On the role of nitrogen in semi-arid regions

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1. Introduction

Arid and semi-arid regions account for about 30% of the total land surface of the earth and could contribute significantly to the total agricultural production, when the constraints limiting the production level were removed. Low and erratic rainfall is the most outstanding characteristic of these areas, so that it seems obvious, that water supply should be the major factor in determining production potential. However, a systematic examination of the processes that are critical for the level of herbage and crop production and their interactions under these conditions which would confirm this hypothesis seemed to be lacking until recently.
In the framework of a joint Dutch-Israeli research project, sponsored by the foreign ministries of both countries (Van Keulen and De Wit, 1975) on, 'actual and potential herbage production under semi-arid conditions' an attempt was made to carry out such a systematic analysis of the production process. Special emphasis was placed on the development of tools to integrate the already existing knowledge and to indicate ways of extrapolating this knowledge to the relevant situation. This was done through the development of dynamic simulation models (De Wit, 1970) which can then be applied under different conditions.
In this paper some of the aspects of the role of the growth factor nitrogen will be discussed and the results of both experimental and model studies are shown.

2. The nitrogen cycle under semi-arid conditions

Traditionally the greater part of the arid and semi-arid lands are used for extensive grazing under a varying degree of nomadism. Therefore, the nitrogen cycle will be discussed with respect to a semi-arid grazing system, a schematic representation of which is given in Figure 1. The level of inorganic nitrogen in the soil, consisting of both NO_3^- and NH_4^+ ions, which is determining the availability of nitrogen to the plant, is in natural ecosystems governed by the balance between supply from mineralization of organic nitrogen, rain-borne nitrogen and fixation, both symbiotic and non-symbiotic and losses through immobilization, leaching, volatilization and uptake by the vegetation. In the grazing situation, there is an additional cycle in which nitrogen passes through the animal body, which retains only a very small portion of the ingested nitrogen (Hilder, 1965) and is returned through faeces and urine to the soil surface.
We will first consider the various processes with respect to their relative importance under semi-arid conditions.

Mineralization and immobilization: The organic matter in the soil, consisting of a mixture of organic compounds of varying stability is being decomposed through the activities of soil micro-organisms. During this decomposition, nitrogen may either be mineralized or immobilized, depending on the type of the decomposition process (Parnas, 1975). When the C/N ratio of the material being decomposed is smaller than the optimum value for the decomposers, mineral nitrogen is released during the process, while in the reverse case mineral nitrogen is incorporated in the organisms body. Both processes occur simultaneously and their relative rates determine whether net immobilization or net mineralization results. Under arid conditions, with a distinct rainy season, the situation is generally that at the beginning of the growing season there is a net mineralization from the humus, the least digestible organic matter however at a low rate, while at the same time decomposition of fresh organic material requires more nitrogen, which results in net immobilisation. Later on, when the C/N ratio of the fresh organic matter has dropped sufficiently the situation is reversed. The timing of this turning point, which is crucial for the availability of nitrogen to the plants is largely determined by the quality of the fresh organic matter and the prevailing environmental conditions.

Rain-born nitrogen: in semi-arid regions the nitrogen level in the rainwater, which originates from photochemical processes, as well as from volatilized ammonia from industrial and agricultural sources, is about 2-3 ppm. With an average rainfall of 200-300 mm this amounts to 4-9 kg ha^{-1} $year^{-1}$, which is a substantial contribution in a natural system.

Symbiotic fixation: This process, which may improve the nitrogen status of soils considerably, is mainly connected with the presence of leguminous species in the vegetation, although recently also other species have been found active. The amount of atmospheric nitrogen that is fixed by the Rhizobium bacteria is depending on environmental conditions, mainly temperature and moisture content in the soil, but it may amount to up to 200 kg N per year on a hectare basis (Henzell, 1968). In a natural ecosystem the fraction of leguminous plants in a sward may fluctuate considerably from year to year. Their very presence, however, creates unfavourable conditions for their own succession as increased nitrogen availability favours growth of grasses and weakens the competitive power of the legumes in a next season. In the semi-arid conditions prevailing in the northern Negev, normally 10-20% of the dry matter consists of legumes.

Fixation by free living micro-organisms: In semi-arid conditions non-symbiotic nitrogen fixation may contribute up to 5 kg N ha^{-1} $year^{-1}$. This amount is fixed, when moisture and temperature conditions are favourable for the micro-organisms and easily decomposable organic material is present.

Leaching: Nitrate, either given directly through fertilizers or converted by microbial activity from ammonium, are completely dissolved in the soil solution, and may therefore be subject to leaching when water drains below the root zone. The importance of this process depends on the intensity of the rain, the water holding capacity of the soil and the rooting habits of the plants, and no general conclusion is possible.

Denitrification: Circumstances favouring loss of nitrogen by denitrification are rare under semi-arid conditions, as generally no anaerobic conditions do occur.

Volatilization: Under semi-arid conditions temperatures are generally high, favouring volatilization of ammonia. The loessial soil in the northern Negev has moreover a high pH (±7.5) and a relatively low adsorption capacity. Considerable losses may therefore be expected when ammonium fertilizer is applied (Denmead, 1974).

Uptake by plants: Growing plants extract inorganic nitrogen from the soil as both nitrate and ammonia, the amount being determined by the need of the plants or the availability in the soil solution. Theoretical (van Keulen et al., 1975) and experimental evidence suggests that practically all the inorganic nitrogen in the rooting zone is available for immediate uptake by the plants. When the concentration in the soil solution is too low to provide adequate supply with the transpiration stream, diffusion towards the roots can make up for the difference, even at relatively low rooting densities.
Part of this nitrogen is removed from the system when the plants are harvested, while another fraction is returned in the form of roots, stubble and shedded leaves. The proportion that is actually removed depends on the kind of crop and the management system: when small grains are grown and the straw is removed from the field, about 80% of the total nitrogen is taken off. In a grazing system on the other hand, where the final product is meat and/or wool, only 5-10% of the nitrogen leaves the system at 'harvest'.

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In a number of experiments carried out at the experimental area in the northern Negev, Harpaz (1975) found for artificially applied and evenly distributed excretions about 10% recovery from faecal N and about 65% from urine N. The low recovery from the faeces is due partly to volatilization losses, partly to ineffective breakdown and decomposition of the material which remains at the soil surface for a considerable period. The recovery from urine artificially applied is likely to be more favourable than under grazing conditions as a large proportion is then excreted at camping sites, which are not contributing to plant production. The recovery values may vary widely also from year to year as recovery depends on the distribution of rainfall, the volatilization losses being much higher under dry conditions. On the whole, however, the contribution of 'recycled' nitrogen may have a significant effect on crop production in a natural ecosystem, where the level of input of nitrogen is low.

3. The influence of nitrogen on plant production under semi-arid conditions

During several growing seasons, experiments were carried out to determine the growth curve and the water use of the natural vegetation (Van Keulen, 1975; Lof, 1976) in the northern Negev in Israel. A total area of 4.8 ha was amply fertilized with 150 kg K ha^{-1} and 100 kg P ha^{-1} in October 1971, while two quarters received an additional single application of 400 kg N ha^{-1} as ammoniumsulfate. To ensure proper mixing and to minimize volatilization losses, the fertilizer was duly disked in.
An additional fertilization with 40 kg N ha^{-1} was carried out at the beginning of the 1972/73 growing season. At irregular intervals during the growing season plant samples were taken and analyzed for nitrogen content. Some results of the first two seasons are shown in Figures 2 and 3.

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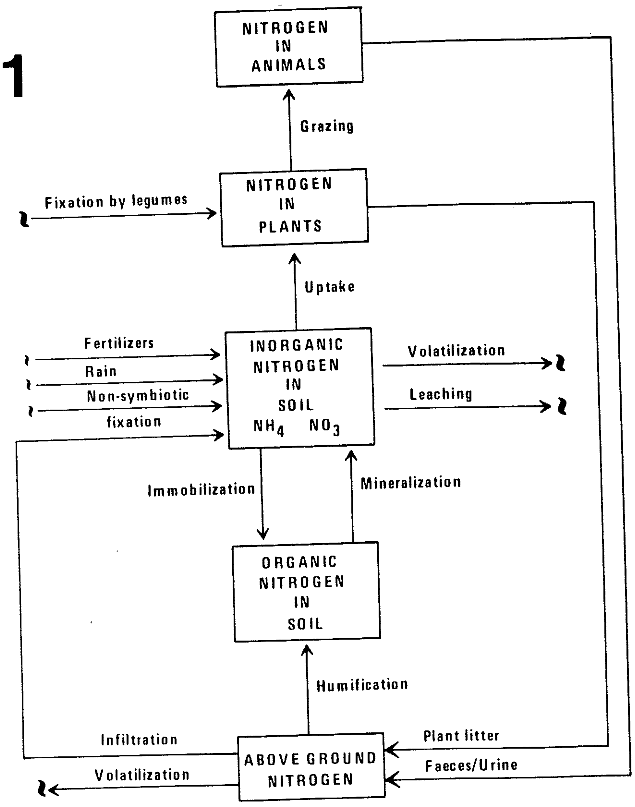


Figure 1
Schematic representation of the nitrogen cycle in a semi-arid grazing system.

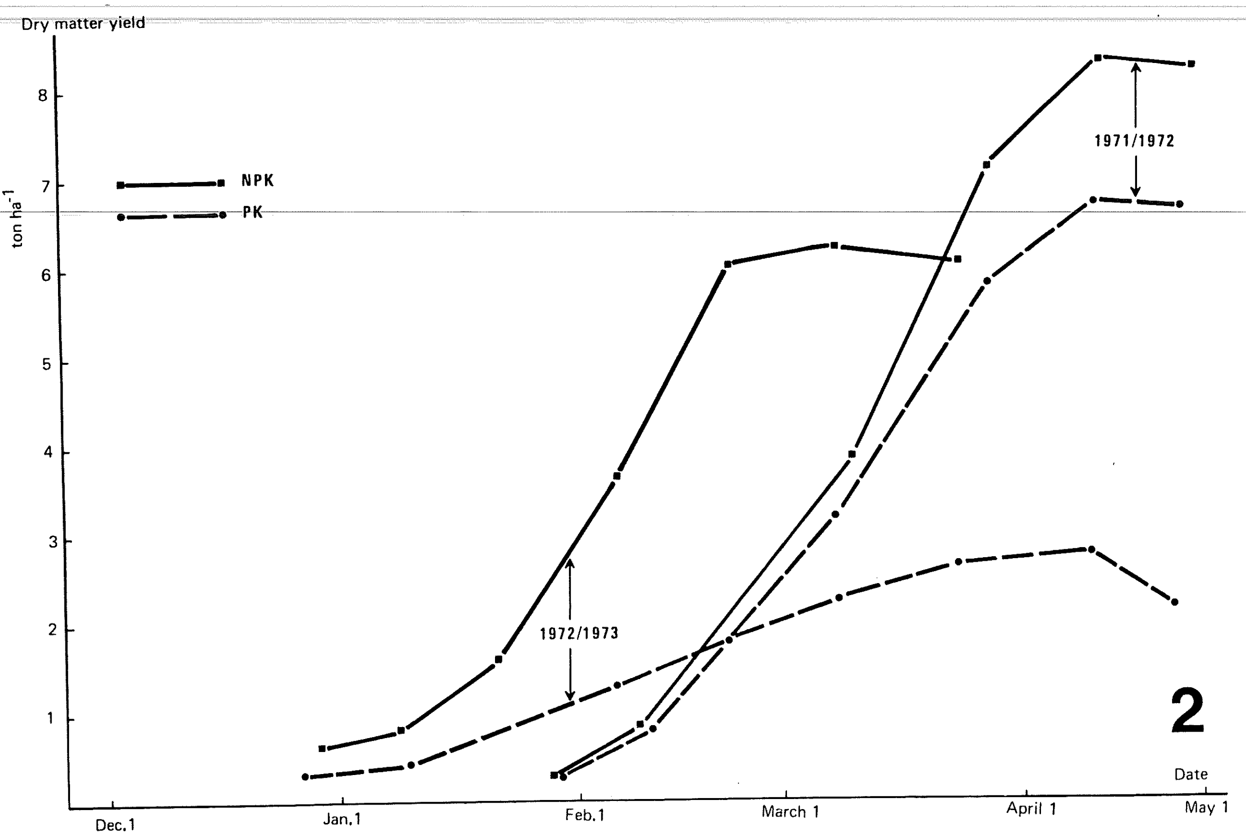
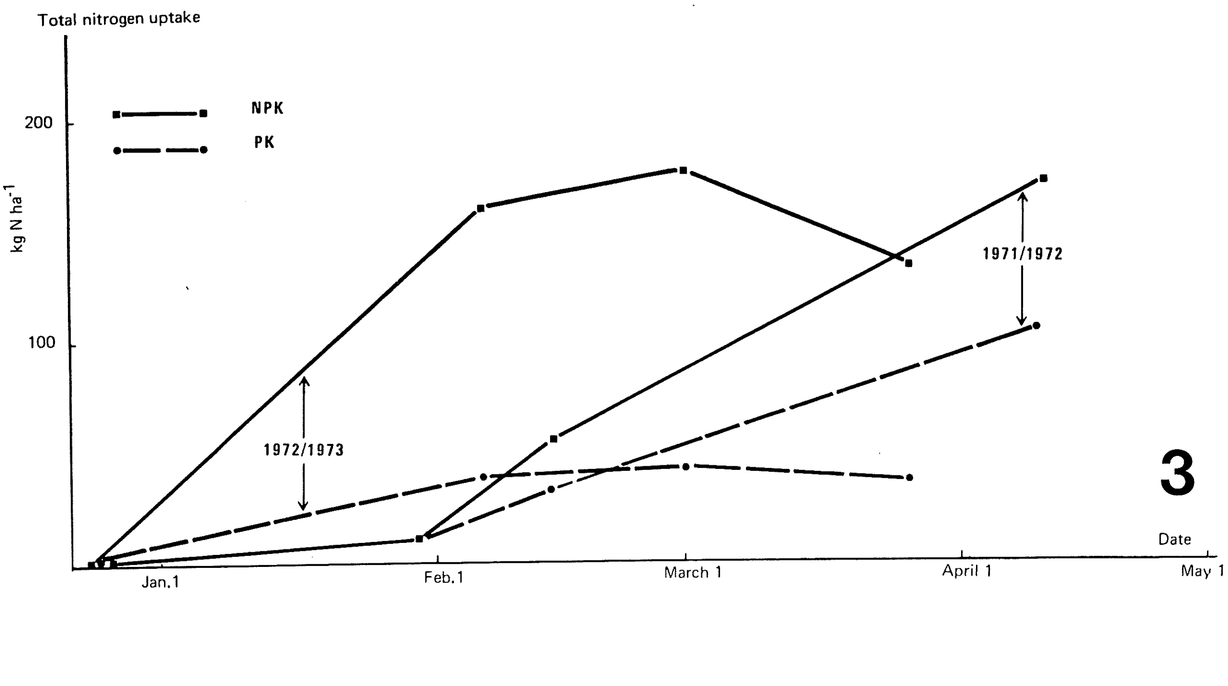


Figure 2
Time course of dry matter production for two years in a natural vegetation in the Northern Negev desert, with and without nitrogen fertilization.

Figure 3
Cumulative nitrogen uptake by the natural vegetation for two years, with and without nitrogen fertilization.



Dry matter production: Both years were 'wet' years, with rainfall amounts of 350 and 245 mm respectively and a favourable distribution, the vegetation being never short of water during the main growing period. It is obvious from Figure 2 that in both seasons the production was limited by the availability of nitrogen for the plants, the yield of the NPK treatment being much higher than that of the PK. The fact that the difference was relatively small in the 1971/72 season must be attributed to increased nitrogen supply caused by effects of disking. Both, fresh organic matter and accumulated dry sheep droppings from previous years were worked into the soil and gave rise to enhanced mineralization. As shown in Figure 3 the amounts of nitrogen taken up by the crop in both treatments did not deviate appreciably until the end of the growing season, while the differences in growth rate also showed up only after the 1st of March. The observed maximum growth rates in the NPK treatment of 170-180 kg dry matter ha^{-1} day^{-1} are equal to the maximum growth rates calculated according to De Wit (1965) for the existing climatic conditions, showing that the production capacity of the natural vegetation equals that of modern agricultural species.

Nitrogen uptake: The uptake pattern as given in Figure 3 differs for both seasons but that could be a reflection of the difference in sampling procedure as well as in crop behaviour. The decline in N- uptake in 1972/73 after the beginning of February might be attributed to a decrease in demand by the canopy, resulting from the fact that at early stages the optimum N- content is high, while it decreases towards maturity (Seligman et.al., 1975) but it could also reflect decreased availability. The fertilizer given at the beginning of 1971/72 was in ammonia form and it is difficult to estimate how much of that could have been lost by volatilization before the first rains started. The rates of volatilization reported by Denmead (1974) however, could lead to considerable losses when NH_3 concentrations are as high as was the case just after the first fertilization. It is therefore preferable to use nitrate fertilization under these conditions. Anaerobic conditions favouring denitrification seldom occur, whereas in these perma-dry situations there are virtually no drainage losses. Recovery of nitrate nitrogen should therefore be always complete, either in the same season or when moisture conditions are unfavourable for growth, in a subsequent season. Hence, each kilogram of NO_3-N applied to deep soils should eventually yield about 6.25 kg of plant protein under semi-arid conditions.

Water use: The relation between the use of water by plants and their dry matter production has been extensively studied. De Wit (1958) in his analysis of experimental data, showed that the relation between both processes depends on the prevailing radiation intensity during the growth period. Transpiration is practically always proportional to the available radiant energy. Photosynthesis however reaches a maximum value as eventually the rate of CO_2 diffusion becomes the rate limiting factor. In semi-arid regions, where the radiation intensity is high this situation occurs during the greater part of the growth period. The ratio of transpiration to assimilation is then more or less proportional to the radiation intensity or the free water evaporation. De Wit (op. cit.) demonstrated that under these conditions the relation between production and water loss can be described by:

$$P = MWE_0^{-1}$$

in which P is the dry matter production, W is the measured water loss, E_0 is the average daily free water evaporation and M is a proportionality factor, whose value depends on plant species only.

In table 1 values of M obtained in the experiments reported are listed.

They were calculated assuming that 15% of the water was lost by direct soil evaporation, while average free water evaporation was estimated at 3.5 mm day^{-1} for 1971/72 and 3.0 mm day^{-1} for 1972/73. The very low value for the nitrogen deficient situation is striking. Nitrogen shortage apparently has a much stronger effect on dry matter production than on transpiration, either through a direct effect on photosynthesis (Lof, 1976) or through a lower efficiency of conversion through repetitive breakdown and rebuilding of nitrogenous compounds. The water use efficiency of plants grown under nutrient deficient conditions is consequently much lower (De Wit, 1958: Viets, 1962). Hence, there is in semi-arid regions, where water is a scarce resource, a high proportion of non-productive water loss, even though it is lost by transpiration.

4. Model study on nitrogen under arid conditions

In order to gain insight into the relative importance of nitrogen as a yield limiting factor over the years, as well as to have a tool for extrapolation of the results obtained in the present project to different circumstances, a simulation model was developed. The model, of which a detailed description is given by Harpaz (1975) is based on the annual balance of organic and inorganic nitrogen in a semi-arid grazing system.

The total amount of nitrogen in the system is divided into four compartments (or state variables):

a. Nitrogen in the stable organic fraction.

b. Nitrogen in 'fresh' organic material i.e. crop remnants and faeces of the previous season.

c. Inorganic nitrogen in the soil.

d. Nitrogen present in the standing vegetation.

The contribution of each of the processes, adding or withdrawing nitrogen from the system (as described in section 2) is estimated on an annual basis, to provide the rates of change of the state variables. The result is an estimate of the amount of nitrogen available for plant growth. From this amount the production of dry matter is calculated.

The influence of environmental conditions is taken into account by inputs from another model (Van Keulen, 1975). From this model the calculated yield for moisture limiting

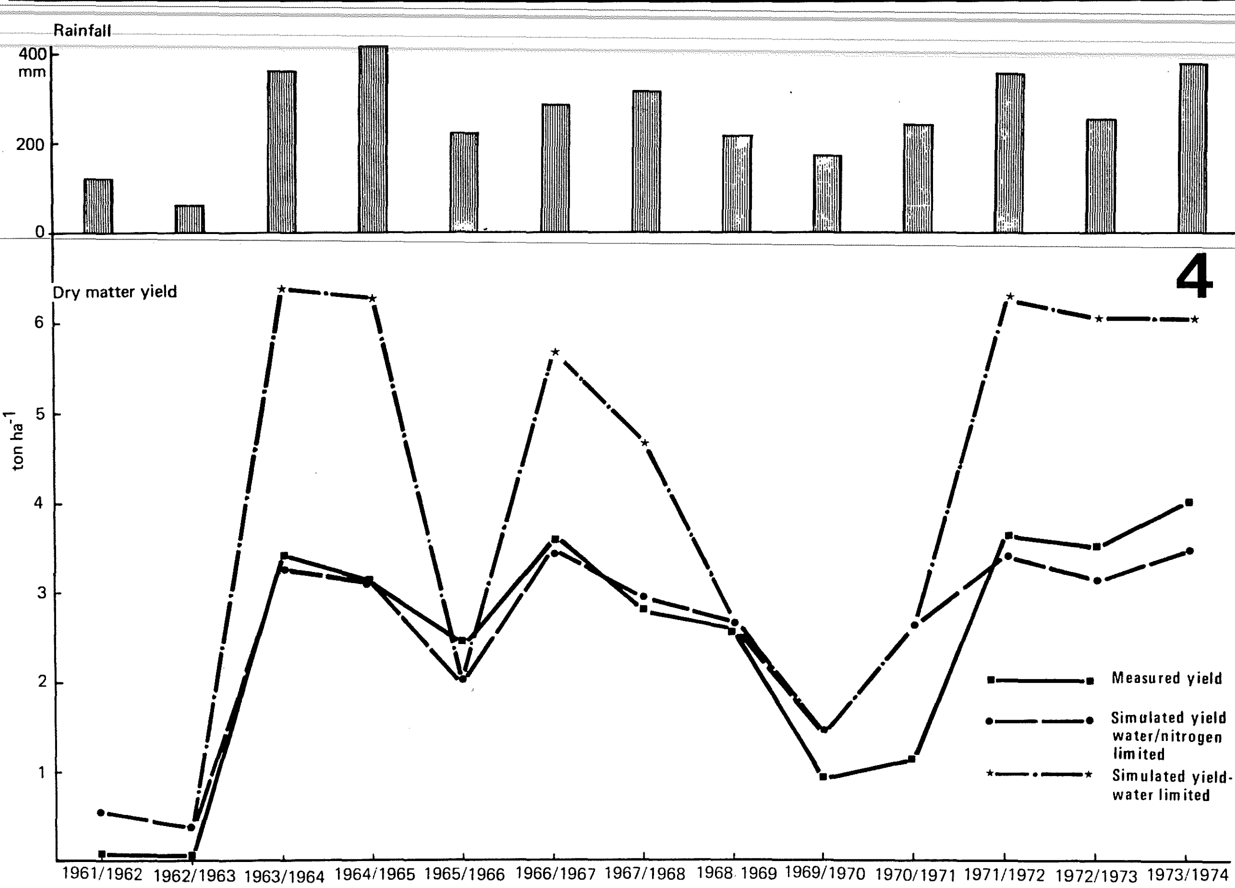


Figure 4
Measured and simulated dry matter yields of natural vegetation for 13 subsequent growing seasons in the northern Negev desert.

conditions is obtained for each year, as well as a weighted integrated soil moisture content, separately for the upper soil layers and for the total rooting zone.

Results of the model: In order to test the reliability of the model for the prediction of yield under semi-arid conditions, it was executed with historical data obtained in the Northern Negev desert of Israel. Dry matter productions of the natural vegetation were determined there as part of a long-term grazing experiment on the main vegetation types of the area (Tadmor et al., 1974).
Potential water limited yields for the area were calculated and reported earlier (Van Keulen, 1975), using weather data collected at a nearby meteorological station. The results, in terms of dry matter production are given in figure 4. in comparison with calculated water limited yields and measured dry matter production. Total annual rainfall for the thirteen years is also given.

The striking phenomenon, confirming the experimental results discussed in section 3 is, that in only five out of thirteen years the production levels calculated on basis of nitrogen availability, coincide with those taking into account moisture supply only. The season '68/'69 is a border case as the moisture limited yield is only 20 kg ha^{-1} higher than the nitrogen limited yield. In the remaining seven seasons nitrogen availability limited production to values averaging little over 50% of the potential set by moisture supply.
The results of the calculations also show that the yields predicted by the nitrogen model are in reasonable agreement with the experimental data. Relatively large discrepancies show up in the severe drought years ('61/'62, '62/'63 and '69/'70), in which case however estimation of the real peak biomass in the field may have been influenced by the presence of grazing animals in the field. This surely holds for the 1970/71 season when the yield determination was carried out before the moment of peak biomass of the stand-

Table 1. **M. values calculated for some experiments with natural vegetation (see text for explanation).**

season	treatment	M (kg ha^{-1} day^{-1})
1971/72	NPK	98
1971/72	PK	80
1972/73	NPK	89
1972/73	PK	39.5

ing vegetation and moreover an unusually high grazing pressure was maintained throughout.
On the other hand, fairly accurate yield predictions are obtained in the 'wet' nitrogen limited years.

5. Conclusions

The experimental results and model study reported here as well as earlier findings (Tadmor et. al., 1966-70) clearly show that increased nitrogen input could significantly increase the level of primary production under semi-arid conditions. Fertilization with nitrate —N fertilizer forms appears to be a low-risk operation as losses are small and eventually all the nitrogen is recovered in the vegetation. Whether this is an economically feasible practice however, depends on the price ratio between fertilizers and livestock products. Is may very well be, that the only possibility to increase the nitrogen level and hence the agricultural output of these regions is by introducing stable grass-legume mixtures as has successfully been done in Australia. The results of the calculations of moisture limited yields indicate, that when nitrogen limitation is removed, the average productivity increases considerably. However the fluctuations from year-to-year increase proportionally, due to the higher maximum values. That phenomenon causes a serious management problem in a situation where the dry matter is mainly used for animal food, as the size of a herd cannot be adapted on that short a term.
The results obtained with the model show that a systems approach in which existing knowledge about relevant processes is combined to yield quantitative results, is also a powerful tool to describe agricultural systems. Moreover carefully designed simulation experiments with such models can lead to an early discovery of the relative importance of various factors and hence to better oriented field and laboratory experimentation, which is especially important in developing countries where research resources are often limited.

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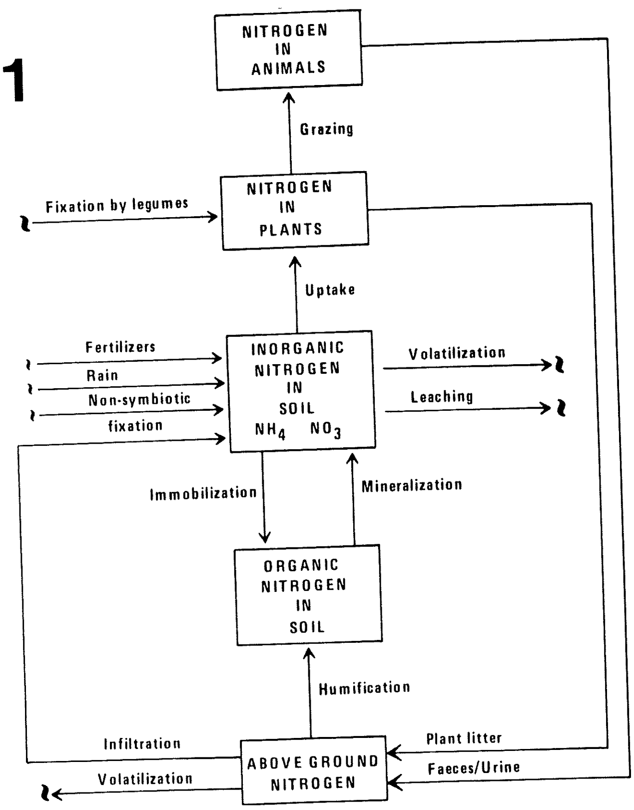

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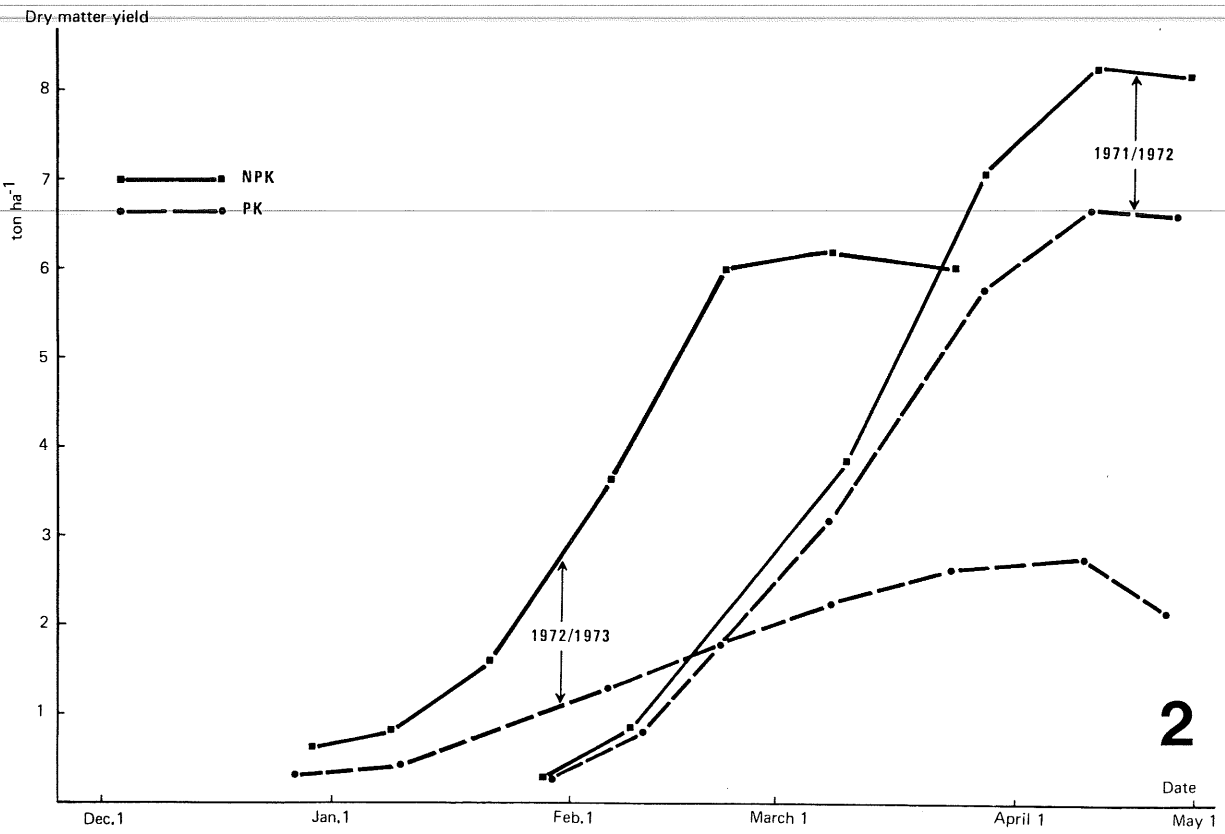

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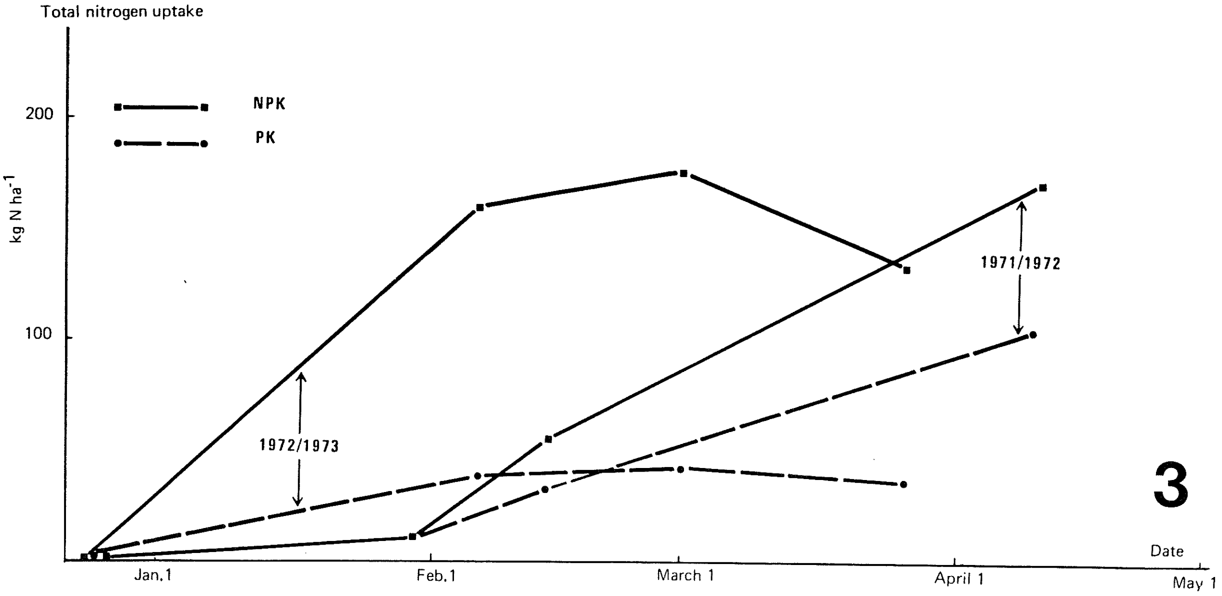

Dry matter production: Both years were 'wet' years, with rainfall amounts of 350 and 245 mm respectively and a favourable distribution, the vegetation being never short of water during the main growing period. It is obvious from Figure 2 that in both seasons the production was limited by the availability of nitrogen for the plants, the yield of the NPK treatment being much higher than that of the PK. The fact that the difference was relatively small in the 1971/72 season must be attributed to increased nitrogen supply caused by effects of disking. Both, fresh organic matter and accumulated dry sheep droppings from previous years were worked into the soil and gave rise to enhanced mineralization. As shown in Figure 3 the amounts of nitrogen taken up by the crop in both treatments did not deviate appreciably until the end of the growing season, while the differences in growth rate also showed up only after the 1st of March. The observed maximum growth rates in the NPK treatment of 170-180 kg dry matter ha^{-1} day^{-1} are equal to the maximum growth rates calculated according to De Wit (1965) for the existing climatic conditions, showing that the production capacity of the natural vegetation equals that of modern agricultural species.

Nitrogen uptake: The uptake pattern as given in Figure 3 differs for both seasons but that could be a reflection of the difference in sampling procedure as well as in crop behaviour. The decline in N- uptake in 1972/73 after the beginning of February might be attributed to a decrease in demand by the canopy, resulting from the fact that at early stages the optimum N- content is high, while it decreases towards maturity (Seligman et.al., 1975) but it could also reflect decreased availability. The fertilizer given at the beginning of 1971/72 was in ammonia form and it is difficult to estimate how much of that could have been lost by volatilization before the first rains started. The rates of volatilization reported by Denmead (1974) however, could lead to considerable losses when NH_3 concentrations are as high as was the case just after the first fertilization. It is therefore preferable to use nitrate fertilization under these conditions. Anaerobic conditions favouring denitrification seldom occur, whereas in these perma-dry situations there are virtually no drainage losses. Recovery of nitrate nitrogen should therefore be always complete, either in the same season or when moisture conditions are unfavourable for growth, in a subsequent season. Hence, each kilogram of NO_3-N applied to deep soils should eventually yield about 6.25 kg of plant protein under semi-arid conditions.

Water use: The relation between the use of water by plants and their dry matter production has been extensively studied. De Wit (1958) in his analysis of experimental data, showed that the relation between both processes depends on the prevailing radiation intensity during the growth period. Transpiration is practically always proportional to the available radiant energy. Photosynthesis however reaches a maximum value as eventually the rate of CO_2 diffusion becomes the rate limiting factor. In semi-arid regions, where the radiation intensity is high this situation occurs during the greater part of the growth period. The ratio of transpiration to assimilation is then more or less proportional to the radiation intensity or the free water evaporation. De Wit (op. cit.) demonstrated that under these conditions the relation between production and water loss can be described by:

$$P = MWE_0^{-1}$$

in which P is the dry matter production, W is the measured water loss, E_0 is the average daily free water evaporation and M is a proportionality factor, whose value depends on plant species only.
In table 1 values of M obtained in the experiments reported are listed.
They were calculated assuming that 15% of the water was lost by direct soil evaporation, while average free water evaporation was estimated at 3.5 mm day^{-1} for 1971/72 and 3.0 mm day^{-1} for 1972/73. The very low value for the nitrogen deficient situation is striking. Nitrogen shortage apparently has a much stronger effect on dry matter production than on transpiration, either through a direct effect on photosynthesis (Lof, 1976) or through a lower efficiency of conversion through repetitive breakdown and rebuilding of nitrogenous compounds. The water use efficiency of plants grown under nutrient deficient conditions is consequently much lower (De Wit, 1958: Viets, 1962). Hence, there is in semi-arid regions, where water is a scarce resource, a high proportion of non-productive water loss, even though it is lost by transpiration.

4. Model study on nitrogen under arid conditions

In order to gain insight into the relative importance of nitrogen as a yield limiting factor over the years, as well as to have a tool for extrapolation of the results obtained in the present project to different circumstances, a simulation model was developed. The model, of which a detailed description is given by Harpaz (1975) is based on the annual balance of organic and inorganic nitrogen in a semi-arid grazing system.
The total amount of nitrogen in the system is divided into four compartments (or state variables):
a. Nitrogen in the stable organic fraction.
b. Nitrogen in 'fresh' organic material i.e. crop remnants and faeces of the previous season.
c. Inorganic nitrogen in the soil.
d. Nitrogen present in the standing vegetation.
The contribution of each of the processes, adding or withdrawing nitrogen from the system (as described in section 2) is estimated on an annual basis, to provide the rates of change of the state variables. The result is an estimate of the amount of nitrogen available for plant growth. From this amount the production of dry matter is calculated.
The influence of environmental conditions is taken into account by inputs from another model (Van Keulen, 1975). From this model the calculated yield for moisture limiting

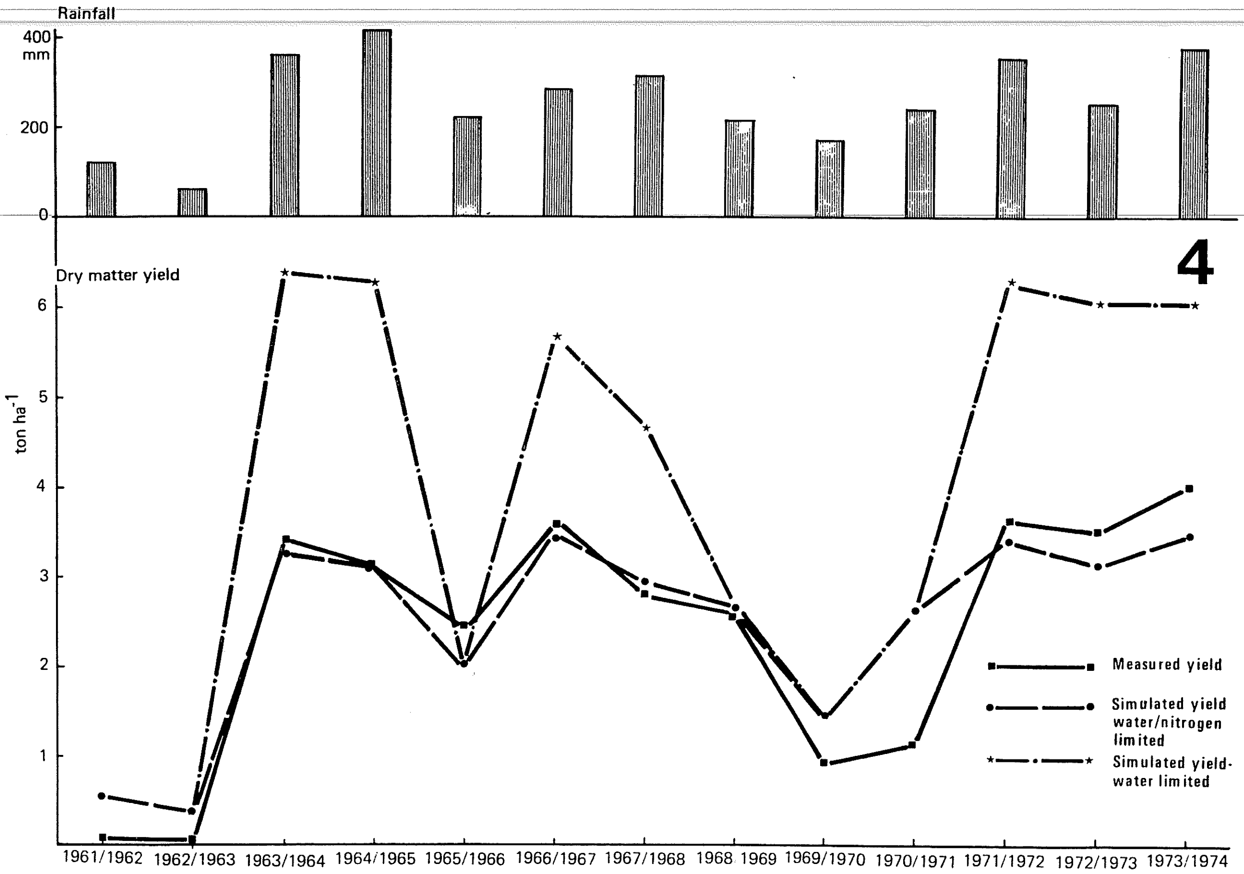

Figure 4
Measured and simulated dry matter yields of natural vegetation for 13 subsequent growing seasons in the northern Negev desert.

conditions is obtained for each year, as well as a weighted integrated soil moisture content, separately for the upper soil layers and for the total rooting zone.

Results of the model: In order to test the reliability of the model for the prediction of yield under semi-arid conditions, it was executed with historical data obtained in the Northern Negev desert of Israel. Dry matter productions of the natural vegetation were determined there as part of a long-term grazing experiment on the main vegetation types of the area (Tadmor et al., 1974).
Potential water limited yields for the area were calculated and reported earlier (Van Keulen, 1975), using weather data collected at a nearby meteorological station. The results, in terms of dry matter production are given in figure 4. in comparison with calculated water limited yields and measured dry matter production. Total annual rainfall for the thirteen years is also given.

The striking phenomenon, confirming the experimental results discussed in section 3 is, that in only five out of thirteen years the production levels calculated on basis of nitrogen availability, coincide with those taking into account moisture supply only. The season '68/'69 is a border case as the moisture limited yield is only 20 kg ha^{-1} higher than the nitrogen limited yield. In the remaining seven seasons nitrogen availability limited production to values averaging little over 50% of the potential set by moisture supply.
The results of the calculations also show that the yields predicted by the nitrogen model are in reasonable agreement with the experimental data. Relatively large discrepancies show up in the severe drought years ('61/'62, '62/'63 and '69/'70), in which case however estimation of the real peak biomass in the field may have been influenced by the presence of grazing animals in the field. This surely holds for the 1970/71 season when the yield determination was carried out before the moment of peak biomass of the stand-

Table 1. **M. values calculated for some experiments with natural vegetation (see text for explanation).**

season	treatment	M (kg ha^{-1} day^{-1})
1971/72	NPK	98
1971/72	PK	80
1972/73	NPK	89
1972/73	PK	39.5

ing vegetation and moreover an unusually high grazing pressure was maintained throughout.
On the other hand, fairly accurate yield predictions are obtained in the 'wet' nitrogen limited years.

5. Conclusions

The experimental results and model study reported here as well as earlier findings (Tadmor et. al., 1966-70) clearly show that increased nitrogen input could significantly increase the level of primary production under semi-arid conditions. Fertilization with nitrate —N fertilizer forms appears to be a low-risk operation as losses are small and eventually all the nitrogen is recovered in the vegetation. Whether this is an economically feasible practice however, depends on the price ratio between fertilizers and livestock products. Is may very well be, that the only possibility to increase the nitrogen level and hence the agricultural output of these regions is by introducing stable grass-legume mixtures as has successfully been done in Australia. The results of the calculations of moisture limited yields indicate, that when nitrogen limitation is removed, the average productivity increases considerably. However the fluctuations from year-to-year increase proportionally, due to the higher maximum values. That phenomenon causes a serious management problem in a situation where the dry matter is mainly used for animal food, as the size of a herd cannot be adapted on that short a term.
The results obtained with the model show that a systems approach in which existing knowledge about relevant processes is combined to yield quantitative results, is also a powerful tool to describe agricultural systems. Moreover carefully designed simulation experiments with such models can lead to an early discovery of the relative importance of various factors and hence to better oriented field and laboratory experimentation, which is especially important in developing countries where research resources are often limited.

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