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Acid Precipitation in Japan and Its Impact on Plants

2. Effect of acid precipitation on growth or yield of crops and forest decline

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Abstract

In most of the studies, no effects of simulated acid rain on the growth of agricultural crops and tree seedlings were reported when the pH of the applied solution exceeded a value of 3.0. Therefore, significant effects on agricultural crops and tree seedlings at current ambient levels of acid rain (pH 4.0-5.0) are unlikely. However, acid rain potentially could affect trees in natural forests in a variety of ways including the increase of soil acidity, increase of the solubility of phytotoxic aluminum ion, acceleration of acidic leaching of foliar nutrients and soil nutrients, and inhibition of activity of mycorrhizae. Therefore, acid rain may be one of the many environmental stresses contributing to forest decline. However, the cause of forest decline in Japan as well as in Europe and North America has not yet been clearly and completely determined.

Discipline: Agricultural environment
Additional key words: Japanese cedar, pH, simulated acid rain, stress

Introduction

In the previous paper[23], the current status of ambient precipitation in Japan and foliar visible injury due to acid precipitation were discussed. The present paper reviews the possible impact of acid precipitation on the growth or yield of agricultural crops and new type of forest decline phenomenon.

Effects of acid rain on growth or yield of crops

Until now there have been no reports on visible injury or crop loss under field conditions due to naturally occurring acid precipitation except for volcanic eruptions[17,34]. Therefore, most of the studies on the effects of acid rain on the growth or yield of agricultural crops have been carried out using simulated acid rain. Rain treatments are simulated through nozzles suspended above the plant canopy. Simulated acid rain is usually prepared with deionized water to which sulfuric or sulfuric and nitric acids are added. In many cases nonacidic salts at low levels are added to simulate important inorganic components of natural rain. Studies on the effect of simulated acid rain on the growth or yield of crops have been carried out mainly in the U.S.A. In Japan, however, attempts to assess the effects of acid rain on crops are still limited[8,15,16,31]. In particular, experiments on the effect of simulated acid rain on field-grown crops have not been conducted yet.

1) Controlled environment experiments

Plant growth may be stimulated, inhibited or not affected by exposure to simulated acid rain. Lee et al.[18] conducted experiments using 28 crops grown in pots in field chambers. Simulated sulfuric acidic rain was applied at pH levels of 5.6, 4.0, 3.5 and 3.0. Marketable yield was inhibited in five crops (radish, beet, carrot, mustard green, and broccoli) and stimulated in six crops (tomato, green pepper, strawberry, alfalfa, orchardgrass, and timothy). No consistent effects were observed in 16 other crops. They found that foliar injury was not generally related to the effects on yield. They also reported that dicotyledonous plants (e.g. bean) were more susceptible to simulated acid rain than the monocotyledonous ones (e.g. corn) and within the dicotyledonous group, the sensitivity decreased in the order of root, leaf, cole and tuber, legume and fruit crops. However, Irving[11] noted that there were both supporting and conflicting data for this classification.

In our Institute, Hosono and Nouchi[8] exposed to simulated acid rain at pHs of 5.6, 4.0, 3.0 and 2.7 (or 2.5) three species of crops, radish, spinach and bush bean, throughout the growing period in four greenhouses. The plants were subjected to acid rain treatment three times a week, for 1 hr with 10 mm of precipitation at a time. In these experiments, treatment at pH 3.0 or higher did not significantly affect the increase of the leaf area and dry weight of whole plant in the three species. When radish and spinach plants were exposed to simulated rain at a pH of 2.5, the dry weight of the hypocotyl of radish and dry weights of whole plant in spinach decreased significantly compared to the plants exposed to rain at pH 5.6 (Fig. 1). On the other hand, pod dry weights and dry weights of whole plant in bush bean plants exposed to acid rain at pH 2.7 were not significantly reduced.

One of the most comprehensive dose-response studies illustrating the possible impact of acidic precipitation on crop yield was conducted on greenhouse-grown radish by Irving[10]. Radish plants were exposed to simulated acid rain throughout a growing season at pH values ranging from 5.6 to 2.6. The results indicated the presence of a threshold for significant yield loss from rain acidity for pH

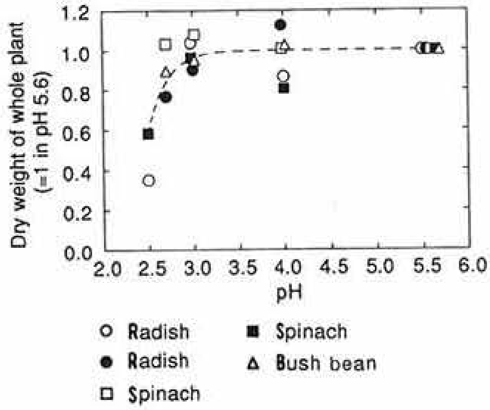

Fig. 1. Relationship between pH of simulated acid rain and relative reduction of dry weight of whole plant of radish, spinach and bush bean[8]
The dotted curve indicates the response of radish plants.

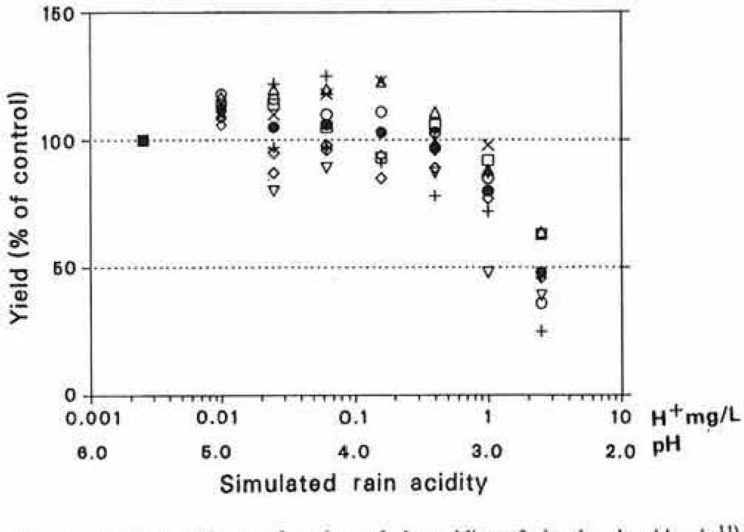

Fig. 2. Radish yield as a function of the acidity of simulated acid rain[11]
Data are means for one or two experiments in six different laboratories.

values between 3.0 and 3.4 throughout the growing season (Fig. 2). Jacobson et al.[13] calculated the threshold for yield loss using Irving's radish data described above[10] and a Mitcherlich function where the pH value associated with a 10% reduction in hypocotyl yield (root) was 3.3 ± 0.3.

2) Field experiments

Hypocotyl (root) yields of radish plants were reduced after exposure to simulated acidic rainfall under controlled environmental conditions[3,10,18]. In contrast to these results, Troiano et al.[32] recorded higher yields under high acidity rainfall compared with controls in radish plants grown under field conditions and Evans et al.[3] did not observe a significant yield loss in radish. Generally, the growth or yield of plants cultivated under growth chamber or greenhouse conditions appeared to be more adversely affected by acid rain compared with the plants grown under field conditions[9], for unknown reasons. Shriner[28] pointed out that cuticular development under the radiation, temperature and humidity conditions prevailing in the greenhouse was markedly different from that under similar conditions in the field, and that these differences may account for the difference in sensitivity between greenhouse and field-grown plants with respect to acid rain.

One of the most important objectives of research relating to the effects of acidic rain on agricultural crops is to determine the impact of acidic rain on the growth and yield of crops cultivated under field conditions. In such experiments, for example, automatically mobile rainfall-exclusion shelters have been employed in acidic deposition experiments conducted in the field[1,5]. These shelters cover the vegetation and exclude ambient precipitation when natural precipitation occurs and when artificial treatments are applied. Rain exclusion shelters were moved by a motor that was controlled by a rain-sensing detector. This type of research facility allows experimental plants to grow in a microclimate comparable to a normal agricultural field except during natural or simulated precipitation. Open-top field chambers, which have been used to expose crops to air pollutants such as ozone, were also used with automatic rain exclusion shelters to expose crops to acid rain[14].

Irving[11] summarized the results of a field experiment on eight crops (corn, soybean, wheat, timothy/clover, tobacco, potato, oat and snap bean) using simulated acid rain and ambient rain exclusion conditions in the National Acid Precipitation Assessment Program (NAPAP). None of the crops tested exhibited consistent reductions in yield from simulated rain within the range of average ambient acidity levels (pH 4.1 to 5. 1) during the growing season or even from higher acidity levels found in occasional rain events in the eastern part of the U.S.A. (pH

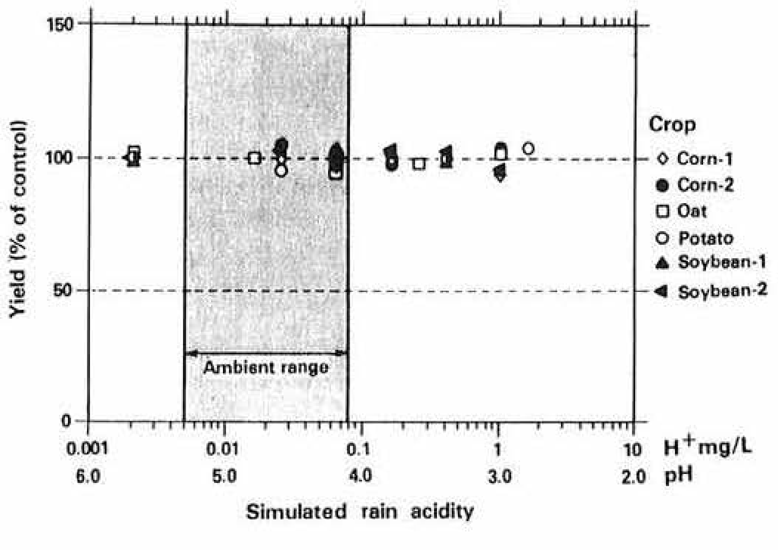

Fig. 3. Effects of simulated acid rain throughout the growing season on the yield of several important agricultural crops[11]

3.0 to 4.0) when compared with the yield of plants which were exposed to rain without strong acidity (pH 5.6) (Fig. 3). Variable results were obtained for some cultivars of soybean. However, Evans et al.[3,4,6,7] reported that simulated acid rain at pH values from 3 to 4 reduced the yields of field-grown crops such as soybean when compared to exposures at pH 5.6. Interim report of NAPAP[22] concluded that the impact from acidic deposition on regional crop production in the United States was negligible.

Mechanism of growth or yield reduction associated with acid precipitation

There are few studies on the physiological and biochemical changes associated with acidic rain. One possible physiological change which has often been suggested could operate by means of alterations of intracellular pH levels. Jacobson[12] pointed out the direct effects of hydrogen ion on biochemical reactions, including enzyme activity and cell elongation. Such effects may account for physiological changes because the acidity of the cell sap is normally maintained within a relatively narrow pH range necessary for the preservation of enzyme configuration and reactivity. As buffering systems are weakened, H^+ ion concentrations in plant tissues are likely to increase and lead to the increase of leaf acidity. Indeed, Bytnerowicz et al.[2] found that leaf extracts of pinto bean plants exposed to mist at pH values of 2.8, 2.4 and 2.0 showed a pH decrease of 0.05, 0.12 and 0.18 units, respectively. In addition, Sakaki and Kondo[25] reported that the photosynthetic activity was inhibited by the reduction of cytoplasmic pH. However, there are few reports on the changes in the rates of photosynthesis or respiration except in the case of rainfall with very low pH such as pH 2.0[24,30], which makes it difficult to explain the reduction in growth of sensitive crops such as radish, beet and certain varieties of soybean attributed to simulated acidic rain at pH values from 3.0 to 3.5. It is possible that the "energy redirection" hypothesis may account for the net growth reduction of crops due to acidic rain[33], which implies that the energy for growth may decrease. The energy which would be used for growth may be directed to consumption for protection and recovery from acid rain.

Forest decline in Europe and North America

In recent years, symptoms of a new type of damage to forest trees first appeared in West Germany in the late 1970s, initially on silver fir, *Abies alba*, and then on Norway spruce, *Picea abies*. For example, Norway spruce trees showed symptoms such as yellowing and early loss of needles, loss of fine roots, and decreased growth, leading to premature death. This phenomenon is currently widespread in Europe and North America[20], but the causes are complex and controversial[26].

The complexity of plant-environment interactions, including acid precipitation phenomena, in the forest decline problem was illustrated in the review by Schütt and Cowling[26]. They reviewed the problem from a historical perspective as well as common symptoms along with five hypotheses about its cause, as follows:

(1) The acidification-aluminum toxicity hypothesis

Natural acidification of soil increases as a direct or indirect result of deposition of acidic or acidifying substances from the atmosphere. Increased acidity in the soil leads to the increase of the concentrations of soluble aluminum ions. Aluminum toxicity results in the necrosis of fine roots, which leads to water stress and nutrient stress and eventually to the "drying out" and death of the trees.

(2) The ozone hypothesis

Based on this hypothesis, ozone damage to foliage results in dieback.

(3) The Mg-deficiency hypothesis

This hypothesis is based primarily on field observations of yellowing symptoms and low concentrations of magnesium in both soil and leaves at high elevations. Element leaching from foliage is presumably accelerated by ozone or frost damage to cuticles and cell membrances.

(4) The excess-nitrogen hypothesis

Nitrogen is an essential nutrient generally in limited supply in a forest. Most of the nitrogen is provided by root uptake, but some can be absorbed through the foliage as nitrate (NO_3^-), ammonium (NH_4^+) or ammonia (NH_3) from the atmosphere. Presently, nitrogen inputs from the atmosphere to forests have increased with industrialization. Excess nitrogen promotes growth and hence increases the demand for all other essential nutrients, leading to deficiencies in these elements. Furthermore, excess nitrogen inhibits the activity of mycorrhizae, increases the susceptibility to frost, root-disease fungi, changes the root-shoot ratio, and alters patterns of nitrification, denitrification and possibly N fixation.

(5) The general stress hypothesis

Air pollutants lead to a decrease in net photosynthesis and modify the carbohydrate status. The decrease in the amount of energy to the roots leads to poor development of fine roots and mycorrhizae and foliar decline symptoms. Reduced energy status increases the susceptibility of the trees to other stress factors, such as drought, nutrient deficiency, and biotic pathogens.

The cause of forest decline in Europe and North America has not been yet clearly and completely determined. However, many researchers consider that forest decline is the result of complex interactions between the environmental factors and natural ecosystems[19]. These complex environmental factors (stresses) may include cold injury, drought stress, soil acidity, aluminum toxicity, insect attacks, high concentration of ozone, acid precipitation and others.

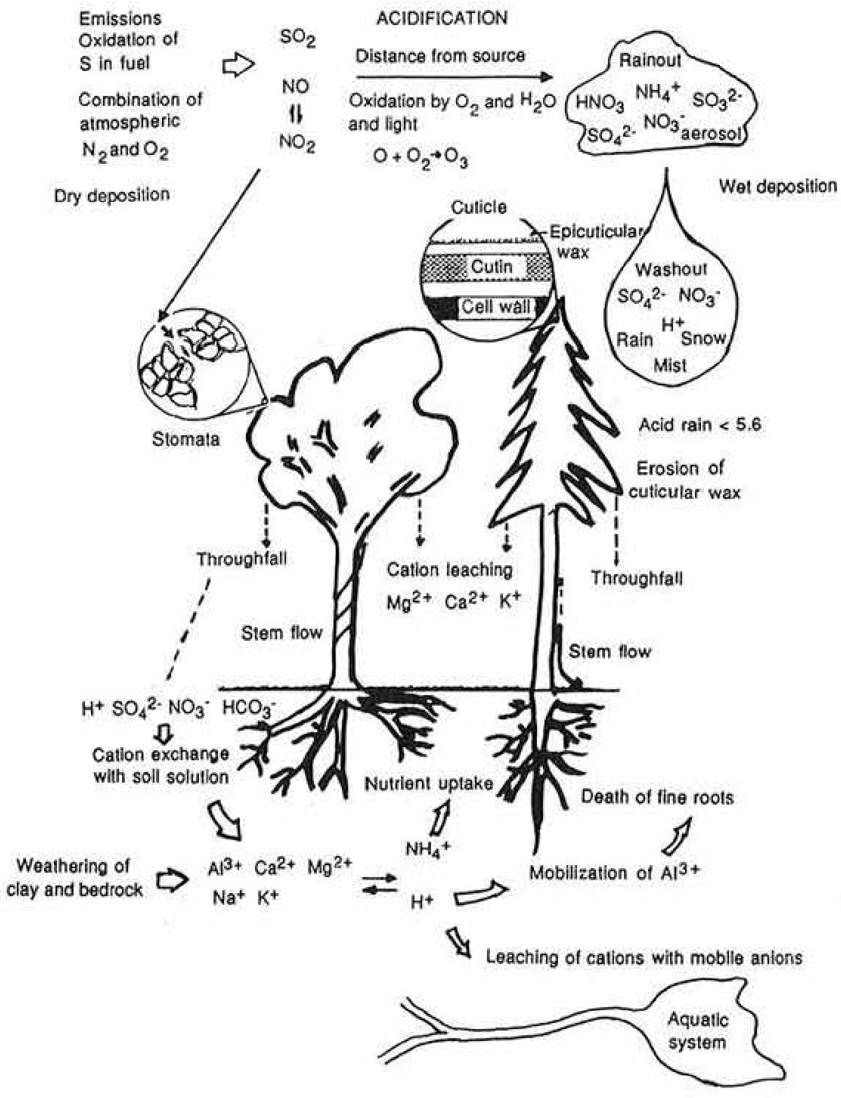

Fig. 4. Conceptual diagram of the reaction of wet- and dry-deposition on forest ecosystems (modification of figures of Wellburn[33] and McLaughlin[20])

Forest decline may be caused by the combination of factors even when one factor is dominant. Conceptual diagram of the effect of wet- and dry-deposition on forest ecosystems is shown in Fig. 4.

Forest decline in Japan

In Japan, although severe forest decline like in Europe and North America has not been detected yet, symptoms of tree crown damage in mature Japanese cedar, *Cryptomeria japonica*, have been observed in the Kanto district. Japanese cedars in the Kanto plain have been commonly planted in shrines and temple yards for religious purposes. Sekiguchi et al.[27] and Takahashi et al.[29] reported that acidic deposition including that of photochemical oxidants is a major factor affecting Japanese cedar because the distribution of Japanese cedar decline and the map of acid deposition including photochemical oxidants coincided. On the other hand, Morikawa et al.[21] concluded that the cause of the decline of mature forests of Japanese cedar is not clear. They suggested three possible causes as follows: (1) recent climate changes; especially lower precipitation and low air humidity, (2) gaseous air pollutants; complex effects, and (3) physiological properties of mature old trees; water stress in tree crown at higher position and decrease in the amount of photosynthetic products in the crown.

In addition to Japanese cedar, numerous cases of death of fir trees at Mt. Oyama in Kanagawa Prefecture and Mt. Homan in Fukuoka Prefecture, and birch, *Butula platyphyll* var. japonica, at Mt. Akagi in Gunma Prefecture have been recorded. However, the causes have not yet been determined.

Conclusion

At present, the current ambient levels of acid precipitation in Japan, where the annual mean pH value was about 4.7, may not affect the growth or yield of crops. On the other hand, acid precipitation may affect the growth or viability of forest trees by direct (foliar injury, leaching) or indirect means (soil acidity, soil nutrient effect, resistance to attacks by pathogens or insects). It is anticipated that if the current level of acid precipitation persists, some effects of acid precipitation on forest could become apparent like the phenomenon of forest decline in Europe and North America. Since acid deposition is a gradual process requiring a long period of time before its impact can be evaluated, delayed effects on terrestrial ecosystems may be caused by the acidification of the environment. The recovery of the ecosystems is very difficult once these effects become apparent. Therefore, utmost efforts should be made to reduce the emission of SO_2 and NO_x in order to protect agricultural and natural ecosystems.

References

1) Banwart, W. L. (1988): Field evaluation of an acid rain-drought stress interaction. *Environ. Pollut.*, **53**, 123–133.
2) Bytnerowicz, A., Temple, P. J. & Taylor, O. C. (1986): Effects of simulated acidic fog on leaf acidification and injury development of pinto bean. *Can. J. Bot.*, **64**, 918–922.
3) Evans, L. S. et al. (1982): Effects of simulated acidic rain on yields of field-grown crops. *New Phytol.*, **91**, 429–441.
4) Evans, L. S. et al. (1983): Productivity of field-grown soybeans exposed to simulated acid rain. *New Phytol.*, **93**, 377–388.
5) Evans, L. S., Levin, K. F. & Patti, M. J. (1984): Effects of simulated acid rain on yields of field-grown soybeans. *New Phytol.*, **96**, 207–213.
6) Evans, L. S. et al. (1985): Effects of frequency and duration of simulated acidic rainfalls on soybean yield. *New Phytol.*, **100**, 199–208.
7) Evans, L. S. et al. (1986): Comparison of yields of several cultivars of field-grown soybeans exposed to simulated acidic rainfalls. *New Phytol.*, **102**, 409–417.
8) Hosono, T. & Nouchi, I. (1992): Effects of simulated acid rain on the growth of radish, spinach and bush bean plants. *Taiki Osen Gakkaishi* (*J. Jpn. Soc. Air Pollut.*), **27**, 111–121 [In Japanese with English summary].
9) Irving, P. M. (1983): Acidic precipitation effects on crops: A review and analysis of research. *J. Environ. Qual.*, **12**, 442–453.
10) Irving, P. M. (1985): Modeling the response of greenhouse-grown radish plants to acid rain. *Environ. Exp. Bot.*, **25**, 327–338.
11) Irving, P. M. (1987): Effects on agricultural crops. *In* National Acid Precipitation Assessment Program; Interim assessment: the cause and effects of acidic deposition, Vol. IV, Washington D. C., 6.1–6.50.
12) Jacobson, J. S. (1980): The influence of rainfall composition on the yield and quality of agriculture crops. *In* Ecological impact of acid precipitation, Proceedings of an International Conference, eds. Drablos, D. & Tollan, A., SNSF Project, Oslo, Norway, 41–46.
13) Jacobson, J. S. et al. (1988): A collaborative effort to model plant response to acidic rain. *J. Air Pollut.*

Assoc., **38**, 777-783.
14) Johnston, J. W., Shriner, D. S. & Abner, C. H. (1986): Design and performance of an exposure system for measuring the response of crops to acid rain and gaseous pollutants in the field. *J. Air Pollut. Assoc.*, **38**, 894-899.
15) Kohno, Y. & Kobayashi, T. (1989): Effect of simulated acid rain on the growth of soybean. *Water, Air, Soil Pollut.*, **43**, 11-19.
16) Kohno, Y. & Kobayashi, T. (1989): Effect of simulated acid rain on the yield of soybean. *Water, Air, Soil Pollut.*, **45**, 173-181.
17) Kratky, B. A. et al. (1974): Volcanic air pollution; Deleterious effects on tomatoes. *J. Environ. Qual.*, **3**, 138-140.
18) Lee, J. J. et al. (1981): Effect of simulated sulfuric acid rain on yield, growth and foliar injury of several crops. *Environ. Exp. Bot.*, **21**, 171-185.
19) Likens, G. E. (1989): Some aspects of air pollutant effects on terrestrial ecosystems and prospects for the future. *AMBIO*, **18**, 172-178.
20) McLaughlin, S. B. (1985): Effects of air pollution on forest: A critical review. *J. Air Pollut. Cont. Assoc.*, **35**, 512-534.
21) Morikawa, Y. et al. (1990): Forest decline in Japan: Mature *Cryptomeria japonica* declines in the Kanto plains. *In* Proceeding of 19th IUFRO World Congress, Division 2, 397-405.
22) National Acid Precipitation Assessment Program (NAPAP). (1987): Interim assessment: the cause and effects of acidic deposition. Vol. I-IV. Washington D. C.
23) Nouchi, I. (1992): Acid precipitation in Japan and its impact on plants: I. Acid precipitation and foliar injury. *JARQ*, **26**, 171-177
24) Porter, J. R. & Sheridan, R. P. (1981): Inhibition of nitrogen fixation in alfalfa by arsenate, heavy metals, fluoride, and simulated acid rain. *Plant Physiol.*, **68**, 143-148.
25) Sakaki, T. & Kondo, N. (1985): Inhibition of photosynthesis by sulfite in mesophyll protoplasts isolated from *Vicia faba* L. in relation to intercellular sulfite accumulation. *Plant Cell Physiol.*, **26**, 1045-1055.
26) Schütt, P. & Cowling, E. B. (1985): Waldsterben, a general decline of forest in central Europe: Symptoms, development and possible causes. *Plant Disease*, **69**, 548-558.
27) Sekiguchi, K., Hara, Y. & Ujiie, A. (1986): Dieback of *Cryptomeria japonica* and distribution of acid deposition and oxidant in Kanto district of Japan. *Environ. Tech. Letters*, **7**, 263-268.
28) Shriner, D. S. & Johnson, J. W., Jr. (1987): The effects of acid rain, alone and in combination with gaseous pollutants, on growth and yield of crop plants. *In* Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems. eds. Hutchinson, T. C. & Meema, K. M., Springer-Verlag, Berlin. 365-388.
29) Takahashi, K., Okitsu, S. & Ueda, H. (1986): Acid deposition and Japanese cedar decline in Kanto region, Japan. *Shinrin Ricchi*, **28**, 11-17 [In Japanese].
30) Takemoto, B. K., Bytherowicz, A. & Olszyk, D. M. (1988): Depression of photosynthesis, growth, and yield in field-grown green pepper (*Capsicum annuum* L.) exposed to acidic fog and ambient ozone. *Plant Physiol.*, **88**, 477-482.
31) Taniyama, T. & Saito, H. (1981): Studies on injurious effects of air pollutants on crop plants. 16. Effects of acid rain on apparent photosynthesis and grain yield of wheat, barley and rice plants. *Rep. Environ. Sci. Mie Univ.*, **6**, 87-101.
32) Troiano, J., et al. (1983): Effects of acidity of simulated rain and its joint action with ambient ozone on measures of biomass and yield in soybean. *Environ. Exp. Bot.*, **23**, 113-119.
33) Wellburn, A. (1988): Air pollution and acid rain: The biological impact. Longman Scientific & Technical, Essex.
34) Yamaguchi, T. et al. (1988): Plant damages by volcanic acid rain: A case of near Sakura-zima. *Nogyo Kisho* (*J. Agr. Met.*), **44**, 219-223 [In Japanese].

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