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Potassium availability in relation to soil moisture

I. Effect of soil moisture on potassium diffusion, root growth and potassium uptake of onion plants

Kaliumverfügbarkeit in Beziehung zur Bodenfeuchte

I. Wirkung des Wassergehaltes auf die K-Diffusion, das Wurzelwachstum und die K-Aufnahme von Zwiebelpflanzen

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Summary The objective of this research is to evaluate the influence of soil water content on
- the mobility of potassium in soil,
- plant growth and
- K uptake of plants.

The mobility of K increased with soil moisture. Increasing the volumetric water content (θ) from the 0.1 to 0.4 resulted in a rise of the effective diffusion coefficient (D_e) by a factor of about 10. This is mainly due to the increase of the tortuosity or impedance factor with higher soil moisture.

In order to relate K mobility in soil to the availability of K for plant uptake, onion plants were grown in special containers under constant water content in the range of 0.1 to 0.4 cm^3 H_2O cm^{-3} of soil. Results are
- both K content and growth of the plants increased with soil moisture,
- water content below $\theta = 0.1$ reduced root growth
- K inflow per unit of root surface increased with soil moisture. Maximum rate of inflow occurred with $\theta = 0.25$ in the soil used.

It is therefore concluded that soil moisture affected K availability by affecting both K mobility and root growth.

Zusammenfassung Die Arbeit hat das Ziel, den Einfluss des Wassergehaltes des Bodens auf
- die Mobilität der Kaliumionen im Boden,
- das Pflanzenwachstum und
- die K-Aufnahme

zu bestimmen. Hierzu wurden einerseits Messungen der Mobilität von Kalium im Boden durchgeführt. Sie ergaben eine Erhöhung des effektiven Diffusionskoeffizienten (D_e) mit ansteigendem volumetrischen Wassergehalt (θ). D_e nahm um mehr als das Zehnfache zu während θ von 0,1 auf 0,4 anstieg. Dies ist der Erhöhung des Tortuositäts- oder Widerstands-faktors mit steigendem Wassergehalt zuzuschreiben. Um zu prüfen, in welchem Masse die Diffusionsbedingungen im Boden die Pflanzenverfügbarkeit von Kalium beeinflussen, wurde ein Vegetationsversuch durchgeführt. Hierzu wurden Zwiebelpflanzen in speziellen Versuchsgefässen bei konstanten Wassergehalten zwischen 0,1 und 0,4 cm^3 H_2O/cm^3 Boden kultiviert. Die Ergebnisse sind:
- K-Konzentration und Ertrag der Pflanzen wurden mit zunehmedem Bodenwassergehalt erhöht.

– Der Wassergehalt des Bodens beeinflusste das Wurzelwachstum; unter $\theta = 0{,}1$ nahm die Wurzellänge stark ab.
– Die K-Aufnahmerate eines Wurzelabschnitts stieg mit dem Wassergehalt an; bei $\theta = 0{,}25$ war die maximale Aufnahmerate in diesem Boden erreicht.

Bie niedrigem Wassergehalt des Bodens wird die Kalium-Verfügbarkeit demnach beeinträchtigt sowohl durch den Rückgang der Mobilität von Kalium im Boden als auch die Verringerung des Wurzelwachstums.

Introduction

Soil moisture content affects the availability of K in soil. Van der Paauw[14] observed a positive relation between the number of days without rain in the growing season and K response of grass, potato and wheat. Barber[2], Mengel and von Braunschweig[11] and Grimme and von Braunschweig[7] found greater efficiency of K fertilizer with increasing soil moisture.

This can be explained by the mechanisms which govern K transport from the soil to plant roots. According to Barber[3] nutrient transport depends on both mass flow and diffisuion as shown in equation 1

$$F = - D_e \frac{\Delta C}{\Delta X} + vC_l \qquad (1)$$

The diffusive flux is determined by the effective diffusion coefficient (D_e) and the concentration gradient ($\Delta C/\Delta X$) whereas mass flow depends on water flux (v) and K concentration in the soil solution (C_l). Compared to the total uptake of crop plants the contribution of mass flow of potassium to the roots is usually very small. It will therefore be neglected in this study.

Diffusive flux is related to soil moisture via the effective diffusion coefficient according to Nye[13], equation (2)

$$D_e = D_l \theta f \frac{\Delta C_l}{\Delta C} \qquad (2)$$

It shows that the effective diffusion coefficient is proportional to the volumetric water content (θ). D_l is the diffusion coefficient in pure water. The tortuosity or impedance factor (f) also depends on the water content of the soil, because the tortuosity of the diffusion path around soil particles decreases with increasing volume of water present. Another influence of water on K diffusion can arise from buffer power (b). Since $b = \Delta C/\Delta C_l$, the buffer power will vary if the total proportion of K participating in diffusion (ΔC) does not change as the K concentration of the soil solution (C_l) varies with the water content of the soil. According to the theoretical considerations diffusive flux of

Table 1. Properties of Söderhof silt loam soil

Clay (%)	Silt (%)	Sand (%)	C (%)	pH($CaCl_2$)	$CaCO_3$ (%)	Exch. K (μmol/cm^3)
9.2	74	14.4	2.3	7.0	0.1	5.88

Tabelle 1. Kenngrössen des Bodens 'Söderhof'

nutrients to the plant roots will be markedly influenced by the water content of the soil. This has been confirmed experimentally by various authors[9,16,18,19,21].

Besides transport of K from the soil to the root surface, root properties are also important for K supply to plants. The quantity of a nurtient taken up by a plant depends on the rate of inflow per unit of root length and the total root length. A literature review of Pearson[15] indicates that root growth may vary with water content of the soil.

The aim of this work is first to study the influence of soil moisture on both root growth and K mobility in soil in regard to their influence on K uptake of onion plants and then to separate and quantify the factors involved.

Materials and methods

Soil

The top layer of Söderhof loess derived silt-loam soil was used. Some properties are shown in Table 1.

Methods of soil analysis

Soil texture: As described by Hartge[8].

Exchangeable potassium: Leaching of 1 g soil five times with 10 ml aliquots of 1*N* NH_4OAc.

Diffusible potassium (ΔC): Maximum depletion of exchangeable potassium at the soil-root interface of young rape seedlings by using the method of Kuchenbuch and Jungk[10]. This value was found to be 3.64 μmoles cm^{-3} for the soil used.

Potassium concentration of the soil solution (C_{li}): Displacement of the soil solution as described by Adams[1] and determination of K.

Potassium buffer power (b): calculation of the ratio $\Delta C/\Delta C_l$: Instead of ΔC_l the value of C_{li} was used since plant roots can deplete the soil solution at the root surface to values of about 1 μmolar[5] which is close to zero.

Effective diffusion coefficient (D_e): According to the method of Vaidyanathan and Nye[10]. Proton saturated ion exchange paper is brought into contact with the soil. Afterwards, the amount of K that diffused in time (t) to the paper (M_t) is measured. D_e is then calculated by

$$D_e = \frac{M_t^2 \pi}{t 4 \Delta C^2} \tag{3}$$

Tortuosity factor (f): Equation 3 was inserted into equation 2 and rearranged to calculate f as shown in equation (4)

$$f = \frac{M_t^2 \pi}{4 \theta \Delta C t D_l C_{li}} \tag{4}$$

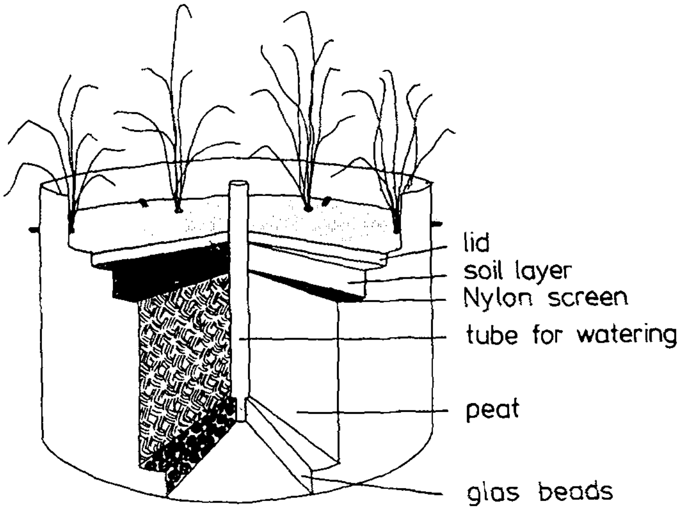

Fig. 1. Experimental apparatus for growing plants.
Abb. 1. Aufbau der Versuchsgefässe (schematisch).

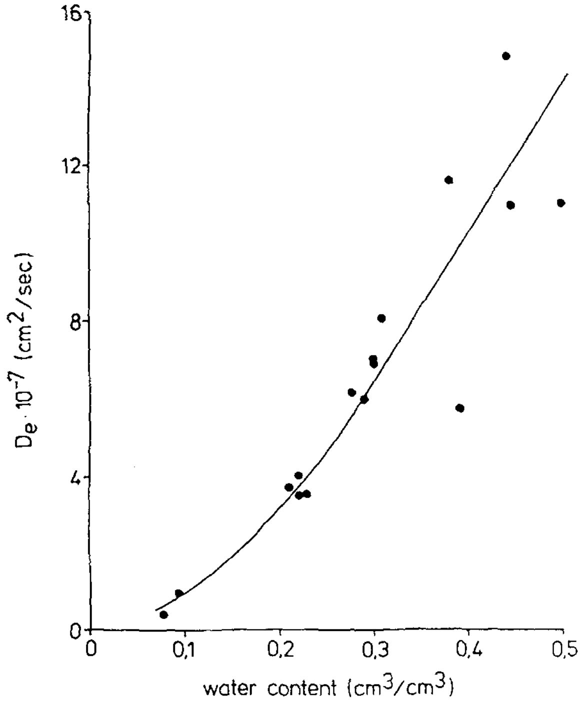

Fig. 2. Effective potasssium diffusion coefficient in relation to the water content of the soil.
Abb. 2. Effektiver K-Diffusionskoeffizient in Abhängigkeit vom Wassergehalt des Bodens.

Growing the plants: Onion seedlings (*Allium cepa* cv 'Stuttgarter Riesen') were grown in special containers as shown in Figure 1. A 1 cm soil layer is placed on top of a layer of Sphagnum peat which served as a reservoir for soil water. Peat and soil were separated by a fine meshed Nylon screen which prevented roots from growing into the peat. The whole device was covered with polythene foil in order to minimize evapotranspiration. Twelve pregerminated onion seeds were planted into each container and grown 19 days under a constant water content of $\theta = 0.24$ in a growth chamber. After this period 4 pots were harvested (Harvest 1). The remaining pots were brought to different water contents and grown for another 19 days. The water contents of these treatments were adjusted daily.

After harvesting the plants (Harvest 2), dry weight and K content were determined by usual methods. Roots were separated from the soil and their fresh weight and length measured by the method of Newman[12]. Root surface area was calculated by assuming fresh weight to be equal to root volume and that the root is a cylinder.

Rate of potassium uptake ($K\text{-}I_n$) into the roots was calculated by equation 5 (Evans[6]).

$$K - I_n = \frac{U_2 - U_1}{t_2 - t_1} \quad \frac{2}{A_1 + A_2} \tag{5}$$

U is K uptake of the plants, t is time and A is root surface. The index numbers 1 and 2 refer to the first and the second harvest.

Results

1. Influence of soil moisture on the mobility of K

The influence of the volumetric water content of the soil on the effective diffusion coefficient is shown in Figure 2. Increasing θ from 0.1 to 0.4 raised D_e by a factor of about 10. Hence, the mobility of K is considerably affected by soil moisture.

According to equation 2, D_e should increase with increasing K buffer power. However, as can be seen from Table 2, K concentration of the soil solution (C_{li}) decreased with increasing θ. Assuming the diffusible K content (ΔC) remains constant, the K buffer power (b) increases from 2.7 to 3.4. D_e did not decrease however but increased with increasing water content. This is because the tortuosity factor (f) also increases with θ as shown in Figure 3. Its influence has obviously the overriding effect compared to the K buffer power and therefore D_e increases with increasing volumetric water content.

2. Influence of soil moisture on growth and K uptake of onion plants

The effect of volumetric water content on both shoot growth and potassium concentration of onion seedlings is shown in Figure 4. While dry matter production increased linearly with soil moisture within the range of the experiment, potassium concentration of the plants tends to show a curvilinear response. These data imply that the uptake of potassium increases with increasing soil moisture. The strongest change of K content is observed at moisture levels below $\theta = 0.2$.

In order to separate individual reasons for these changes in K uptake, both root growth and rate of K uptake per unit of root surfaces were

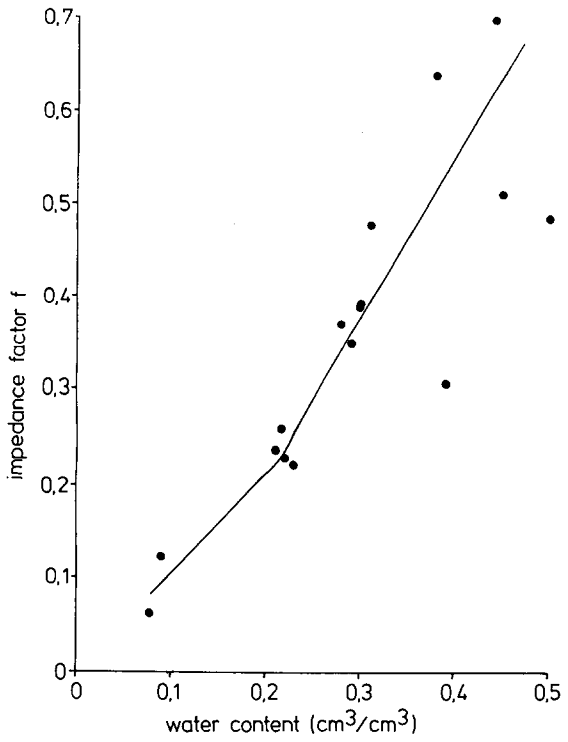

Fig. 3. Impedance factor in relation to the volumetric water content of the soil.
Abb. 3. Widerstandsfaktor in Anhängigkeit vom Wassergehalt des Bodens.

Table 2. Influence of the volumetric water content (θ) of the soil on the K concentration of the soil solution (C_{li}) buffer power (b) and effective diffusion coefficient (D_e) of K

θ (cm^3 cm^{-3})	C_{li} (μmol cm^{-3})	ΔC (μmol cm^{-3})	b	D_e (cm^2 sec^{-1})
0.19	1.36	3.64	2.68	$2.55 \cdot 10^{-7}$
0.26	1.18	3.64	3.09	$4.91 \cdot 10^{-7}$
0.34	1.06	3.64	4.42	$6.40 \cdot 10^{-7}$

Tabelle 2. Einfluss des volumetrischen Wassergehaltes θ auf die K-Konzentration der Bodenlösung, C_{li}, die K-Pufferung und den effektiven K-Diffusionskoeffizienten D_e.

determined. Root growth is shown in Figure 5 in terms of root length per unit of shoot weight. Below $\theta = 0.2$ root growth was markedly reduced by the shortage of water, whereas above $\theta = 0.2$ no influence was observed.

Previously it was shown that the mobility of K depends on θ and f. Herewith in agreement, as can be seen from Figure 6, the rate of uptake of K per cm^2 onion roots also increases considerably with the product of $\theta \cdot f$. This is particularly pronounced in the range below 0.1. Above

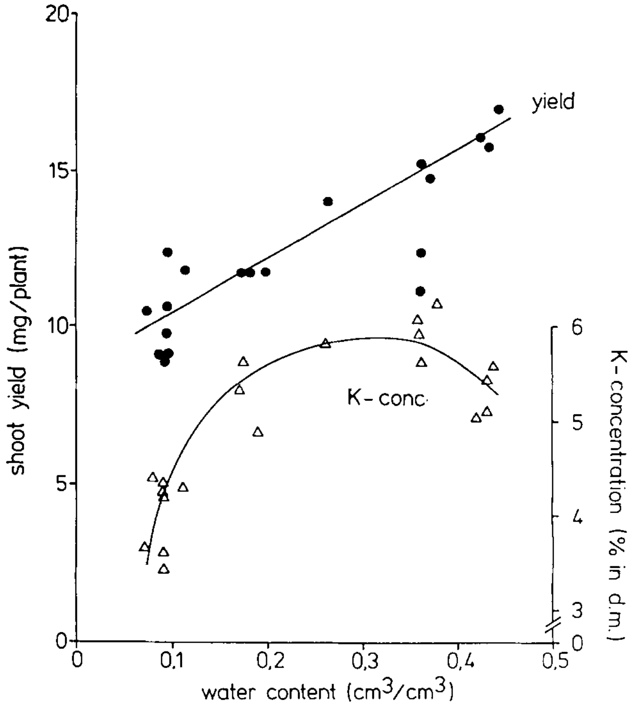

Fig. 4. Influence of soil moisture of Söderhof silt loam on growth and K content of onion plants.

Abb. 4: Einfluss des Wassergehaltes von Boden Söderhof auf Ertrag und K-Konzentration von Zwiebelpflanzen.

this value, which is equivalent to $\theta = 0.25$, only small increases in uptake are observed.

Discussion

The results indicate that soil moisture influences both diffusivity of potassium in soil and root growth. This in turn is apparently the reason for the increasing rate of potassium uptake per unit of root surface and total uptake of potassium with the increase of soil water content.

One of the problems in determining the effective diffusion coefficient (D_e) is finding the proper value of diffusible potassium (ΔC) which together with ΔC_l gives the buffer power (b) of a soil. Since soil solution concentration (C_{li}) is reduced to very low values at the root surface[5] the value of equilibrium concentration of soil solution seems appropriate to describe the maximum depletion at the soil root

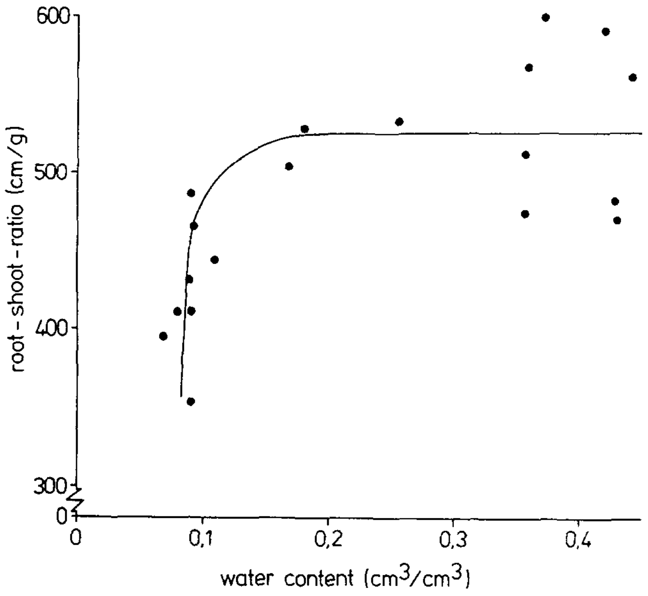

Fig. 5. Influence of soil moisture on the root/shoot ratio of onion plants.
Abb. 5. Einfluss des Wassergehaltes von Boden auf das Wurzel/Spross-Verhältnis von Zwiebelpflanzen.

interface (ΔC_l). If ΔC is measured by the desorption technique, its value will increase with the number of desorption steps. No definite final point will be found. This method will therefore given an approximation of ΔC only. Exchangeable potassium, which is regarded to be in equilibrium with the potassium of the soil solution, is not satisfactory either, because plant roots do not deplete this value down to zero, even in the immediate vicinity of the root surface. In order to determine D_e, it therefore appeared appropriate to use as ΔC the actual decrease of exchangeable K at the root surface as measured by the method of Kuchenbuch and Jungk[10]. This value was used in equations (2) and (3).

It was shown in Table 2 that K concentraton of the soil solution decrease with increasing volumetric water content which increases the buffer power. According to equation (2) the diffusion coefficient decreases with increasing buffer power and increases with θ and f. The data in Figure 2 show that D_e increased by a factor of about 10 with increasing soil moisture.

Therefore, the effect of both θ and f on potassium diffusion is much more important than the influence of volumetric water content on the buffer power of this soil.

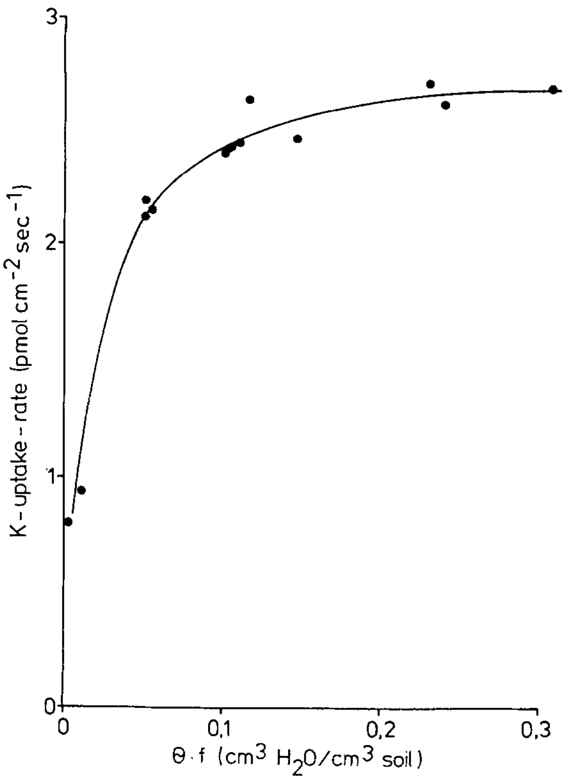

Fig. 6. Rate of potassium uptake per unit surface in relation to the product of volumetric water content (θ) and impedance factor (f).
Abb. 6. K-Aufnahmerate in Abhängigkeit vom Produkt $\theta \cdot f$ bei Zwiebelpflanzen.

The relationship between θ and f (Fig. 3) is similar to the results of Rowell *et al.*[17] and Barraclough and Tinker[4]. These authors also found a linear relationship between volumetric water content and tortuosity. However, their values, which had been obtained with chloride or bromide, are 20–30% lower than ours. The reason for this difference is attributed to the problem of ΔC for potassium mentioned above. This problem does not occur with the anions used because they are hardly adsorbed in soil. Furthermore anions may be excluded from fine pores or close to charged surfaces decreasing their diffusion path cross section. This is not the case for cations. Increasing the volumetric water content raised both D_e (Fig. 2) and the tortuosity factor (Fig. 3). As shown in Fig. 6, the rate of K uptake also increased with θ.f. However, in contrast to the other relations, rate of K uptake by plant roots strongly increased in the range of the lower values and levelled off at higher values. Transport of K from the soil cannot be the reason. It is assumed that the root uptake ability limits inflow of K in this case.

It can therefore be concluded that depending on water content a plant root in the same soil may be insufficiently or sufficiently supplied with K. In addition, the root system may be reduced as a result of a shortage of soil moisture which adds another restraint on the availability of K under dry conditions. These results may well explain the observation of van der Paauw[14] and Barber[2] that crop response to K fertilizers in dry seasons is often greater than in wet seasons.

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