PROBLEMS IN SOIL FERTILITY CHARACTERIZATION BY MEANS OF PLANT NUTRIENT REQUIREMENTS

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KEY WORDS

Active root surface Minimum concentration Nutrient supply Root influx rates Soil fertility

SUMMARY

In this discussion an attempt is made to consider the extent to which rates of uptake by roots, as established in plant physiological research, can be used as supply rates towards the roots in the soil system. Multiplying measured total root length or surface in the field with rates of water influx gives amounts of water use that are usually somewhat higher than those actually occurring in the field. This may be due to the fact that the level of activity of older roots is unknown and cannot be taken into account. The high influx values of mineral nutrients obtained in physiological research can only be used if we can delineate the size and location of the actively absorbing root surface, define the actual soil-root contact and obtain more information on activity variations of roots during periods of stress.

INTRODUCTION

Fertility of a soil is linked to its capacity to produce an abundant and luxurious vegetation or large crops. This implies that here the soil is capable of meeting the plants' requirements corresponding to the high rates of growth.

The traditional way of obtaining information on the required soil parameters was to study the response of a vegetation or crop to variations in single factors. In this manner much research has been performed and has resulted in the establishment of the required level of total available amounts of nutrients in soils[7,28].

This simple approach, however, neglects a number of complicating factors related to the plant's possibility of using the available amount. The main factors which affect utilization are the presence of a sufficiently large and optimally dispersed absorptive root surface and of soil conditions allowing adequate rates of supply of nutrients towards the absorbing root surface.

Gradually a more ecological approach has evolved in which a link can be made between plant physiology and soil physical chemistry. This more functional

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approach, in which nutrient uptake is considered as involving transport processes[4,5], has led to a study of a number of interactions between different parameters. Ultimately this has resulted in the design of simulation models in which plant growth is related to nutrient availability and factors that determine root growth[11,27,29].

In modern intensive agriculture and horticulture attempts are made to create conditions for optimal nutrient supply, either in the soil or in other substrates used. In hydroponics and in the nutrient film technique the supply is even more precisely regulated[35].

Do we have sufficient information on plant demand to define a number of parameters with sufficient precision to meet the requirements of the model or to set single values for a number of parameters? The most important plant nutrient requirements we need to characterize are: (*a*) the rate of uptake per unit root (influx) under conditions of optimal growth; and (*b*) the minimum concentration at the root surface allowing unrestricted growth.

In respect to these requirements the conditions which enable the soil to supply adequate amounts can be calculated, if the necessary physical/chemical equilibria are known.

Recently a number of useful data on minimum concentration have been obtained. As their use does not meet with difficulties, our discussion will be restricted to problems related to the determination of influx values.

THE REQUIRED RATES OF SUPPLY

The older measurements of uptake were made mainly on excised young root pieces for the purpose of obtaining information on the characteristics of the uptake process. The parameter root length or surface has not often been determined in these experiments, where mainly batches of identical root weights were used. But rates of uptake can also be calculated by dividing uptake from a substrate during a certain period by length or surface of the root system. It might be wise to base the required influx value on that occurring during the phase of highest rate of growth.

Information on rates of water influx, obtained with intact plants growing in nutrient solution, has now become available[10,16]. Whether these values are of actual ecological significance can only be decided by comparing them with data derived from measurements of roots in the soil. In Table 1 a few values are given of the approximate root surface as compiled from some data available. The influx rate for water was calculated assuming a transpiration of 5 mm per day.

The resulting values agree reasonably well with values obtained in my own

Table 1. Approximate influx values for water based on a transpiration of 5 mm day^{-1}

	Approx. root surface	Derived water flux
Sunflower[1]	$2 \times 10^4\ cm^2\ m^{-2}$	$25 \times 10^{-2}\ cm^3\ cm^{-2}\ day^{-1}$
Grass-sod[2]	$5 \times 10^5\ cm^2\ m^{-2}$	$1 \times 10^{-2}\ cm^3\ cm^{-2}\ day^{-1}$
Sugarcane[3]	$2 \times 10^4\ cm^2\ m^{-2}$	$25 \times 10^{-2}\ cm^3\ cm^{-2}\ day^{-1}$

[1] Maertens *et al.*, 1974.
[2] Gass, Oertli, 1980.
[3] Evans, 1938.

research on plants cultivated in nutrient solution. In alfalfa, fluxes were measured of approximately $(1.2 - 15) \times 10^{-2}\ cm^3\ cm^{-2}\ day^{-1}$ as given by Milburn[26].

The total root surface area per unit field area is in the same order of magnitude as the Leaf Area Index. This fact suggests that the flux of transpiration water through the plant needs about the same surface area for entrance as for exit. A relationship of this kind has already been suggested, but it is only recently that more precise root surface area measurements are becoming available.

Table 2. Calculated rates of water influx as derived from root length data and a transpiration of $12 \times 10^{-2}\ cm^3\ m^{-2}\ sec^{-1}$

	Calculated approx. root length in 10^4 cm m^{-2}	Derived root water influx in $10^{-7}\ cm^3\ cm^{-1}\ sec^{-1}$
Barley[1,2]	120	1.0
Oats[2]	110	1.1
Wheat[2,3]	110	1.1
Soya[4]	54	2.2
Potatoes[5,6]	40	3.0
Cotton[7]	60	2.0
Grassland[5]	750 (290*)	0.16
Timothy[8]	1300 (1000*)	0.09
Cocksfoot[8]	900 (600*)	0.13
Perennial rye grass[8]	1200 (830*)	0.10
Tall fescue[8]	800 (550*)	0.15

* sod only.
[1] Aboulroos, Nielsen, 1979.
[2] Welbank *et al.*, 1974.
[3] Alston, 1980.
[4] Sivakumar *et al.*, 1977.
[5] Jager, de.
[6] Heringa *et al.*, 1980.
[7] Cannell, 1977.
[8] Garwood, Sinclair, 1979.

Table 3. Some data on directly measured influx rates for water

Broad bean[1]	$2.8 - 22.0 \times 10^{-7}$ cm^3 cm^{-1} sec^{-1}
Onion[2]	$1.2 - 2.4 \times 10^{-7}$ cm^3 cm^{-1} sec^{-1}
Wheat[3]	$1.7 - 11.0 \times 10^{-7}$ cm^3 cm^{-1} sec^{-1}

[1] Brouwer, 1954.
[2] Rosene, 1947.
[3] Hansen, 1974.

Measurements as given are still scarce. More exact data are now available on root length per unit volume. Here we encounter values of up to 10 cm cm^{-3}, while in a grass sod much higher values have been observed. In Table 2 a few values for root length have been derived from data available in literature. Influx values for water have been calculated, assuming a transpiration of slightly more than 5 mm per 12 hours.

Calculated (Table 2) and measured (Table 3) influx rates for water agree reasonably well, but in general the calculated values are lower.

We may now attempt to determine whether the available values of influx of nutrients are also useful as an index of requirement. For this purpose some of the flux data available have been used assuming a root length of 100×10^4 cm m^{-2} or a root surface area of 5×10^4 cm^2 m^{-2}. The results obtained are presented in Table 4.

Table 4. Approximate values of crop nutrient uptake per day, based on root data and measured influx values

Element	Influx value		Calculated crop adsorption in kg ha^{-1} day^{-1}
N	I_{max}	8.64×10^{-6} mol m^{-1} day^{-1}	ca. 12 (a)
	I	11.2×10^{-6} mol m^{-1} day^{-1}	ca. 15.7 (b)
	I	6×10^{-6} g cm^{-2} day^{-1}	ca. 3 (c)
P	I_{max}	1.6×10^{-6} mol m^{-1} day^{-1}	ca. 5 (a)
	I	0.9×10^{-6} mol m^{-1} day^{-1}	ca. 3 (b)
	I	0.6×10^{-6} mol m^{-1} day^{-1}	ca. 2 (d)
K	I_{max}	17×10^{-6} mol m^{-1} day^{-1}	ca. 66 (a)
	I	8.6×10^{-6} mol m^{-1} day^{-1}	ca. 33 (b)
	I	30×10^{-6} mol m^{-1} day^{-1}	ca. 120 (e)
	I	12×10^{-6} g cm^{-2} day^{-1}	ca. 6 (c)

a Barber, 1979.
b Nye, Tinker, 1977.
c Wiersum, 1980.
d Kurvits, Kirkby, 1980.
e Mengel, 1978.

The calculated values of uptake are high and are only comparable to values obtained during periods of very high growth rates[23]. But the results of our calculations show the same trend: field influx rates seem to be lower than those measured in physiological research. To explain these discrepancies, two factors may be important.

First, most physiological experiments have been performed on highly permeable and active young root tissue and under laboratory conditions which are often conducive to high rates of uptake. Also, the I_{max} (highest value of the adsorption curve) values have often been obtained on plants of low nutrient status and therefore high absorption capacity. Thus many data from the literature are apt to indicate maximum rates.

Second, total root length or surface has been used in the calculation. Except for the young seedling and the annual or biennial plant in its younger stage of exponential growth, this is not a valid measure. As plant age increases and roots lose root hairs, epidermis and cortex, and as suberization occurs, the functional root surface will decrease.

We may surmise that the data obtained in physiological research can be useful in the ecological approach as they reflect the ultimate capacity. This capacity is needed to counteract unequal supply rates in the profile, and in recovery from stress. For more general application it would be necessary to establish a reduction factor valid for average field conditions.

DISCUSSION

The size of the root surface actually involved in uptake is not precisely known. This is illustrated by the very low influx rates calculated for grasses in Table 2, caused by inactivation or decay of the older roots.

To extend our scanty knowledge about functional root surface, different types of observations will be needed. Research will have to be based on observation of the sequence of events at the actual root surface *in situ* by means of rhizotrons or observation tubes[6,15,31]. Another approach involves the use of tracers in studying the transverse translocation from substrate to xylem.

At our institute an attempt has been made to compare the development of root surface during growth with that of the amount of water forced through the root system under a given pressure by means of a large pressure bomb. But the assumption that permeability to water reflects the capacity for nutrient uptake will have to be investigated more closely. Nevertheless, the amount of lag in the increase in water uptake relative to increase in root surface can give a first approximation of a reduction factor[36]. A similar approach, based on the lag of Ca-uptake, has been used by Bar-Yosef and Kafkafi[3].

In intensive horticulture and in hydroponics the space available for rooting is often severely restricted. What then is the minimum surface of absorbing roots needed to cope with plant requirement? Does the rate of uptake then correspond with I_{max}, which usually has been measured under different conditions? A similar problem evolves if the root system is dispersed in a heterogeneous medium with only local spots of adequate supply.

A poorly investigated aspect is that of the precise root surface in contact with the soil. We know little about development, length, and period of activity of root hairs *in situ*. Also, there is insufficient knowledge on life span and behaviour of epidermis and cortex. This is especially evident as more and more data are becoming available demonstrating uptake by older roots. Also occurrence and function of mycorrhiza at different fertility levels have been insufficient explored.

Older research in plant physiology has demonstrated that interaction between nutrients occurs in their rates of uptake. These interactions may become even more important as the differences in rate of uptake by the root and rate of supply

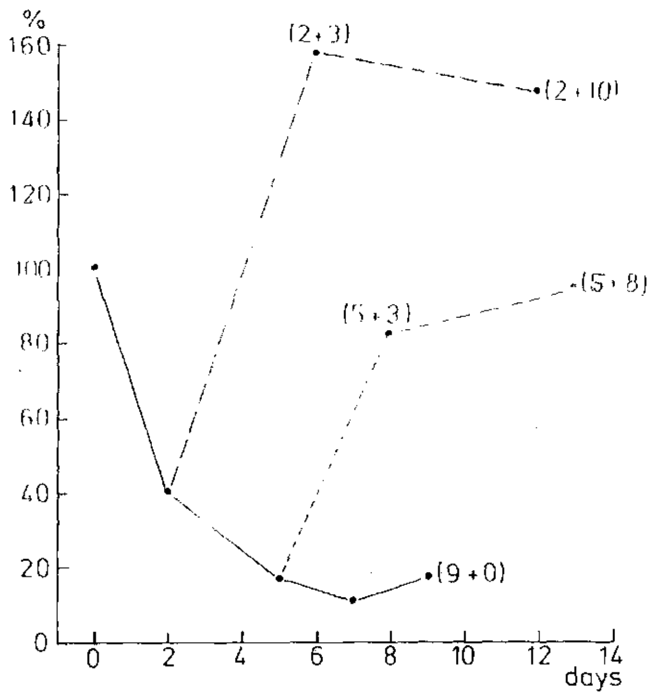

Fig. 1. The amount of water forced through submerged root systems of young potted Ulmus trees in a large pressure bomb. (a + b) a denotes number of days without watering (dry period) and b denotes number of days after rewatering for recovery.

by mass flow may give rise to quite different ionic equilibria and pH at the root surface than those in the soil solution. Also deficiences of any nutrient may impair the health of the plant and its inherent capacity for absorption.

Another problem to be studied is the variation in root activity during and after stress. During water stress, root activity – mainly root permeability – may change to much lower values. Root resistance to waterflow increases temporarily during drought periods[21,33]. An example of decrease and recovery of water permeability during and after a dry period is given for young trees (Fig. 1). Besides this, permanent changes involving suberisation are common. This implies that ion uptake would also be affected. Rates of recovery may be different in various situations and for separate species.

CONCLUDING REMARKS

The question whether we can define the plants' demand by means of influx rates may be answered as follows. In the situation of plant growth under well regulated and favourable conditions, the influx rates are usually higher than those occurring under uniform conditions in the field. But they do give an indication of the ultimate plant capacity.

The fact that they have been utilised successfully in a number of models[11,19,20,29] which relate plant growth to water and nutrient supply, also points to their usefulness. However, most models are as yet only adapted to crops in which the exponential phase of growth dominates. This implies a root system which mainly consists of young, active roots; thus many complications in the model are avoided. Intensive research on the development and performance of roots will be needed to obtain the most useful influx rate data.

The utilization of data on rates of influx and minimum concentration to define soil fertility in terms of nutrient content per unit soil and of physical conditions needed for adequate supply rates is still beset with difficulties. The main problem is that certain conditions conducive to high supply rates, *e.g.* continuity of smaller pores and rather high water contents, are more or less detrimental to root development and function.

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