IRISH FORESTRY

Volume XIX. Autumn, 1962 Number 2

# The Nitrogen Economy of Coniferous Forest Soils in Bavaria *

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1. *Water and nitrogen deficiency.*

I deem it an honour as well as a great pleasure to have the opportunity to speak to you about the work of my Institute. We are engaged in Munich in the study of the nutrient status—especially of nitrogen—of the Bavarian forests and we are seeking to find the connections between the productivity, the state of nutrition and the soil conditions.

The Bavarian state forests occupy an area of 1,8 million acres. 82% of this area is covered by coniferous trees, especially Norway spruce. On many sandy soils however and other soils of low productivity the spruce is substituted by the Scots pine. Approximately 100,000 acres, i.e. 26% of these pine forests, have a yield of 1,0 solid cubic meters Derbholz (i.e. wood having over 7 cm diameter) although the best pine stands in Bavaria have a production of 3,2 solid cubic meters per acre per year.

In former times foresters often puzzled over the reason for this low yield and how they could effectively and profitably increase the soil fertility. If the only cause is a deficiency of water the forester may here and there eliminate the competition of ground vegetation. He could do nothing else to increase the yield as all other tree species give even lower crops on dry sites in Bavaria.

By the thickness of the annual rings of the pines one can actually tell that the production in dry years is less than in years of higher rainfall. Nevertheless it would be jumping to a conclusion to assume that the poor stands are suffering in the first place from a deficiency of water. The great success which we achieved with nitrogen fertilization, even on dry sites, is proof enough of the great nitrogen deficiency in the unproductive pine forests. H. Zöttl (1962) was able to increase the current increment of such pine woods from 2 to 4 cubic meters for several years by a single fertilization with 178 lbs. pure nitrogen per acre. This means a rise in productivity from the IV. to the I. height quality class. We have 5 quality classes in Bavaria.

* Paper read by Professor Doctor Laatsch at an informal meeting at the Agriculaural Institute, Dublin—October, 1961.

Plate 1 may give you an impression of such increment increases on a dry podsolised sandy soil. You see annual shoot increments from the third whorl from the top. The trees were dressed with 178 lbs. nitrogen per acre in the spring of 1956. On the left side there are shoots from the control plot, in the middle shoots from a plot dressed with ammonia

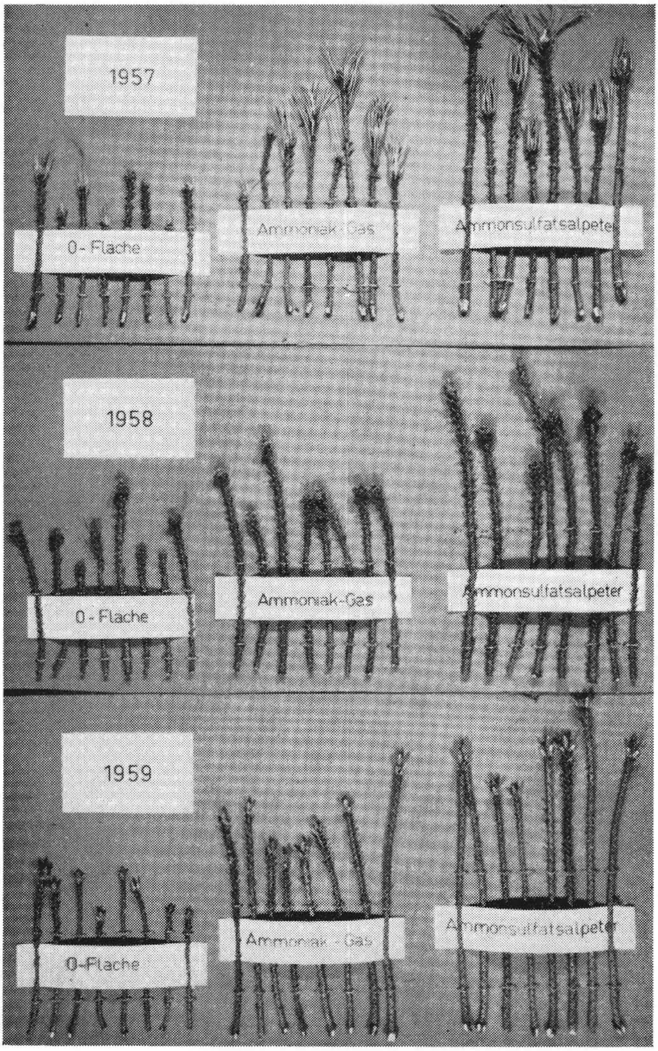


Plate 1 : The effect of a single dressing with 178 lbs. nitrogen per acre in the year 1956 on the size of the annual shoot increments of Scots pine in the years 1957-1959. Left : controls. Middle : ammonia gas. Right : mixture of ammonium nitrate and ammonium sulfate. After H. Zöttl (1962).

gas and on the right shoots fertilized with a mixture of ammonium nitrate and ammonium sulfate.

The salt mixture always gives better results than the gas because it is better distributed in the soil. The gas harms small roots at spots of high concentration. You see that there is an increase of growth over several years after one single dressing in 1956. The net profit from this experiment is greater than double the amount of the expenditure.

In order to explore the distribution of nitrogen deficiencies and possible mineral deficiencies, J. Wehrmann (1959) made needle analysis of 68 pine stands in the years 1957 and 1958. He compared the nitrogen concentration in the dry substance of the current needles, harvested in October, from the uppermost side shoots with the quality class. As you can see from figure 1 there is a good and significant correlation.

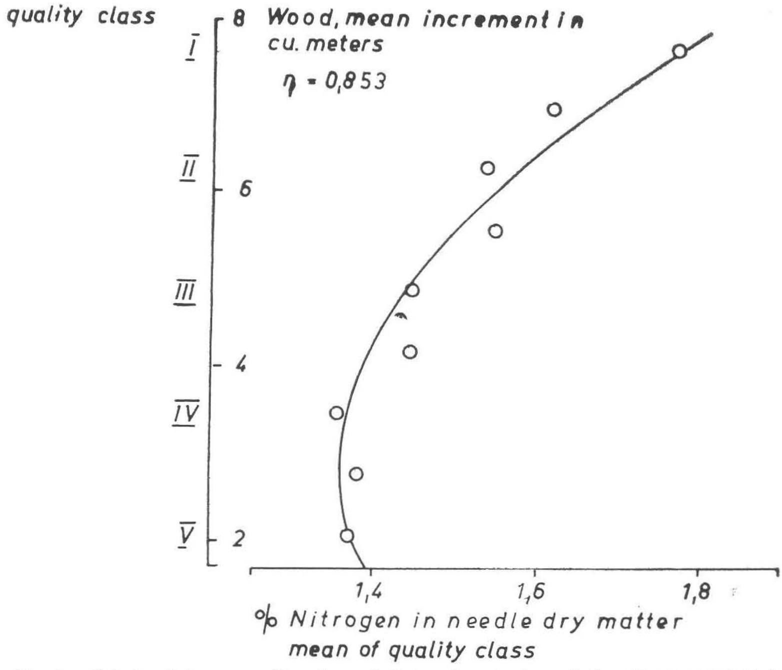


Fig. 1: Relation between quality class of Scots pine stands and the nitrogen content in their current needles.

After J. Wehrmann (1959).

The lowest value of all single measurements was 1,2%, the highest 2,2% nitrogen. All stands with a high rate of production, i.e. all those which belong to the quality classes I and I,5 showed a nitrogen concentration above 1,5%. In the lower classes, i.e. III. to V. quality, there is no case worth mentioning in which the concentration surpassed this level.

The wide-spread distribution of nitrogen deficiencies in our pine forests is reflected by this correlation. We know this from the results of nitrogen fertilization experiments. Nitrogen top-dressing in slow growing stands improves nitrogen concentration in the needles. It also increases the increment of wood and that to the extent shown by the curve in figure 1.

In all mull and moss-humus soils the pines did not suffer from nitrogen deficiency but only in some raw humus soils where the upper layer has a tendency to dry up. The analyses of J. Wehrmann (1961) indicate that the dry sites offer relatively little nitrogen. The extent to which water deficiency reduces nitrogen output, is shown by the continuation of needle analysis in the dry year 1959 and in the following year with a normal amount of precipitation. The mean value of all nitrogen concentrations from the examined sites was clearly below that of the two preceding years. As the pines in the dry year were able to store but little nitrogen for the needle production of the following year, the nitrogen concentration in 1960 was appreciably lower than in 1959. The average of all analyses was only 1,2%. This is the mean concentration of the worst stands in normal years.

It is possible that the pines of most dry sites don't suffer themselves from water deficiency in dry years, in so far as their roots go down to the subsoil. However the microbes, supplying the trees with mineral nitrogen are in dry years badly neglected, because they are concentrated in the uppermost soil layer, which dries up severely. Fungi and bacteria split off ammonia from the organic nitrogen compounds so long as the litter—and humus particles are moist enough. The formation of ammonia, also called nitrogen mineralisation, is the main process supplying nitrogen to the trees. I shall refer to this again.

In our spruce stands, O. Strebel (1960) established a statistically significant correlation between the nitrogen concentration of the needles and the growth of the trees. That this relationship is not only a correlative but also a causative one was shown by successful fertilization trials. Therefore nitrogen is also in our spruce forests, a limiting factor.

2. *The forms of humus and the nitrogen store in the soil as factors of nitrogen supply.*

If we now want to know the factors which beside soil moisture and temperature control the nitrogen supply of the trees, it is necessary to measure the nitrogen mineralisation under controlled conditions, i.e. constant temperature and soil moisture. Hesselmann in Sweden was the first to introduce such incubation methods for the study of soil humus. Humus samples are put in glass jars, closed with cotton wool, for several weeks. At the end of the incubation period, the amounts of ammonia and nitrate nitrogen, accumulated during the experiment, are determined. This sum, reckoned as a percentage of total nitrogen or in ppm (parts per million) of dry matter, gives a measure of the

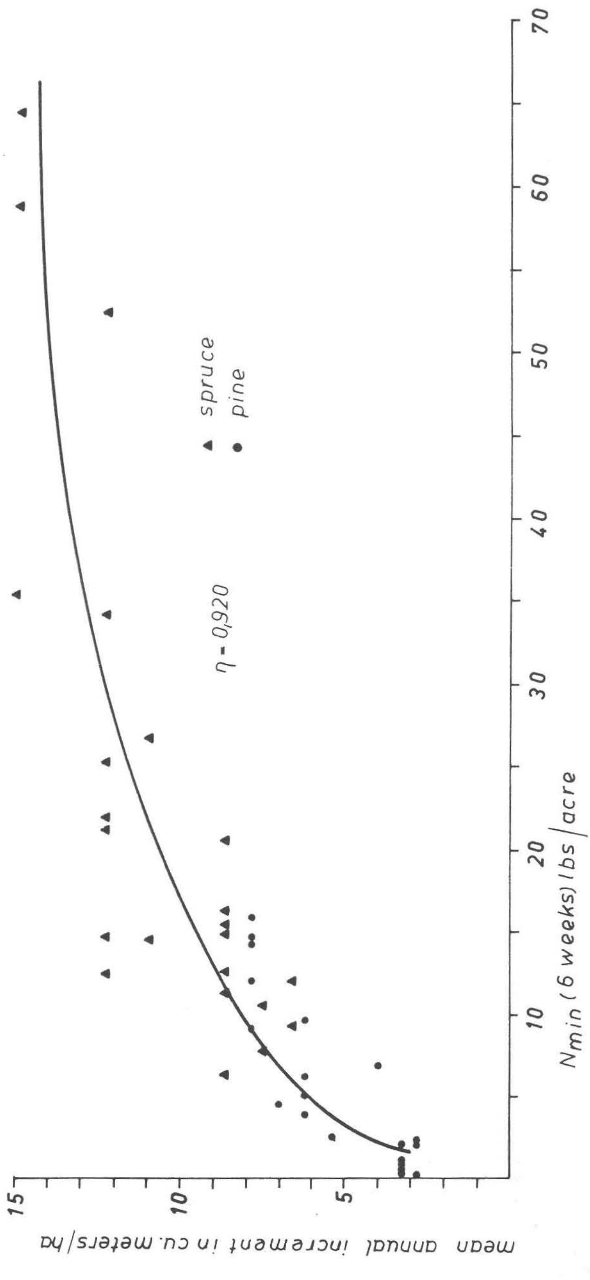


Fig. 2: Relation between the mean annual increment of Bavarian spruce and pine stands and the amounts of mineralised nitrogen in the humus layer.

After H. Zöttl (1960b).

mineralisation capacity of the sample and also of its ability to nourish the vegetation with nitrogen.

In our Institute H. Zöttl (1960a) found by comprehensive methodical experiments, that an incubation time of 6 weeks and a water content of 60% maximum water capacity was especially suitable for evaluation of the nitrogen supply. During this time, only 1% of the nitrogen content was mineralised from inactive forms of raw humus poor in nitrogen. The rate of mineralisation in active raw humus, moss humus and some forms of mull may amount to between 4 and 7 odd %. In samples of mull without plant remains, the rate of mineralisation is very low, because their nitrogen is enclosed in resistant humus substances. So one can see that the nitrogen nutrition of the trees depends on the different forms of humus, the nitrogen stock of the soil profile and the weather conditions.

From the accumulated amount of mineralised nitrogen in the incubation samples it is possible to calculate the respective amounts in acres. H. Zöttl (1960) has shown that there is a good correlation between these amounts and the current annual increment.

Figure 2 shows quite clearly the nitrogen deficiency in many of our forests. It signifies also the usefulness of the incubation method for the evaluation of the nutritional status of the stands.

3. *Factors of humus form and nitrogen stock.*

If we now have at hand suitable methods for the evaluation of nitrogen deficiencies, the question is: Which is the most economic way of disposing of such deficiencies? Practical advice often proves to be one-sided and tends to generalise, if it does not depend on scientific knowledge of the effective forces and their causal relationships. As the humus form and the nitrogen stock determine the nitrogen nutrition of the trees to a large extent, it is better to know something first about the factors which produce these two soil qualities in the forest.

It is generally known that conifers and dwarf shrubs like *Vaccinium* species and *Calluna vulgaris* promote the formation of raw humus. As raw humus very often initiates podsolisation and thereby robs the upper layer of soil nutrients, the raw humus was very often considered as an undesirable humus form, produced by culture of purely coniferous stands. For this reason many foresters thought fit to cultivate more natural stands, i.e. forests incorporating mixtures of coniferous and deciduous trees.

Numerous fertilization trials in spruce forests of the South West State of Western Germany showed however the possibility of changing within a few years inactive raw humus, poor in nitrogen, into active moss humus-like raw humus by a single fertilization with basic phosphate and lime. There is a rapid mineralisation in these ripened humus layers. By additional dressings with nitrogen the transformation would be appreciably accelerated. It is not only a matter of microbial modification but also of an increase of the number of larger soil animals, especially earthworms. These mix the raw humus layer gradually with mineral matter to an extent that moss humus-like forms arise. Thus phosphate and lime, sometimes supplemented by nitrogen fertilizers, make it possible, to change the humus form. Often this transformation is even more effective than the exclusive cultivation of mixed softwood and hardwood stands, particularly because deciduous trees do not thrive on very acid soils without fertilization. Evidently the influence of the base saturation and the phosphorous content of the soil on the humus form seems to be stronger than that of the vegetation. This can be seen clearly in our beech forests, which produce best mull forms or raw humus according to soil conditions.

I wish to turn now to the second factor which determines the nitrogen nutrition of the trees, i.e. the nitrogen store in the soil. Why do soils of low productive pine sites possess so little nitrogen? In the eastern part of Bavaria, sandy soils under a IV. or V. quality class of pine contain down to a depth of 1m about 1,000-2,000 lbs. of nitrogen per acre, whereas S. Emberger and W. Madl (1960) found up to/or even more than 15,000 lbs. per acre in loamy soils under well growing spruce stands in South Bavaria. Only a small part of these amounts is stored in the litter. The main "capital" is banked within the humus and little more than 10% as fixed ammonium between the layers of clay minerals. As not only the litter nitrogen but also the humus nitrogen is subject to mineralisation, the level of humus nitrogen would decrease slowly but steadily, if one part of the litter nitrogen were not continually transformed to humus nitrogen.

In forests which are more than a thousand years old and carefully managed, the nitrogen store has reached a constant level, keeping the balance with those factors, which this equilibrium level determine. Under the same climate and the same standing crop a permeable loam has then usually a greater nitrogen content than a free-draining sand. H. Jenny (1960) has recently shown that this relationship also refers to Indian soils.

Because of the greater content of clay in loam, the freshly formed humus substances have in these soils more opportunity to be bound to mineral colloids and thereby protected from quick mineralisation. The greater amount of water and the lower air-permeability of loamy soils will also promote the accumulation of humus and therewith of nitrogen.

It is not possible however to deduce the great variability of nitrogen store in our Bavarian forest soils from their amounts of mineral colloids alone. A second factor of importance which determines their nitrogen content is the gathering of litter by agriculture. Over the centuries this removal of litter and of underlying raw humus has badly damaged many soils, especially the sandy ones, poor in mineral nutrients and leaning to raw humus formation. By this practice the soil-vegetation system is robbed not only by organic matter but also by the loss of a great part of those nutrient amounts circling from the soil to the vegetation and back to the soil.

4. *The reserves of phosphorus as a factor of nitrogen accumulation.*

The possibility exists that the higher phosphorus content of many loamy soils may also stimulate nitrogen accumulation and in this way improve the nitrogen nutrition of the stands. According to the analysis of J. Wehrmann (1959) in pine forests and of O. Strebel (1960) and W. Madl (1960) in spruce stands there is a positive correlation between the nitrogen and phosphorus content in the needles and in the upper humus layer. The average values over a number of years show that needles rich in phosphorus are usually also rich in nitrogen, and a soil rich in phosphorus is able to deliver more nitrogen to the trees than a phosphorus deficient soil. How may these connections be understood?

I suppose that a high amount of phosphorus favours the nitrogen economy of the forest soil in two different ways. Firstly, a high phosphorus concentration in the forest litter and in the top soil may stimulate the fixation of nitrogen from the air. Much data from the literature point to a positive influence of higher phosphate concentration in the soil solution on nitrogen fixation. Secondly, phosphorus may also stimulate the accumulation of the fixed nitrogen in the soil profile. This may happen by an increased rate of multiplication of earthworms. As already mentioned we can actually observe such thriving of the earthworm population and of many other members of the macrofauna after dressings with basic slag or ground rock phosphate.

According to these observations and conclusions it should be possible to increase the nitrogen fixing capacity of the forest soil and the accumulation of humus nitrogen within it by phosphate dressings in as much as the phosphate supply of the soil limits nitrogen fixation and accumulation. Should this conjecture prove correct, the forester would have at least four different methods at his disposal for improving the nitrogen nutrition of the stands:

1. Nitrogen fertilization.
2. Preliminary or simultaneous cultivation of nitrogen enriching plants like alder or legumes.
3. Phosphate dressing.
4. Growing mixed hard—and softwood stands after preliminary fertilization.

Hardwood trees with fast decomposing litter stimulate the earthworm population. In the south-west German spruce forests surprising results have actually been obtained by single dressings with basic slag or a mixture of lime and basic slag. In some cases significant responses in height increment are continuing over several decades. These effects can only be understood by assuming that on the dressed plots the supply of the trees was currently increased not only in respect to phosphorus but to nitrogen also, since, according to experience, we have to regard all these experimental plots as nitrogen deficient.

O. Strebel (1960) has even described remarkable increases in the nitrogen concentartion of spruce, showing high growth responses to phosphate dressing. Here increasing nitrogen supply must have played a part, since an increase in the nitrogen uptake of the trees is already established, if the nitrogen concentration in the needles of trees with increasing height growth remains constant.

However, an increased nitrogen supply after phosphate fertilization is no proof of an increased nitrogen level in the soil. The stimulation of nitrogen mineralising microbes may also bring about higher rates of nitrogen supply. In such a case the improved nitrogen nutrition of the trees would be possible at the expense of the nitrogen reserve stored in the soil, i.e. one part of this reserve is transformed to available nitrogen and enters into the nutrient cycle moving from the soil to the trees and back again to the soil.

It is not yet clear whether the fertilized phosphorus raises the nitrogen level in the soil or improves nitrogen mineralisation. We hope that laboratory experiments will help us to settle this question. H. Zöttl is currently testing the influence of small amounts of potassium phosphate on the carbon dioxide production and nitrogen mineralisation in samples of raw humus. In preliminary experiments several raw humus samples from pine and spruce stands showed an increase in carbon dioxide evolution, even if there were no rise of the pH-values involved with the addition of the phosphate. The observed increase in respiration means a general stimulation of the microbial population. It follows that for the micro-organisms of these undressed raw humus samples, phosphorus is a minimum factor.

This result is very interesting as J. Wehrmann could not find a phosphorus deficiency of pines in his 68 pine stands already mentioned. There was an excellent growth of some trees with the lowest detected P-concentration in their needles. Thus a P-deficiency of the soil micro-organisms, seems to be more frequent than a P-deficiency of the pines. This result runs parallel with the water deficiency of nitrogen mineralising microbes in soils, which may store enough available water for the pines.

If a small dose of phosphate improves carbon dioxide production in some raw humus forms, nitrogen mineralisation in these samples decreases simultaneously. H. Zöttl (1958) obtained the same result also after fertilizing with lime, as can be seen in fig. 3.

The solid lines represent the course of microbial activity in a raw humus sample of an undressed plot, the broken lines refer to a sample from the neighbouring plot, dressed with lime. Both plots belong to a pine stand of low productivity. It can be seen from the upper diagram, that the lime, given one year before sampling, has increased respiration. The lower diagram shows on the other hand, that nitrogen mineralisation in the dressed sample is nearly blocked for about 10 weeks.

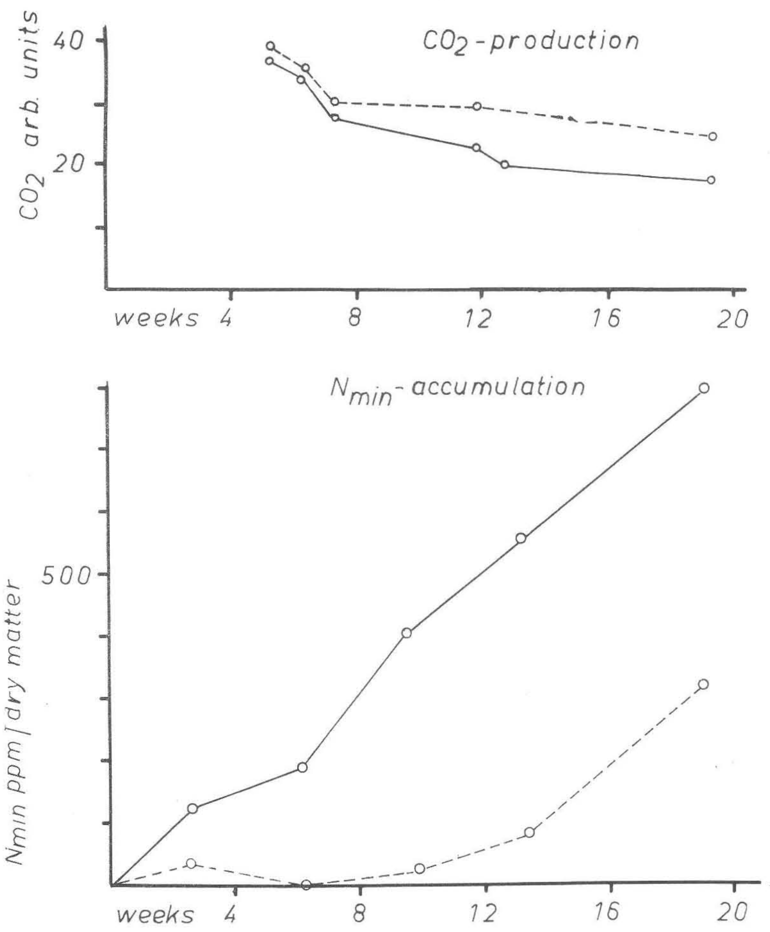


Fig. 3: The influence of lime on the respiration (upper diagram) and the nitrogen mineralisation (lower diagram) of raw humus samples from a pine stand of low productivity.
Solid lines: undressed plot.
Broken lines: plot dressed with lime. After H. Zöttl (1958).

The reasonable inference can be draw that the increase in the sample's pH by lime as well as dressings with a suitable amount of phosphate to a raw humus, poor in phosphorus stimulates many organisms which break down cell walls of plant residues. These microbes consume the nitrogen mineralised during the incubation time for the synthesis of new cell material. Thus only a small amount of mineral nitrogen will accumulate. This lack in mineral nitrogen however is a necessary condition for the propagation of non-symbiotic nitrogen fixing organisms. They will grow preferentially in ecological gaps where there may be suitable sources of energy and mineral salts but nearly no mineral nitrogen. In these gaps they escape the competition of all microorganisms depending on mineral nitrogen. Thus it is not unlikely that combined dressings of lime and phosphate will bring about a temporary increase in nitrogen fixation in some layers of raw humus. But as soon as the C/N-ratio in the raw humus has fallen considerably by the decomposition of plant residues, an increased net mineralisation of nitrogen and therewith blocking of nitrogen fixation has to be expected. Thus far, our knowledge about these changes in microbial activity and about the amounts of nitrogen fixation is very scanty.

5. *Measurements of nitrogen fixation in humus samples.*

For some time we have been trying to get a conception of the extent and the factors of nitrogen fixation in samples of forest litter and humus, using the heavy isotope $^{15}N$ as a tracer. Yet until now we have not succeeded to get reproducible results, as the rate of nitrogen fixation depends strongly on the water conditions : especially on changes in the water content of the samples during the time of incubation. Anyhow previous experiments, accomplished by R. Hüser (1960), have sometimes shown a jerky acceleration of nitrogen fixation if the samples are dried up slowly during the incubation time and are not held at a constant water content of 60% maximum water capacity.

Now, I should like to show you by figure 4 our apparatus for the measurement of nitrogen fixation constructed by R. Hüser (1960). The soil samples are placed in an air-tight glass jar. As there is no need to weigh the samples at the beginning of the incubation time,

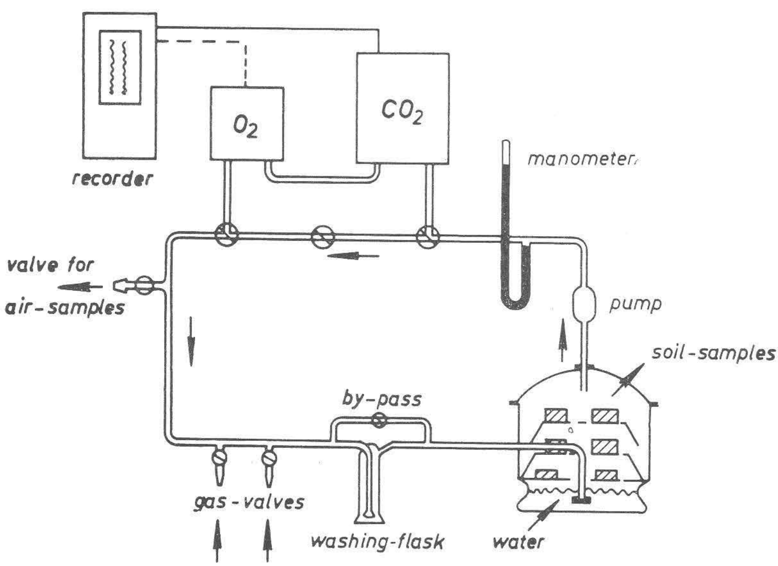


Fig. 4 : Apparatus for the measurement of nitrogen fixation in humus samples. After R. Hüser (1960).

their natural structure may remain undisturbed. The nitrogen in the artificial air, which enters the glass vessel, previously emptied of air, contains about 15% $^{15}N$. A pump puts the gas mixture into circulation. At first the air streams through devices recording continuously the concentration of carbon dioxide and oxygen. Then the carbon dioxide, produced by microbes during the experiment, is absorbed by potash lye in a washing flask. By means of a valve in a by-pass the carbon dioxide may be adjusted to the desired concentration. The air stream, returning to the incubation vessel, is remoistened by passing through a water layer at the bottom of the vessel. Before the air reaches the washing flask, it passes two gas valves, one permitting the replacement of oxygen consumed and the other leading argon into the system. This inert gas expels remaining air, after the trial air has been pumped off at the end of the incubation time. During the experiment small air samples may be taken from a third valve for control measurements by way of mass spectrometry. At present three devices of this kind are standing in our laboratory in an air-conditioned room (20°C.).

At the end of the incubation time the amount of nitrogen fixation can be calculated from the isotope ratio in the humus samples. Measuring the isotopic (abundance) ratios is at least a hundred times more accurate than the Kjeldahl procedure. If the whole amount of nitrogen in a humus sample increases during the incubation time by 0,02%, our mass spectrometer is just able to detect it.

Finally, I want to show you by figure 5 the great influence of a decrease of the water content on nitrogen fixation during the incubation time. In the beginning of the incubations, the results of which are represented by fig. 5, the water content of all humus samples was 60% of their maximum water capacity. According to their position in the incubation vessel, the samples lose more or less water during the experiment. But as already mentioned, a partial drying up seems to be necessary for getting fixation amounts, which are of practical importance. The upper part of figure 5 shows the water content of the single samples at the end of the incubation time. Each humus form examined is represented by five samples from the same incubation experiment. The lower part of figure 5 shows the amounts of nitrogen fixation for the same samples in per cent. of their initial nitrogen content.

In comparing the lower with the upper diagram, one can see that samples which dried up very little, showed little or no increase in nitrogen. Whereas those, which dried up considerably often showed an increase, sometimes amounting to more than 1% of the original nitrogen content, and this within an incubation period of four weeks. Calculated for the whole humus layer, this amounts to 1-6 lbs. per acre.

To get a better understanding of such influences of water content we have recently begun to isolate the nitrogen fixing microorganisms and to become acquainted with their requirements. As we are not familiar with this field of study, I have come to Dublin to get suggestions and advice from Prof. Küster and I would like here to thank

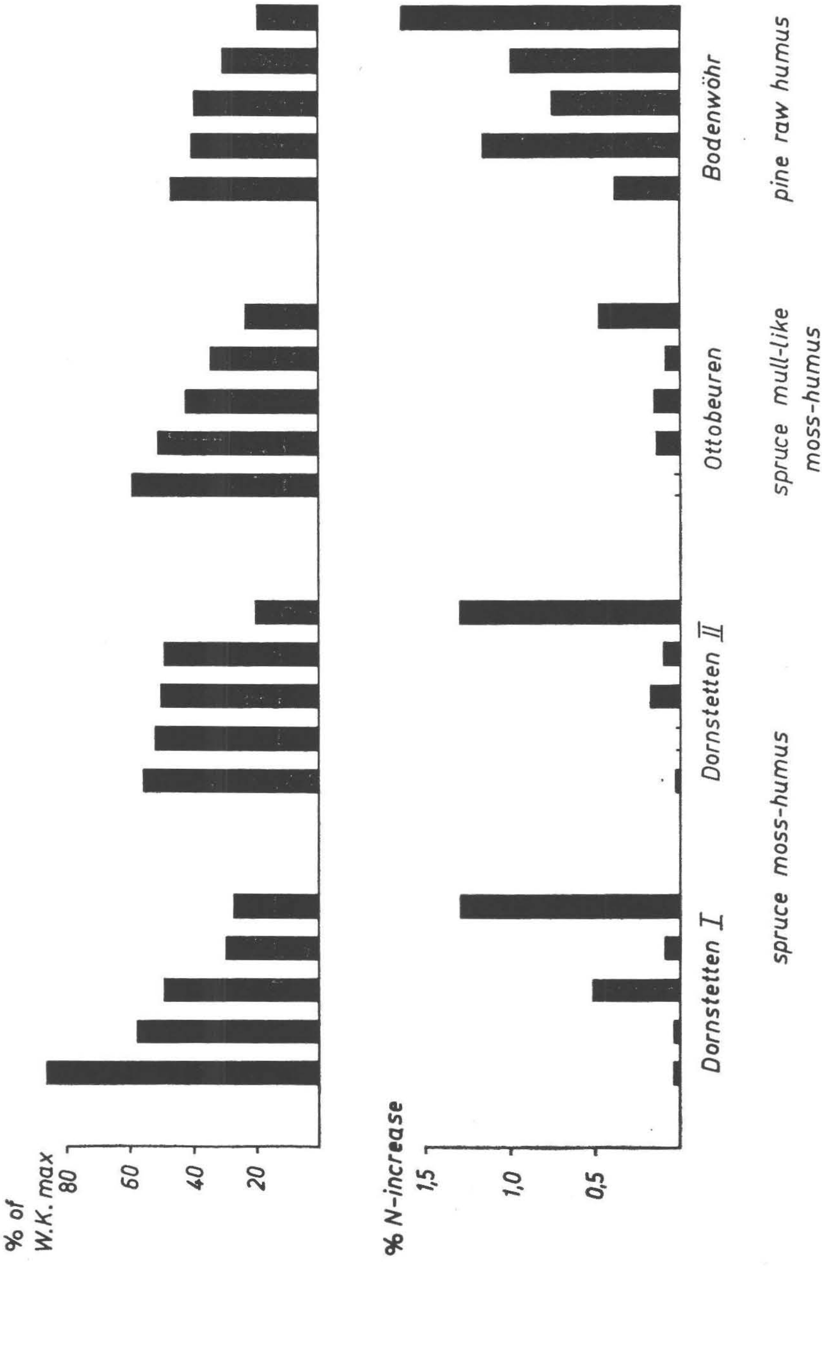


Fig. 5: Influence of a decrease in the water content on nitrogen fixation during the incubation time.
Upper part: Water content of the single humus samples at the end of the incubation time.
Lower part: Nitrogen fixation of the same samples in per cent. of their initial nitrogen content.
After R. Hüser (unpublished).

him heartily for his kind help and hospitality. My thanks also for your patience and attention.

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*Acknowledgement*

I wish to thank Mr. R. E. Parker of the Queen's University of Belfast for help in preparing this address for publication.

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