucose and finally convert it into biomass. After harvest biological and chemical soil processes decompose roots and residues.

Table 5. Influence of elevated CO_2 levels on root development of grassland plants (open-top chamber experiment, Braunschweig, 1994)

CO_2 concentration [ppm]:	360	440	520	660
Lolium perenne L.				
Stubble dry matter (g pot^{-1})	22.8	24.4	24.8	25.8
Root dry matter (g pot^{-1})	17.2	19.2	31.7	27.3
Total residues (g pot^{-1})	40.0	43.6	55.5	52.1
Trifolium repens L.				
Stolons dry matter (g pot^{-1})	22.1	25.0	27.0	25.5
Root dry matter (g pot^{-1})	5.0	5.7	6.0	6.4
Total residues (g pot^{-1})	27.1	30.7	33.0	31.9

Counter Measures and Conclusions

Air pollutants affect agriculture and may endanger a sustainable crop production. That is inconsistent with the requirement to protect the natural resources soil, water, atmosphere, and energy. A successful counter measure to reduce anthropogenic air pollution is to increase the sink potential of soils for greenhouse gases and the efficiency of agricultural inputs. An environmentally sound management will provide nutrients site-specifically and in time at rates, which are required for an optimized plant growth, whilst reducing undesired losses from the soil-plant system. A reduction of acidification, eutrophication and ground-level ozone needs to lower the emissions of air pollutants, such as sulfur, nitrogen oxides volatile organic compounds and ammonia.

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