# Growth and nutrient uptake by lettuce grown on NFT

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# Contents

# Abstract

A nutrient film technique system equipped with an automatic pH and water level control system was used to determine water and nutrient use by lettuce (*Lactuca sativa* cv Sitonia). The composition of the nutrient solution was controlled manually based on daily measured nitrate concentrations and known uptake ratios. Uptake by plants and loss from the nutrient solution were compared: the cumulative loss of ions exceeded uptake at all times and at the end of the growth period this was, for anions and cations together, 12.5% more than uptake. For the individual nutrients N, P, K, Ca, and Mg this final difference with uptake was 16.7%, 21.4%, 13.0%, 28.4%, and 21.4%, respectively. This difference decreased in time until maximum growth and uptake rate were reached, and then increased again. A simple simulation model with an extra constant daily loss, used for demonstration purposes only, yielded a similar pattern. Growth and cumulative uptake of nutrients were well described by a logistic model. Relative cumulative uptakes, i.e. cumulative uptakes divided by fitted maximum uptakes, of N, P, K, S, Cl, B, and Zn and to a lesser extent those of Ca and Mg, showed good agreement with relative dry mass increase in time. This means that the contents of these elements in the plant remain constant in time, and that mutual constant uptake ratios may exist. Many constant uptake ratios between the macronutrients were obtained, but constant uptake ratios between micro- and macronutrients were also found, i.e. for B, Cu, Zn, Cl and Na, but not for Fe, Mn and Mo. This means that the dosage of those micronutrients can be related to that of macronutrients. The nitrate content of the lettuce heads fluctuated in time, so that it is not possible to predict the final nitrate content based on intermediate measurements. At the end of the growth period, June-July 1991, the fresh and dry masses of the heads were 333 and 18.3 g, respectively, with a dry shoot/root ratio of 7.4. The average transpiration per plant was 2.86 $g \cdot l^{-1}$, and the average transpiration per unit increase in radiation was 3.8 $l \cdot cm^2 \cdot kJ^{-1}$. Results were compared with those of another experiment. The nitrate content of the lettuce crop was determined in time as well. At the end the nitrate content of the heads was 2700 $mg \cdot kg^{-1}$, based on fresh mass. Intermediate contents fluctuated, so that it seems not possible to predict final nitrate content based on early analyses. The automatic water and pH regulation system functioned well. Additionally, two membrane $NO_3^-$ and one glass $K^+$ ion selective electrodes (ISE) and an EC sensor were used to monitor the composition of the nutrient solution continuously. The behavior of the $NO_3$ ISE's was satisfactory, but not that of the K ISE.

Keywords: nutrient film technique, NFT, lettuce, *Lactuca sativa* cv Sitonia, nutrient uptake, growth and uptake models

# 1. Introduction

With soilless culture systems, such as nutrient film technique (NFT) or growing methods based on rockwool, a better control of crop production (quantity and quality) may be possible than with soil-based systems (Heinen et al., 1990; 1991). In free drainage systems nutrient losses of 40 to 70% have been observed (De Willigen and Van Noordwijk, 1987). In recirculating systems, water and fertilizer use are more efficient, and environmental pollution is reduced. With inert artificial substrates, which have a small buffer capacity, the composition of the nutrient solution can be easily monitored and adjusted. With such a system uptake patterns of a crop can be determined. Water cultures have long been used to determine uptake patterns, e.g. a first publication stems from 1660 (Steiner, 1985).

Recently, Heinen et al. (1990; 1991) described a partly automatic NFT system. For lettuce grown on this system they observed that:

a. the increase in dry mass of lettuce was well described by a logistic model;
b. nutrient uptake computed from losses from the nutrient solution exceeded nutrient uptake obtained by observed increase in plant nutrient content;
c. cumulative uptake of all nutrients was well described by a logistic model;
d. for most nutrients the relative cumulative uptake equalled the relative increase in dry mass of the plant;
e. the relative cumulative uptake of N, P and K per plant as a function of cumulative daily radiation was well described by a logistic model;
f. dry mass as a function of the transpiration per plant was well described by a logistic model, with an average dry mass production of 3.1 g per liter transpired;
g. the transpiration per plant as a function of daily radiation was well described by a logistic model, with an average transpiration of 5.8 l per unit increase in radiation; some constant uptake ratios between the nutrients could be indicated.

Heinen et al. (1990; 1991) gave several reasons why uptake and loss were not equal: removal at harvest of poor quality plant material and thus nutrients, immobilization by microorganisms present in peat and solution, denitrification, precipitation, and the fact that two laboratories were involved, one for nutrient solution analysis and one for plant analysis.

The purpose of this study is to repeat the experiment of Heinen et al. (1990; 1991), without peat in the growing system, with automatically controlled water and pH levels in the supply tank, and with one laboratory for all analyses. The two experiments will be compared, and to avoid continuous reference to the previous publications, the first and second experiments will be denoted by their IB-DLO experiment numbers, viz. 5132 and 6705, respectively.

# 2. Materials and Methods

## 2.1 Experimental setup

The experimental NFT system as described by Heinen et al. (1990; 1991) was used. Only part of the automatic measuring and control system was used, i.e. the pH and water level control systems. The pH was kept between 5.5 and 6.5, with set point 6.0. Ion selective electrodes (ISE) and an EC sensor were present, but only to measure the change in composition of the nutrient solution. There were one glass K and two membrane $NO_3$ ISE's. No control actions based on ISE measurements were carried out due to poor behavior of the electrodes and control system (Heinen, 1990a; 1992; Heinen and Harmanny, 1992), but dosage was carried out manually, which will be described later. As proposed by Heinen and Harmanny (1992) the ISE's and pH electrode were calibrated regularly, viz. at days 1 (pH only), 4, 16, 19, 26, 33, 40, and 51.

The climate inside the greenhouse was automatically controlled: day temperature was set at 15 $^0$C with ventilation at 17 $^0$C, and night temperature was set at 10 $^0$C. The temperature inside and outside the greenhouse and the global radiation outside were monitored every two hours and daily averages were computed.

## 2.2 Water supply and system volume

The automatic water supply system of Heinen et al. (1990) was used to keep the water in the supply tank at a constant level. The initial volume of nutrient solution was approximately 150 l, which is half of the volume used in experiment 5132. It was assumed that no evaporation in the total systems occurs, so that all the water added by the automatic water supply system can be regarded as transpiration plus increase in water content of the crop assuming that the net daily hydration and dehydration processes are zero. However, due to frequent nutrient solution sampling as described below, the daily amounts replenished should be diminished by the sampling volume of that day in order to obtain plant water uptake. It is also known that, due to an increase in volume of the root mat in the gullies, the amount of nutrient solution held by this root mat increases. This lowers the nutrient solution level in the supply tank, not corresponding to transpiration. The process of water retention by the roots becomes complicated in case some plants are harvested during the growth period. Then the volume of water held by the roots is reduced, and the level in the supply tank will rise. The transpiration of the next day will then be underestimated. Because of this complexity it was decided to ignore this complication when computing the transpiration rate.

Initially, the system was rinsed several times with demineralized water and then emptied as completely as possible and the supply tank was filled with 153 l nutrient solution. The concentration of the nutrient solution will be diluted due to the presence of remaining rinsing water (demineralized water) in the various parts of the NFT system. Samples of the original and diluted solutions were taken for macronutrient analysis. From the change in concentration the dilution of the nutrient solution can be computed, and thus the initial volume can be obtained:

$$V_2 = \frac{V_1\, C_1}{C_2} , \qquad (1)$$

where $V_2$ is the initial system volume (l), $V_1$ is the amount of original nutrient solution (153 l), and $C_1$ and $C_2$ are the concentrations of a nutrient in the original and diluted nutrient solution, respectively. Eq. (1) can be solved for each of the nutrients, and the average initial volume can be computed.

At the end of the experiment the final system volume was determined by adding two highly concentrated $KNO_3$ solutions (1 l 0.400 M each). Before and after each addition the nutrient solution was sampled in order to determine the change in $NO_3$ concentration. After each addition 1 h equilibration time was allowed. After each addition the volume can be determined and the mean final volume then follows from:

$$V_f = \frac{A - C_{1f}}{2\,(C_{1f} - C_{0f})} + \frac{A - C_{2f}}{C_{2f} - C_{0f}}, \qquad (2)$$

where $V_f$ is the mean final system volume (l), $A$ is the amount of $NO_3$ added in each addition (mmol), and $C_{0f}$, $C_{1f}$ and $C_{2f}$ are the initial $NO_3$ concentration and the $NO_3$ concentrations after the first and second addition (mmol·l$^{-1}$), respectively.

## 2.3 Crop

The lettuce plants, *Lactuca Sativa* cv Sitonia, in this experiment were not placed in peat blocks (as was the case in 5132). Seeds were sown on pure sand, and after emergence the plants were transferred to styrofoam trays. The roots were flooded with half-strength nutrient solution one or two times a day. Three weeks after sowing the plants were transferred to the NFT gullies. The plants were placed in small blocks of foam and the roots were surrounded by filter paper. The plant roots with filter were located such that the filter paper was in contact with the nutrient solution, so that all roots were in contact with the solution. In this way it was prevented that roots dried out in the early stages of growth and that they were able to take up water and nutrients at the required rate. The total growth period was seven weeks, from June 3 to July 22, 1991. This period is one week longer than experiment 5132, but it is in the same time of the year.

## 2.4 Harvests

Harvests were carried out at times $t$ = 0, 1, 2, 4, 5, 6, and 7 weeks, with the harvest pattern described by Heinen et al. (1990). Per harvested plant the fresh masses of shoot and root were determined. The harvested shoots and roots were combined to get one shoot and one root sample, which were oven-dried (70 °C) and weighed to get the dry masses. The shoot samples of each harvest were analyzed for macro- and micronutrient contents and Na and Cl, viz. $N_{deys}$, $NO_3$, P, S, K, Ca, Mg, Na, Cl, Fe, Mn, B, Cu, Zn, Mo. Since in the beginning insufficient dry matter was available for complete analysis, at least (if possible) N, P and K were analyzed. From week 4 on, all elements could be analyzed. The nitrate content of the crop was analyzed to follow the change in nitrate content in time, and to determine if the final $NO_3$ content based on fresh mass was lower than the maximum of 2500 mg·kg$^{-1}$ legally allowed in the Netherlands.

## 2.5 Composition and control of composition of the nutrient solution

The set point concentrations of the macro-nutrients in the nutrient solution were half of those used in 5132 (Table 2.1), but for micronutrients the same set points were used. The nutrient solution was sampled each day. In each sample the concentrations of the macro-nutrients and Na and Cl were analyzed, viz. $NO_3$, $NH_4$, S, P, K, Ca, Mg, Na, Cl. Bi-weekly extra samples were taken for the micronutrient analysis (except for Mo), viz. Fe, Mn, B, Cu, Zn.

Table 2.1 Set point concentrations of macro- (mmol·l⁻¹) and micronutrients (μmol·l⁻¹).

| Macronutrient | Set point | Micronutrient | Set point |
|---|---|---|---|
| $NO_3$ | 5.000 | Fe | 179 |
| P | 0.333 | Mn | 6.73 |
| K | 2.624 | B | 32.6 |
| Ca | 1.172 | Cu | 0.58 |
| Mg | 0.392 | Zn | 2.0 |
| $SO_4$ | 0.168 | Mo | 0.41 |
| | | Cl | 0.08 |

The metering scheme of Heinen et al. (1990; 1991) was adapted (Table 2.2) and the same stock solutions were used. The manual dosage procedure was as follows. The concentration of $NO_3$ was measured daily. Based on the decrease of $NO_3$ in the nutrient solution, and based on observed uptake ratios of the previous days, the amounts of all nutrients to be added were known, so that the amounts of stock solutions to be added to the nutrient solution could be calculated. These amounts were added manually each day. The uptake ratio was computed and if necessary adapted during the experiment based on bi-weekly analysis of the macro-nutrients. This analysis was carried out within three days after sampling. The initial uptake ratios were set equal to the average uptake ratios observed by Heinen et al. (1990; 1991). The Fortran source code listings of the computer programs for dosage and ratio computations are listed in Appendices 1 and 2, respectively. In the dosage scheme corrections were made to account for any $NO_3$ given through the automatic pH regulation.

The dosage program assumed a constant system volume of 150 l. Thus when the system volume is, e.g., larger, the computed amounts supplied to the system would cause a smaller increase in concentration. This was accounted for in the loss computations, as described in section 2.7 'Uptake and loss'. This also implies that the actual concentration of the nutrient solution will be lower than the set point concentration.

To check the behavior of the automatic pH control system and the effect of manual dosage, each day the pH and EC in a small sample of the nutrient solution were measured in the laboratory with pH and EC electrodes.

## 2.6 Modeling growth and cumulative nutrient uptake

Heinen et al. (1990, 1991) found that lettuce growth and cumulative uptake of nutrients by lettuce was well described by a logistic function:

Table 2.2 Salt dosage scheme (after Heinen et al., 1990; 1991). The salt formula represents the amount of salt solution (ml) to be added to 1 l of nutrient solution. Square brackets represent the concentrations of the elements to be added or the salt concentrations of the stock solutions (mmol·l⁻¹).

| | |
|---|---|
| $CaCl_2$ | $= 0.5 \cdot [Cl]/[CaCl_2]$ |
| $KH_2PO_4$ | $= [P]/[KH_2PO_4]$ |
| $Ca(NO_3)_2$ | $= ([Ca]-0.5 \cdot [Cl])/[Ca(NO_3)_2]$ |
| $Mg(NO_3)_2$ | $= [Mg]/[Mg(NO_3)_2]$ |
| $K_2SO_4$ | $= [S]/[K_2SO_4]$ |
| $KNO_3$ | $= MIN\ \{([K]-[P]-2 \cdot [S]),\ ([N]-2 \cdot [Ca]-2 \cdot [Mg])\}/[KNO_3]$ |

$$y(t) = \frac{y_i \cdot y_f}{y_i + (y_f - y_i) \cdot \exp(-k \cdot t)}, \tag{3}$$

where $y$ represents mass (g) or cumulative uptake (mol), $t$ represents time (week), $k$ (week$^{-1}$) is a proportionality factor and a measure for the relative growth rate at the point of inflection (Heinen, 1990b), and $y_i$ and $y_f$ refer to initial ($t = 0$) and asymptotic final ($t \rightarrow \infty$) value of $y$.

Data on growth and cumulative uptake can be modeled by Eq. (3) through standard Genstat curve fit procedures (Genstat 5 Committee, 1987; Heinen, 1990b).

## 2.7 Uptake and loss

Heinen et al. (1990; 1991) defined two methods to determine uptake of nutrients by a crop. Ideally, the loss of nutrients from the nutrient solution is equal to the increase in nutrient content of the crop. The uptake by the crop is defined as:

$$U = (A_t - A_{t-1}) \cdot N, \tag{4}$$

where $U$ (mmol·week$^{-1}$) is the total uptake by $N$ plants during the time interval of one week. $A_t$ and $A_{t-1}$ (mmol) are the nutrient contents of a plant at the end and start of a week, respectively. The loss from nutrient solution is defined as:

$$L = (C_{t-1} - C_t + D) \cdot V - S, \tag{5}$$

where $L$ (mmol·week$^{-1}$) is the loss of nutrient from the solution, $C_t$ and $C_{t-1}$ (mmol·l$^{-1}$) are the nutrient concentrations at the end and start of a week, respectively, $D$ (mmol) is the total amount of nutrient added to the supply tank, $V$ (l) is the constant volume of the supply tank, and $S$ (mmol·week$^{-1}$) represents the removal of nutrients due to frequent sampling of the nutrient solution. Note that in experiment 5132 the $S$ term in Eq. (5) was not included. It was not considered to be of importance due to the less frequent sampling of the nutrient solution, and a two times larger volume of nutrient solution present in the system.

# 3. Results and Discussion

## 3.1 Introduction

Data analysis of transpiration and nutrient loss from the nutrient solution became somewhat complicated due to two known electrical failures. This caused a system misfunctioning ending in a loss of nutrient solution. This happened on days 23 and 34. The loss of nutrient solution was resupplied by fresh nutrient solution, i.e. 32.5 and 28.5 l, respectively. On days 34 and 35 no information on transpiration was available. Transpiration on these two days can only be estimated on the basis of available radiation data, assuming linear relationship between transpiration and radiation as observed in experiment 5132. The loss of nutrients, according to Eq. (5), must be corrected for an extra dosage due to the difference in concentration of the nutrient solution lost and that of the fresh nutrient solution. This extra dosage can be added to the $D$ term in Eq. (5). The exact procedures will be described in the corresponding sections below.

## 3.2 Climatic conditions

The mean daily temperatures inside and outside the greenhouse and the daily radiation sum outside are given in Figure 3.1. The temperature during the first four weeks was around 15 °C and increased after that to temperatures between 20 and 25 °C. The temperature during experiment 5132 (in the same period of the year and with the same climatic control system) always was in the range 15 to 20 °C. During the first weeks the crop in 6705 was exposed to lower temperatures and less radiation than the crop in 5132, but during the last weeks the opposite is true. This may cause differences in growth of the crops in the two experiments.

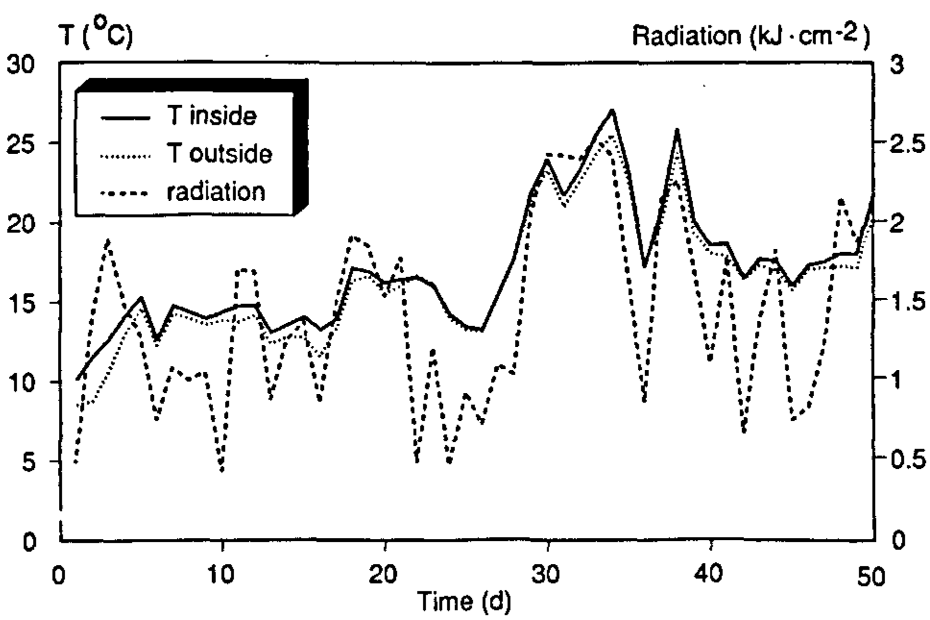



Figure 3.1 Mean daily temperatures inside and outside the greenhouse and the daily radiation sum during the growth period of lettuce in experiment 6705.

## 3.3 System volume

The initial volume based on Eq. (1) averaged over all macronutrients was 168.0 l (cv = 1.3%), so that initially 15 l demineralized water was already present in the NFT system. The final system volume according to Eq. (2) was 176.4 l, which is 8.4 l or 5% more than the initial system volume. The increase in nutrient solution is due to the increase in solution remaining in the gullies where it is held by the roots. The root mass in the gullies increases with time, but each week some plants were harvested, and thus roots were removed. This makes it impossible to know the exact amount of nutrient solution present in the system at any time. Moreover, since the final volume is only 5% more than the initial volume, it was decided to set the system volume in the computations equal to the initial volume. This has not much effect on the computation of $L$ in Eq. (5). Ideally, $C_t = C_{t-1}$ so that $L = D{\cdot}V$. Thus, $L$ is the total amount given divided by the system volume times the system volume, i.e. $L$ is independent of $V$.

## 3.4 Fresh and dry masses

The fresh and dry masses of shoots and roots are listed in Table 3.1. A more detailed table is given in Appendix 3. The masses of the crop of 6705 were less than those of 5132. The percentages dry matter decreased in time and are somewhat higher than those of 5132, but the final value of 5.5 is normal according to the range of 3.5 to 5.5 reported by Roorda van Eysinga and Smilde (1971). The dry shoot/root ratio increased in time as was also observed in 5132. The dry shoot/root ratio of 7.42 at the end of the growth period is in good agreement with values computed (assuming 5% dry matter) from data by Reinink and Eenink (1988), Silva and Toop (1986), and Toop et al. (1988): 6.5 to 8.5. The fresh and dry masses of the shoots and roots were well described by the logistic model (Eq. (3); Table 3.2). The increase in dry mass in time lagged behind that observed in 5132 (Figure 3.2). However, the initial masses of the plants differed, only after 10 d of growth the plants in 6705 had the same mass as the initial mass of experiment 5132. This lag in time was obtained by assuming initial exponential growth. After shifting the data 10 d backward, the dry mass increase in time of 6705 was similar to that of 5132 (Figure 3.2). The deflection in 6705 is less pronounced than that of 5132, so that time of inflection and final estimated mass in 6705 are larger than for 5132. The larger inflection time may be explained by the fact that the climatic conditions for 6705 at the last weeks were favorable (see above) for an extended exponential growth.

## 3.5 Nutrients: introduction

As mentioned above, electrical failures caused leakage of nutrient solution with concentration $C_L$ (mmol·l$^{-1}$). This leak was in the best possible way replenished by the same volume of fresh nutrient solution with concentration $C_F$ (mmol·l$^{-1}$). Since $C_L$ was not equal to $C_F$, there is an extra dosage of nutrients during the weeks 4 and 5: if $C_L < C_F$ this means a positive dosage, else a negative dosage. This dosage should be added to $D$ in Eq. (5). The following procedure to estimate the unknown $C_L$ was used. The concentration of the nutrient solution at the time of leakage was the same as the concentration of the latest sample taken from the nutrient solution minus the average amount of nutrient taken up during the time between sampling and leakage:

$$C_L = C_s - \frac{R}{V_1} t_s , \qquad (6)$$

Table 3.1 Fresh and dry masses of shoots and roots, percentages of dry matter of shoot, root and crop, and shoot/root ratios based on dry masses, all per plant.

| Week | Shoot fresh (g) | Shoot dry (g) | Shoot d.m. (%) | Root fresh (g) | Root dry (g) | Root d.m. (%) | Shoot/root (-) | Crop d.m. (%) |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.10 | 0.007 | 6.96 | 0.033 | 0.005 | 14.15 | 1.50 | 8.73 |
| 1 | 0.43 | 0.031 | 7.25 | 0.157 | 0.009 | 5.96 | 3.36 | 6.91 |
| 2 | 1.95 | 0.126 | 6.47 | 0.568 | 0.033 | 5.80 | 3.84 | 6.32 |
| 4 | 44.63 | 2.203 | 4.94 | 7.248 | 0.430 | 5.93 | 5.12 | 5.08 |
| 5 | 120.18 | 6.683 | 5.56 | 19.052 | 1.304 | 6.85 | 5.12 | 5.74 |
| 6 | 220.64 | 12.108 | 5.49 | 29.773 | 1.863 | 6.26 | 6.50 | 5.58 |
| 7 | 332.58 | 18.300 | 5.50 | 39.728 | 2.467 | 6.21 | 7.42 | 5.58 |

Table 3.2 Estimated parameters of Eq. (3) for fresh and dry masses of shoot and root.

| Parameter | Shoot fresh | Shoot dry | Root fresh | Root dry |
|---|---|---|---|---|
| $y_0$ | 0.726 | 0.033 | 0.097 | 0.004 |
| $y_f$ | 441.9 | 23.8 | 45.5 | 2.7 |
| $k$ | 0.1533 | 0.1582 | 0.1638 | 0.1767 |
| $t^*$ | 41.82 | 41.51 | 37.56 | 36.27 |
| $R^2$ | 99.96 | 99.93 | 99.92 | 99.73 |

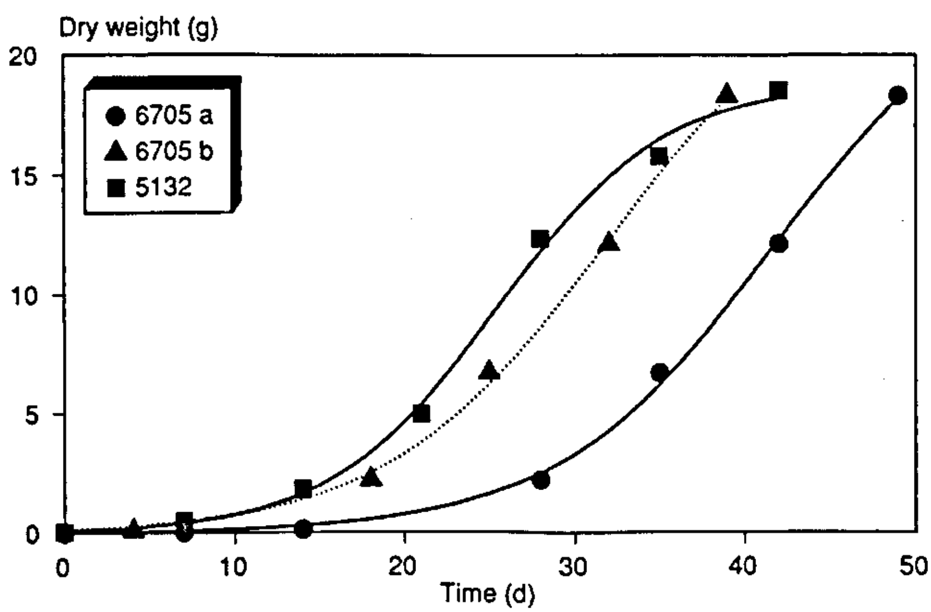



Figure 3.2 Dry mass of lettuce head as a function of time for experiments 5132 and 6705. The solid lines (6705 a and 5132) are the modeled logistic curves (Eq. (3)). The dotted curve (6705 b) represents the 6705 data when shifted 10 d to the right.

where $C_R$ (mmol·l$^{-1}$) represents the concentration of a nutrient in the latest taken sample, $R$ (mmol·d$^{-1}$) represents the average daily uptake obtained from plant analysis during the week when leakage occurred, $V_1$ (l) is the system volume, $t_R$ the number of days (d) between the time when the latest sample was taken and leakage, where it is assumed that uptake only occurs during 14 hours of the total day, i.e. the average daylight period. For example, if sampling occurred at 08:00 and leakage at 10:00 one day later, $t_R$ = 1 + (10-8)/14 = 1.14 d. Sampling and leakage in all cases happened during daylight. The extra dosage now can be computed according to:

$$D^{+} = \frac{V_L}{V_1}\left( C_P - C_L \right) , \tag{7}$$

where $D^{+}$ (mmol·l$^{-1}$) is the extra dosage, $V_L$ (l) is the volume of leakage. $D^{+}$ is a dosage in addition to $D$ in Eq. (5), i.e. Eq. (5) is replaced by:

$$L = \left( C_{t-1} - C_t + D + D^{+} \right) \cdot V - S . \tag{8}$$

The loss data are listed in Appendix 3. For example, for $NO_3$ $D^{+}$ amounts were 3% and 5% of the total $NO_3$ dosage at the ends of weeks 4 and 5, respectively.

## 3.6 Nutrients: uptake and loss

Table 3.3 lists the uptake and losses according to Eqs. (4) and (8); see also Appendices 3 and 4. It is clear from Table 3.3 that for all elements, except S, Cl, Na, Cu and Zn, $L$ exceeds $U$ at all times, as was also the case for all nutrients, except Cu and Zn, in experiment 5132. The increase of Cu and Zn in the nutrient solution can be explained by Cu and Zn dissolving from metal parts and rubber tubing. The amounts of $HNO_3$ added to keep the pH at a constant level were used to obtain the loss of $H^+$ from the nutrient solution. Plant growth on nutrient solution containing only $NO_3$ as nitrogen source (i.e. no $NH_4$) will cause an increase in pH of this solution due to unbalanced anion versus cation uptake. Relatively more anions are taken up, which then causes an apparent $H^+$ uptake ($H^+$ uptake and/or $OH^-$ excretion) to make total ion uptake electrically neutral (Van Beusichem, 1984). First, the total ionic balances of uptake and loss will be described, and second, the uptake and loss data of the separate macronutrients will be discussed.

For macronutrients the total anion uptake and loss can be compared to the total cation uptake and loss, in which case the $H^+$ loss is set equal to $H^+$ uptake (Figure 3.3). The summated loss of nutrients exceeded the summated uptake. Within the two balances the differences between sum of anions and sum of cations is small: from week 4 on this difference with respect to sum of anions is less than 3%, except for uptake during week 4 (12.5%). In the first two weeks this difference is relatively large, but it should be remembered that then the uptake and loss are small in an absolute sense, so that small measurement errors cause larger differences. In all cases, except during week 7, the sum of anions exceeded the sum of cations, which can be explained by the fact that the micronutrients, mostly present as cations, were not included in the mass balance computations. The average difference between loss and uptake was 0.07 eq during the first two weeks, and at the end this was 0.3 eq, i.e. 12.5% with respect to uptake. For comparison, in experiment 5132 the difference between loss and uptake was 54% after week 1, decreased to 17% after week 4, but then increased to 87% at the end of week 6. The following aspects need some discussion:

1) not all elements in plant material could be analyzed at weeks 1 and 2 (see Table 3.3);
2) the small difference between loss and uptake at week 5;
3) *the relatively large difference between sum of anions and sum of cations for the uptake data at week 4.*

Re 1) Not having all data means an underestimation of total uptake. However, excluding the data of those elements that were not analyzed in the plant material from the loss balance did not show much improvement. This can be explained by the fact that the N and K content in the plant material dominates the cumulative uptake balance and also the change in concentration of the nutrient solution and thus the summated loss balance. Thus the underestimation of the total uptake in the first two weeks can be regarded as small.

**Re 2)** At week 4 all elements in the plant material were analyzed, so that the argument under 1) cannot apply here. The data themselves seem reasonable, so that measurement errors may be the cause.

**Re 3)** The differences between loss and uptake at weeks 4, 6 and 7 are of comparable magnitude: on average 0.26 eq. At week 5 this difference is much smaller, i.e. 0.11 eq. It is recalled that two times before this harvest time an electrical failure caused a leakage of nutrient solution. In repairing the damage there may be several sources of error: wrong amount fresh nutrient solution resupplied, wrong concentration of new solution, uptake rate at day 34 differs from average uptake rate of week 5. This may have caused an underestimation of nutrient loss from the solution.

In absolute sense the loss of N and K was the largest, and thus determined the differences in total ion loss versus uptake as just described. The difference between loss and uptake for all macronutrients, except S for which $U > L$, expressed relative to uptake shows that this difference decreased in time in the beginning, but at the end increased again (Figure 3.4). In the beginning this relative difference is high, which is caused by the low values of uptake and

Table 3.3 Uptake by crop (*U*) and loss from nutrient solution (*L*) according to Eqs. (4) and (8) for all elements (*E*) at the harvest times *t* (week). The amounts are expressed in mmol per plant (N, P, K, Ca, Mg, S, Na, Cl, H) or μmol per plant (Fe, Mn, B, Cu, Zn, Mo). Notation: -: insufficient dry matter available to determine *U*; nd: not determined.

| *E* | *U,L* | *t* = 1 | *t* = 2 | *t* = 4 | *t* = 5 | *t* = 6 | *t* = 7 |
|---|---|---|---|---|---|---|---|
| N | *U* | 0.13 | 0.62 | 9.84 | 22.73 | 38.94 | 54.22 |
| | *L* | 0.64 | 1.15 | 12.25 | 22.91 | 43.61 | 63.26 |
| P | *U* | 0.01 | 0.05 | 0.81 | 2.01 | 3.74 | 5.32 |
| | *L* | 0.04 | 0.09 | 1.09 | 2.09 | 4.71 | 6.46 |
| K | *U* | 0.06 | 0.38 | 5.71 | 17.99 | 31.61 | 44.14 |
| | *L* | 0.53 | 0.91 | 8.42 | 18.01 | 34.35 | 49.86 |
| Ca | *U* | - | 0.04 | 0.56 | 1.57 | 2.92 | 4.68 |
| | *L* | -0.00 | 0.04 | 1.04 | 1.57 | 3.86 | 6.01 |
| Mg | *U* | - | 0.02 | 0.23 | 0.58 | 1.04 | 1.68 |
| | *L* | -0.03 | -0.02 | 0.34 | 0.51 | 1.28 | 2.04 |
| S | *U* | - | - | 0.27 | 0.64 | 1.22 | 1.77 |
| | *L* | -0.01 | -0.01 | 0.27 | 0.51 | 1.15 | 1.64 |
| Na | *U* | 0.00 | 0.02 | 0.06 | 0.22 | 0.31 | 0.34 |
| | *L* | 0.02 | 0.02 | 0.07 | 0.10 | 0.11 | 0.19 |
| Cl | *U* | - | 0.03 | 0.36 | 0.80 | 1.44 | 2.17 |
| | *L* | 0.002 | 0.01 | 0.40 | 0.66 | 1.37 | 2.20 |
| Fe | *U* | - | - | 26.06 | 55.82 | 66.17 | 75.94 |
| | *L* | 19.62 | 38.70 | 182.63 | 526.68 | 587.60 | 608.15 |
| Mn | *U* | - | - | 7.05 | 16.09 | 20.51 | 18.76 |
| | *L* | 0.61 | 2.36 | 9.97 | 22.05 | 25.37 | 25.62 |
| B | *U* | - | - | 4.73 | 18.33 | 34.59 | 55.67 |
| | *L* | 4.53 | 5.83 | 16.16 | 18.79 | 56.99 | 76.41 |
| Cu | *U* | - | - | 3.67 | 13.87 | 27.72 | 53.27 |
| | *L* | -0.57 | -0.87 | -147.89 | -250.98 | -282.70 | -373.55 |
| Zn | *U* | - | - | 24.10 | 85.99 | 186.44 | 262.76 |
| | *L* | -1.45 | -3.64 | -47.13 | -65.29 | -35.52 | -34.95 |
| Mo | *U* | - | - | 0.07 | 0.46 | 0.50 | 1.57 |
| | *L* | nd | nd | nd | nd | nd | nd |
| H | *L* | 0.01 | 0.01 | 2.80 | 4.31 | 5.89 | 12.76 |

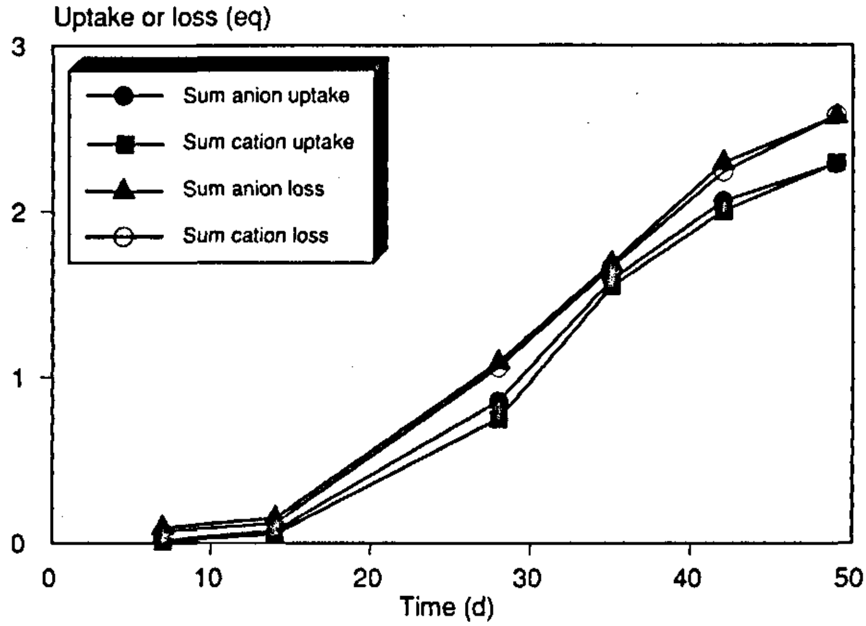



Figure 3.3 Sums of anions and cations (macronutrients and H⁺) for the total uptake by all plants and the total loss from the system as functions of time.

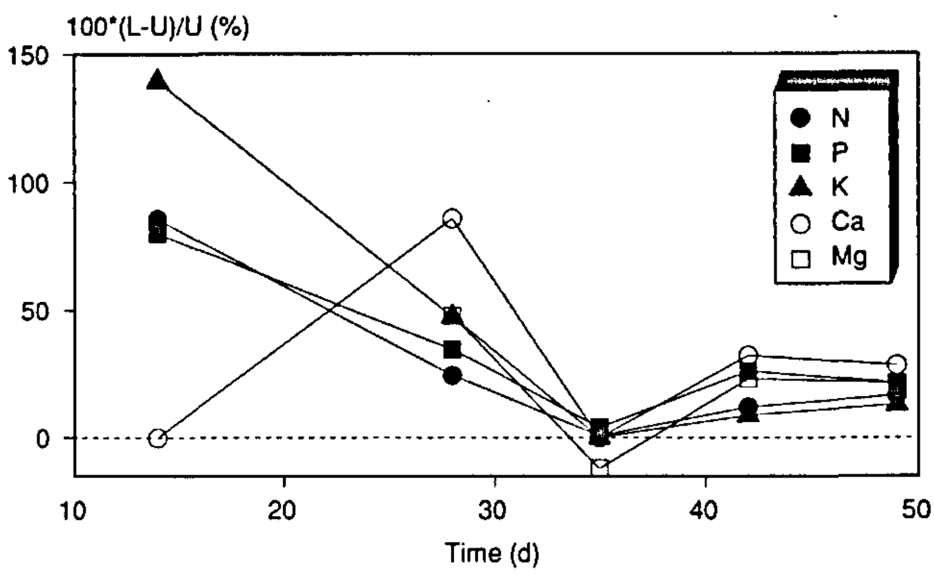



Figure 3.4 Observed differences between $L$ and $U$, according to Eqs. (4) and (8), relative to $U$ as a function of time for macronutrients N, P, K, Ca and Mg.

loss data. It is remarkable that this difference decreased when uptake rates increased and became smallest at the time when uptake rate was largest. At the end, when uptake rates decreased again, this difference increased. For the individual nutrients N, P, K, Ca, and Mg this final difference was 16.7%, 21.4%, 13.0%, 28.4%, and 21.4%, respectively. This observed pattern implies that other independent processes are involved as well. These may be (Heinen et al., 1991; Willumsen, 1980, 1984): immobilization by microorganisms and organic matter, precipitation, denitrification. Just as an illustration, a simple simulation was carried out describing the change in nutrient concentration in the supply tank for given, i.e. observed, logistic uptake (as described below in section 3.7 'Nutrients: logistic cumulative uptake') and a constant daily extra loss of each nutrient. The concentration at the beginning of each day was set equal to the set point concentrations (Table 2.1), the system volume was kept constant at 168 l, and the concentration of the nutrient solution at the end of the day was computed from:

$$C_{end} = \frac{C_s \cdot V - UPT - EL}{V}, \tag{9}$$

where $C_{end}$ is the concentration at the end of the day (mmol·l⁻¹), $C_s$ is the set point concentration (mmol·l⁻¹), $V$ is the system volume (l), $UPT$ is the daily uptake of a nutrient (mmol), and $EL$ is the daily extra loss (mmol). The simulation program computed the total uptake and loss from the system, and took into consideration the number of plants that were present each week. At the end of each week the relative difference between simulated loss from the system and uptake by the crop was computed. Simulations were carried out for different values of $EL$ to minimize simulated and observed relative differences (Table 3.4). For example, a daily extra loss of 7.0 mmol N caused a total loss which is comparable to the observed loss. This is 0.83% of the total daily content of N in the nutrient solution. Figure 3.5 shows simulated and observed relative difference between loss and uptake for N. The simulated pattern is comparable to that of the observed data (cf. Figure 3.4). The simulated concentration at the end of each day is presented in Figure 3.6. The extra loss causes only a small decrease in concentration compared to the case where no extra loss is involved. The abrupt pattern in the concentration course is due to changes in number of plants on the NFT system. For completeness, the concentration course in case 144 plants remained on the NFT system is given as well. It should be stressed that the simulation with an extra constant daily loss is only used for demonstration here, it does not imply that there is such a constant extra loss. In general, it will be a combination of several processes, as mentioned above, which will be dependent on e.g. temperature, oxygen content, exudate content etc. in the nutrient solution.

# 3.7 Nutrients: logistic cumulative uptake

The cumulative uptakes of all elements were well described by a logistic model (Appendix 5). Relative cumulative uptakes, i.e. cumulative uptakes divided by fitted maximum cumulative uptakes, and relative dry matter production were plotted as a function of time (Figure 3.7). In order to judge whether relative cumulative nutrient uptake was similar to relative dry matter production, arbitrary criteria for sum of squares (SSQ) differences between fitted values were used: SSQ < 0.2 good agreement, 0.2 < SSQ < 2.0 moderate agreement, and SSQ > 2.0 no agreement. Relative cumulative uptakes of N, P, K, S, Cl, B and Zn, and to a lesser extent those of Ca and Mg, showed good agreement with relative dry mass. This means that the contents of these elements in the plant remain constant. This was also observed in experiment 5132 (not judged with SSQ analysis, but by eye): good agreement for N, K, B, Zn, and Cl, and to a lesser extent for Ca, Mg, and S. In 5132 the uptake of P was relatively smaller as plants grew older, which was not the case in 6705. In both 5132 and 6705 the uptake of Fe, Mn, and Na was relatively larger as plants grew older, i.e. the uptake curves are to the left of the dry matter

Table 3.4 Constant daily extra losses, *EL* (mmol), of macronutrients which minimized the simulated and measured losses from the system, also expressed as percentage, *P* (%), of total daily content present in the nutrient solution.

| Macronutrient | *EL* | *P* |
|---|---|---|
| N | 7.00 | 0.83 |
| P | 0.52 | 0.93 |
| K | 6.00 | 1.36 |
| Ca | 0.23 | 0.12 |
| Mg | 0.055 | 0.08 |

curve. In 6705 uptake of Cu and especially Mo was relatively smaller as plants grew older, which was not observed in 5132. It should be noted that if two nutrients show good agreement with dry matter production, then the uptake ratio of these two nutrients will be constant in time (see also section 3.8 'Nutrients: constant uptake ratios'). Other research workers have related relative cumulative uptake to dry matter production. For example, van Itallie (1937) presented similar graphs for N, P and K uptake and dry matter production for several agricultural crops. For all eight crops considered he observed that uptake of N, P and K was relatively higher as plants grew older (see also Figure 3.12 in De Willigen and Van Noordwijk, 1987).

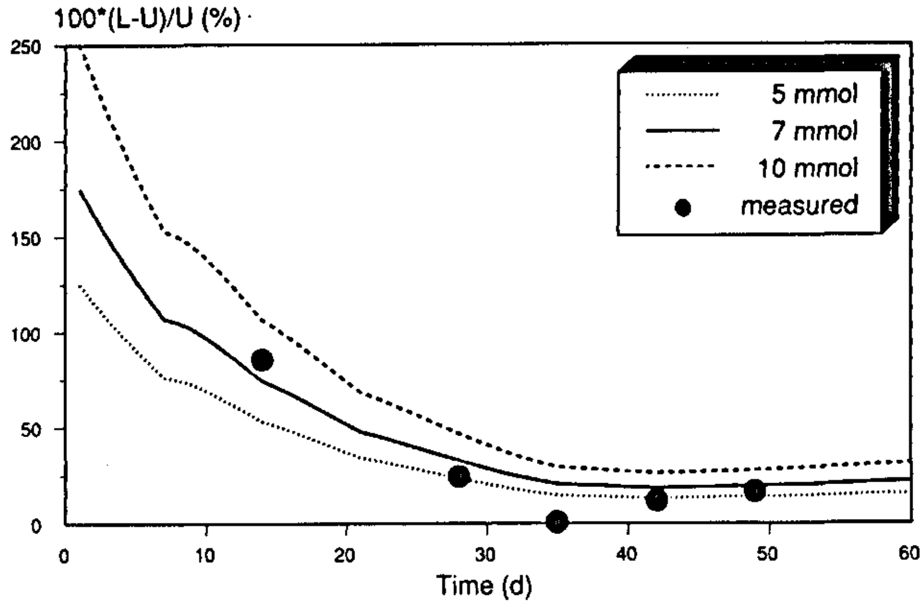



Figure 3.5 Simulated difference between loss, computed as given uptake plus a constant extra daily loss, and given uptake as a function of time for N for three values of constant daily extra loss.

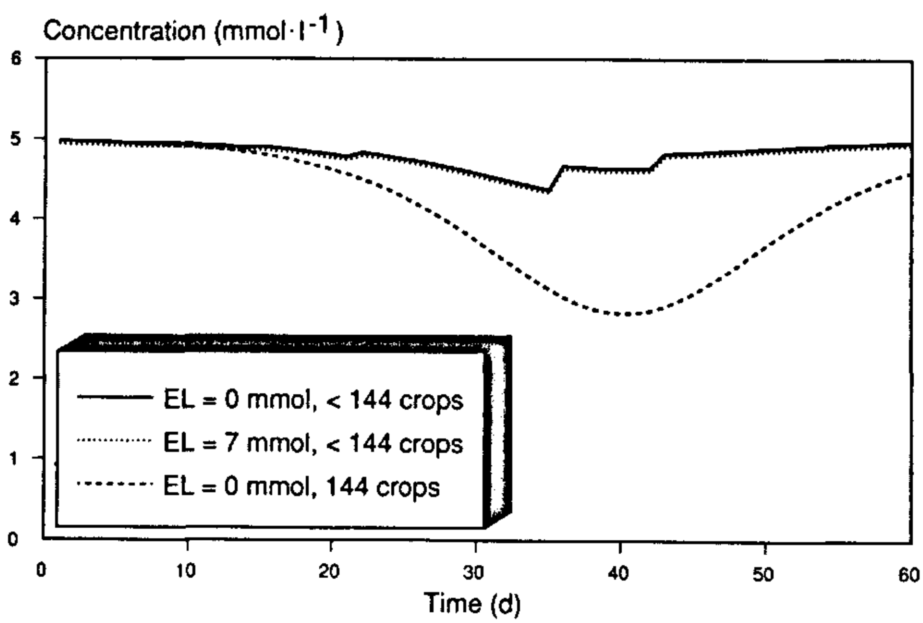



Figure 3.6 Simulated change in N concentration in the supply tank as a function of time for a decreasing number of plants in time and with or without a constant daily extra loss, the situation with a constant number of plants in time and without extra loss; is also shown.

In experiment 5132 the relative cumulative uptake of N, K and P as a function of cumulative daily radiation was well described by a logistic curve (cf Eq. (3); Heinen et al. (1991) their Figure 3.1). This was also observed in experiment 6705 (Figure 3.8; Appendix 6).

## 3.8 Nutrients: constant uptake ratios

The detailed information on changes in composition of the nutrient solution and the increase in element content in the plant makes it possible to determine whether there are constant uptake ratios between any of the nutrients. Heinen et al. (1991) showed results for experiment 5132 for four cases in their Table 3.3 where constant uptake ratios for the last four weeks of growth

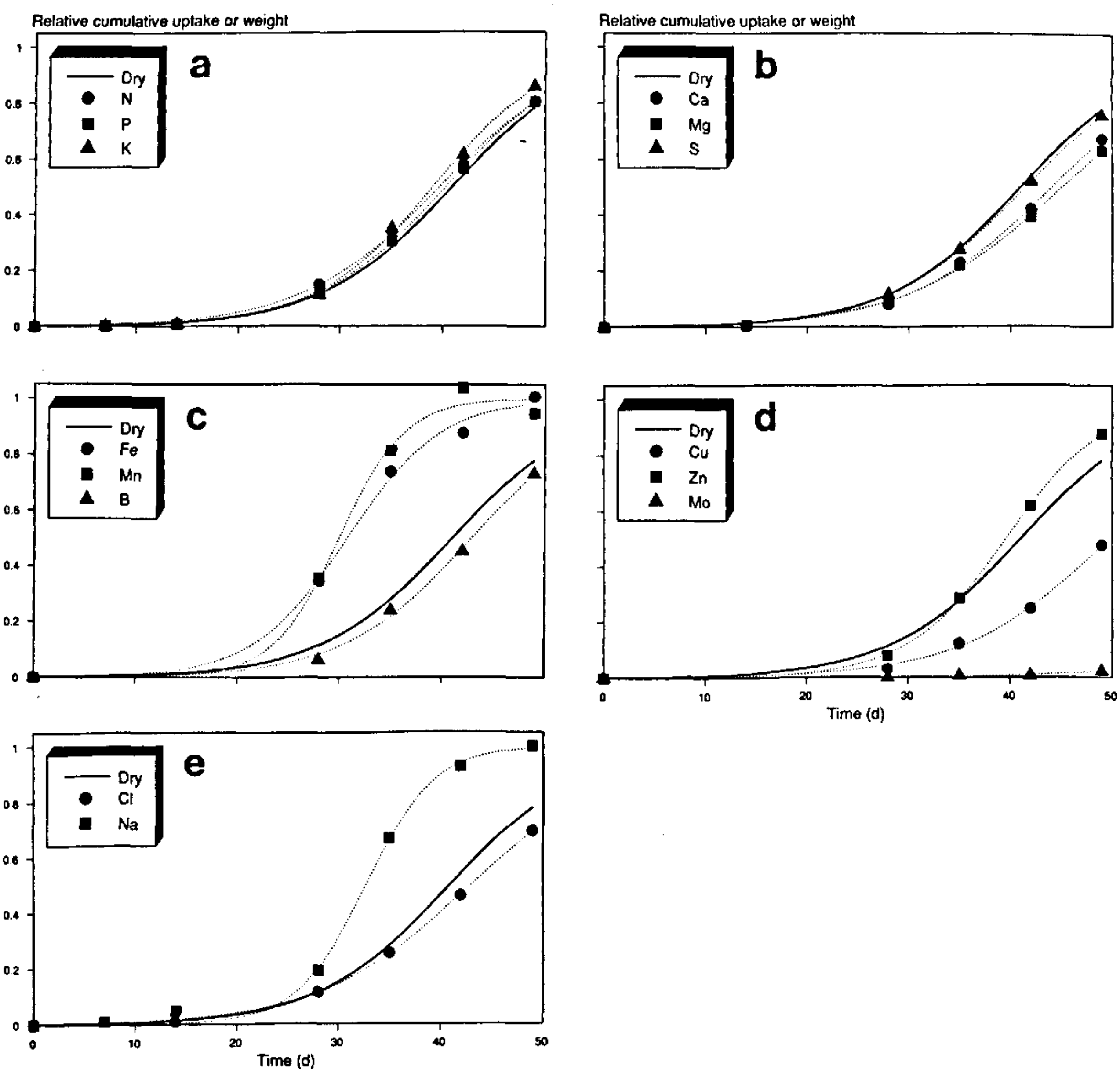



Figure 3.7 Relative cumulative uptake of N, P, K (a), Ca, Mg, S (b), Fe, Mn, B (c), Cu, Zn, Mo (d), Na, Cl (e) by one lettuce head, and relative dry mass as a function of time (experiment 6705). Measured data are described by a logistic model (cf. Eq. (3)).

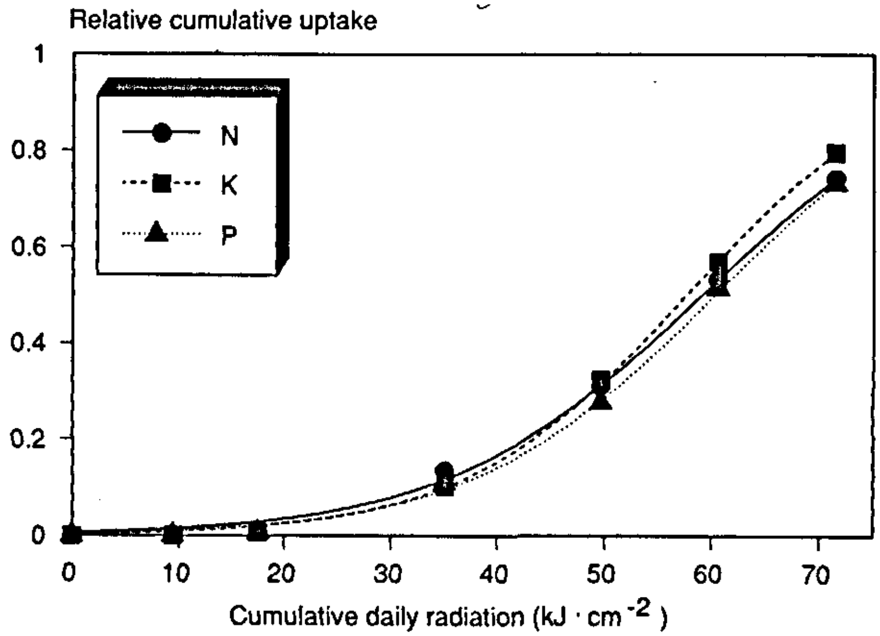



Figure 3.8 Relative cumulative uptake of N, K and P by one lettuce head as a function of cumulative daily radiation. Measured data are described with a logistic model (cf. Eq. (3)).

were presented. In order to compute constant uptake ratios in experiment 6705 and to compare these with results of experiment 5132, it was decided to compare results based on more or less equal dry matter production. As stated before, the dry matter production of the crop in 6705 lagged about 10 d behind that of 5132 (Figure 3.2). Therefore, it was decided to present constant uptake ratios of the last three weeks of 6705 (Table 3.5; Appendix 7 gives constant ratios of last four weeks). In 6705 more constant ratios are observed than in 5132. Any corresponding ratios are of the same magnitude. Note that the uptake ratios differ from the ratios of the original solution, thus uptake ratios cannot be used to determine recipes of nutrient solutions.

As mentioned above, constant uptake ratios between nutrients could be expected when nutrient uptakes showed good agreement with dry matter production (see section 3.7 'Nutrients: logistic cumulative uptake'). This was the case for nutrients N, P, K, S, Cl, B, and Zn, and to a lesser extent also for Ca and Mg. Indeed constant uptake ratios between these nutrients were observed (Table 3.4), but not for all combinations. For example, N and Ca or N and B uptake by a lettuce crop or lettuce head (cases 3 and 4, Table 3.4) did not yield a constant uptake ratio.

In situ monitoring of the micronutrient concentrations or regular analysis is difficult and expensive. Therefore, it is interesting to determine whether or not uptake of micronutrients is related to uptake of macronutrients. Then dosage of micronutrients can be based on known uptake of a macronutrient. In experiment 5132, based on cumulative uptake by one plant, it was observed that Cl may be added in relation to N, K, P or Mg, and B in relation to K. In experiment 6705 it was observed that Cl may be added in relation to N, K, P, Ca, Mg or S, Na in relation to N, B in relation to N, K, P, Ca, Mg or S, Cu in relation to P, Ca, Mg or S, and Zn in relation to N, K, P, Ca, Mg or S. So, there are no constant uptake ratios for Fe, Mn and Mo with any of the macronutrients.

## 3.9 Nitrate content

The $NO_3$ content in shoot and root fluctuated in time, but in general the percentage of total N present as $NO_3$ in the shoot increased with time (Table 3.6). The final $NO_3$ content in the crop

Table 3.5 Uptake or content ratios between macro- (mmol) and micronutrients (μmol), with less than 20% difference between maximum and minimum observed ratios (in relation to their mean) during the last three weeks. If the difference was less than 10% the ratio is underlined. Four cases are considered: case #1: weekly cumulative uptake by whole system; case #2: weekly cumulative loss from solution by whole system; case #3: weekly cumulative uptake by one plant week or content of one plant at the end of every week; case #4: content of one head at the end of every week.

| | K | P | Ca | Mg | S | Fe | Mn | B | Cu | Zn | Mo | Cl | Na |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N | $\underline{0.763}$ | $\underline{0.090}$ | 0.071 | $\underline{0.026}$ | $\underline{0.029}$ | | | 0.794 | | 3.836 | | $\underline{0.036}$ | 0.009 |
| K | 1 | $\underline{0.118}$ | $\underline{0.092}$ | $\underline{0.034}$ | $\underline{0.038}$ | | | 1.040 | | 5.019 | | $\underline{0.047}$ | |
| P | | 1 | $\underline{0.786}$ | $\underline{0.288}$ | $\underline{0.321}$ | | | $\underline{8.831}$ | 7.125 | 42.623 | | $\underline{0.400}$ | |
| Ca | | | 1 | $\underline{0.370}$ | $\underline{0.410}$ | | | $\underline{11.231}$ | 9.049 | 55.287 | | $\underline{0.513}$ | |
| Mg | | | | 1 | $\underline{1.121}$ | | | $\underline{30.403}$ | 24.510 | 149.56 | | $\underline{1.389}$ | |
| S | | | | | 1 | | | $\underline{27.544}$ | 22.208 | $\underline{133.06}$ | | $\underline{1.254}$ | |
| Fe | | | | | | 1 | $\underline{0.287}$ | | | | | | $\underline{0.004}$ |
| Mn | | | | | | | 1 | | | | | | $\underline{0.014}$ |
| B | | | | | | | | 1 | 0.805 | $\underline{4.941}$ | | $\underline{0.046}$ | |
| Cu | | case #1 | | | | | | | 1 | 6.160 | | | |
| Zn | | | | | | | | | | 1 | | 0.009 | |
| Mo | | | | | | | | | | | 1 | | |
| Cl | | | | | | | | | | | | 1 | |
| N | $\underline{0.773}$ | $\underline{0.095}$ | 0.076 | | 0.022 | | | 1.225 | | | | $\underline{0.030}$ | 0.006 |
| K | 1 | $\underline{0.123}$ | 0.099 | | 0.029 | | | 1.586 | | | | $\underline{0.039}$ | 0.008 |
| P | | 1 | $\underline{0.811}$ | 0.252 | $\underline{0.235}$ | | | $\underline{12.924}$ | | | | $\underline{0.310}$ | |
| Ca | | | 1 | $\underline{0.310}$ | $\underline{0.290}$ | | | $\underline{15.895}$ | | | | $\underline{0.392}$ | |
| Mg | | | | 1 | 0.939 | | | 51.184 | | | | 1.270 | |
| S | | | | | 1 | | | $\underline{55.410}$ | | | | $\underline{1.327}$ | |
| Fe | | | | | | 1 | $\underline{0.044}$ | | | | | | 0.000 |
| Mn | | | | | | | 1 | | | | | | 0.006 |
| B | | | | | | | | 1 | | | | $\underline{0.024}$ | |
| Cu | | case #2 | | | | | | | 1 | | | | |
| Zn | | | | | | | | | | 1 | | | |
| Mo | | | | | | | | | | | 1 | | |
| Cl | | | | | | | | | | | | 1 | |
| N | $\underline{0.803}$ | 0.093 | | 0.028 | 0.030 | | | | | | | 0.037 | |
| K | 1 | $\underline{0.116}$ | 0.097 | 0.035 | 0.038 | | | | | | | 0.047 | |
| P | | 1 | 0.830 | 0.297 | $\underline{0.326}$ | | | 9.792 | | 46.340 | | $\underline{0.396}$ | |
| Ca | | | 1 | $\underline{0.362}$ | $\underline{0.398}$ | | | $\underline{11.773}$ | | 59.285 | | $\underline{0.484}$ | |
| Mg | | | | 1 | 1.112 | | | $\underline{32.455}$ | | 163.85 | | $\underline{1.337}$ | |
| S | | | | | 1 | | | $\underline{29.901}$ | | 143.78 | | $\underline{1.213}$ | |
| Fe | | | | | | 1 | | | | | | | 0.004 |
| Mn | | | | | | | 1 | | | | | | |
| B | | | | | | | | 1 | | 5.041 | | 0.041 | |
| Cu | | case#3 | | | | | | | 1 | | | | |
| Zn | | | | | | | | | | 1 | | 0.008 | |
| Mo | | | | | | | | | | | 1 | | |
| Cl | | | | | | | | | | | | 1 | |
| N | $\underline{0.836}$ | $\underline{0.090}$ | | 0.028 | $\underline{0.027}$ | | | | $\underline{0.097}$ | 2.275 | | $\underline{0.042}$ | |
| K | 1 | $\underline{0.107}$ | 0.099 | 0.034 | $\underline{0.032}$ | | | | $\underline{0.116}$ | 2.724 | | $\underline{0.050}$ | |
| P | | 1 | 0.920 | 0.309 | $\underline{0.297}$ | | | 10.551 | $\underline{1.093}$ | $\underline{25.309}$ | 0.151 | $\underline{0.460}$ | |
| Ca | | | 1 | $\underline{0.336}$ | 0.327 | | | $\underline{11.444}$ | 1.192 | 28.704 | 0.172 | 0.510 | |
| Mg | | | | 1 | 0.966 | | | $\underline{33.745}$ | 3.560 | 85.694 | | $\underline{1.495}$ | |
| S | | | | | 1 | | | 35.187 | $\underline{3.676}$ | 84.891 | 0.508 | $\underline{1.549}$ | |
| Fe | | | | | | 1 | | | | | | | |
| Mn | | | | | | | 1 | | | | | | 0.016 |
| B | | | | | | | | 1 | 0.103 | 2.471 | | 0.045 | |
| Cu | | case #4 | | | | | | | 1 | $\underline{23.370}$ | 0.138 | $\underline{0.421}$ | |
| Zn | | | | | | | | | | 1 | $\underline{0.006}$ | 0.018 | |
| Mo | | | | | | | | | | | 1 | | |
| Cl | | | | | | | | | | | | 1 | |

was 2702 mg·kg$^{-1}$, which is more than the maximum permissible content in the Netherlands of 2500 mg·kg$^{-1}$. The $NO_3$ content fluctuated in time, with the highest content halfway during the growth period. Thus, in this experiment growing lettuce on NFT without interference yields too high $NO_3$ contents. Moreover, these results do not show any trend of $NO_3$ content per unit fresh shoot mass, so that there is no way to predict the final $NO_3$ content based on intermediate sampling. An irregular pattern of $NO_3$ content as a function of time for lettuce grown under greenhouse conditions was also reported by Hansen (1976), for different times of the year, except during a winter period. Ways to lower the $NO_3$ content have been described by van der Boon et al. (1990) and Steingröver et al. (1993), viz. increasing the $NH_4$:$NO_3$ ratio in the nutrient solution or adding extra Cl in combination with $NH_4$ to the nutrient solution.

# 3.10 Water use

The total amount of water added to the NFT system was 285.14 l and the total amount of solution removed for laboratory analysis was 43 l, so that indeed it was necessary to compensate the sampling losses in order to obtain water use. The total amount of water uptake used for crop growth was 10.65 l, i.e. 4.4% of total water uptake. During the growth period two major electrical failures caused a leakage of nutrient solution (as mentioned above). During the second period no information on water use by the crop was available. It was decided to compute the transpiration for days 34 and 35 based on average transpiration per unit radiation as observed for lettuce in experiment 5132: 5.8 l·cm²·kJ$^{-1}$. Based on measured radiation during these days, the transpiration for days 34 and 35 then becomes 14.7 and 14.0 l, respectively. The average transpiration per unit increase in radiation was determined: 4.1 l·cm²·kJ$^{-1}$. This is much lower than observed in experiment 5132. Iteratively, the transpiration for the two missing days was adapted such that it corresponded to the computed average transpiration per unit increase in radiation. In this way the transpiration in experiment 6705 was 3.8 l per unit increase in radiation (l·cm²·kJ$^{-1}$) (with both variables expressed per plant). This is smaller than observed in experiment 5132, where it was 5.8 l·cm²·kJ$^{-1}$. The weekly transpiration per plant is presented in Table 3.7. The average dry mass production per unit water transpired per plant in experiment 6705 was 2.86 g·l$^{-1}$, which is about 8% smaller than the value obtained in 5132: 3.1 g·l$^{-1}$. Finally, the average dry mass production per unit increase in radiation was 10.9 g·cm²·kJ$^{-1}$, which is

Table 3.6 $NO_3$ content of shoot and root, percentage N as $NO_3$ of total N present in shoot and root, and $NO_3$ content of shoot and root per unit fresh mass as a function of time.

| Time (week) | $NO_3$ shoot (%) | $NO_3$ root (%) | N as $NO_3$ shoot (%) | N as $NO_3$ root (%) | $NO_3$ shoot (mg·kg$^{-1}$) | $NO_3$ root (mg·kg$^{-1}$) |
|---|---|---|---|---|---|---|
| 0 | | | | | | |
| 1 | 3.13 | | 12.85 | | 2236 | |
| 2 | 4.97 | | 19.45 | | 3206 | |
| 4 | 6.56 | 6.07 | 27.69 | 28.98 | 3238 | 3601 |
| 5 | 4.54 | 4.20 | 25.89 | 22.91 | 2525 | 2875 |
| 6 | 4.99 | 4.72 | 29.34 | 24.61 | 2738 | 2953 |
| 7 | 4.91 | 5.27 | 30.88 | 28.61 | 2702 | 3273 |

Table 3.7 Cumulative weekly transpiration per plant, *T* (l), corrected for water removal by sampling and including estimated transpiration for days 34 and 35.

| | Week | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 4 | 5 | 6 | 7 |
| *T* | 0.155 | 0.324 | 0.972 | 2.635 | 5.005 | 7.374 |

smaller than obtained in experiment 5132: 18.0 $g \cdot cm^2 \cdot kJ^{-1}$. Linear relationships between dry matter production, transpiration and radiation were given. A slightly better description was obtained using a logistic function, except for the relationship between dry matter production and transpiration. But since in all cases $R^2$ was larger than 98% for linear or logistic relationships, it was decided to present linear relationships.

It is stressed here that the data for experiment 5132 were not adjusted for amount of water lost due to sampling and amount of water held by the crop. Since less frequent samplings were carried out the effect of disregarding water loss due to sampling will be small. This causes a small overestimation of the transpiration. Disregarding increase in water content of the crop also causes an overestimation of the transpiration. There were also unknown amounts of water lost at leakages which also causes an overestimation of the transpiration. Thus the dry matter production per liter water transpired would have been higher in experiment 5132, and the amount of water transpired per unit increase of radiation would have been smaller.

The amount of water held by the roots in the gullies was not taken into account when computing the daily transpiration (see section 2.2 'Water supply and system volume'). The difference between final and initial system volume was 8.4 l. This is 3.4% of the total amount transpired by the system. This small amount will not have a large effect on the miscalculated, i.e. overestimated, transpiration.

## 3.11 Automatic pH control

The pH electrode in the automatic pH control system was regularly cleaned and calibrated (Appendix 8). According to the constant calibration line in time the pH electrode performance can be qualified as good. The time course of pH is presented in Figure 3.9. Although measure-

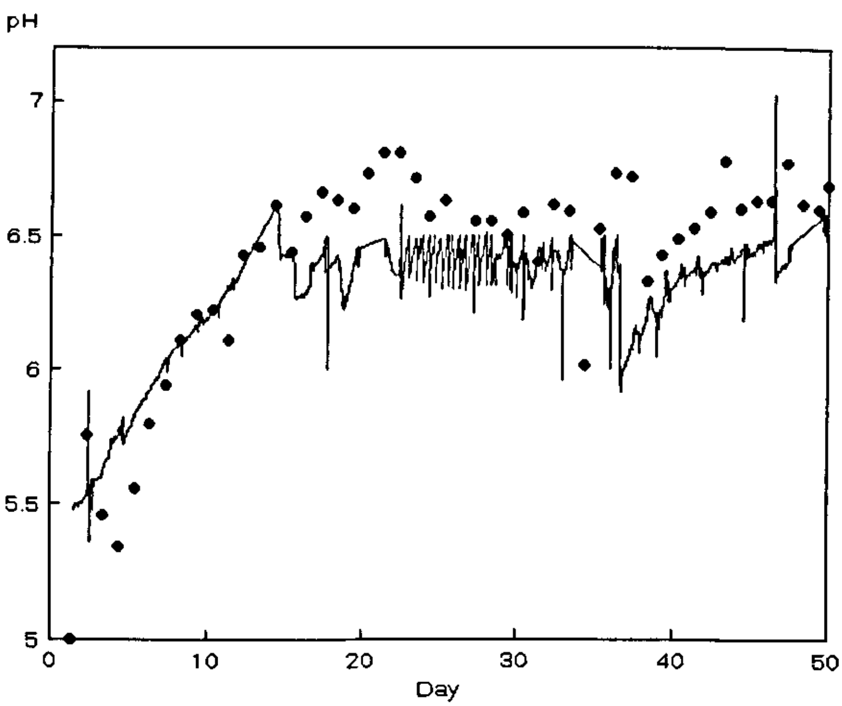



Figure 3.9 The pH of the nutrient solution in experiment 6705 as a function of time (solid line). Measurement interval was 15 min. The daily laboratory pH measurements are given as solid dots.

ments were carried out every 5 minutes, only 15 min time interval results are shown in Figure 3.9. The laboratory measurements of pH to check the behavior of the automatic pH control system follow the same pattern, and were no reason to manually interfere in the control system. The pH control system was able to keep the pH between 6.0 and 6.5: the average pH was 6.27 (cv 3.9%). The rising and falling pattern, e.g. at days 22 to 30, shows that regular pH adjustments were carried out, in this period 2 to 3 times a day. The sharp drop in pH at day 37 is caused by an extra dosage of $KH_2PO_4$ to increase the low concentrations of K and P. The addition of P apparently caused pH buffering resulting in a lower pH. At day 47 a low pH of 4.59 was measured which caused the system to add 0.6 l 0.1 M KOH, the daily maximum allowed addition. This resulted in a increase in pH of the nutrient solution up to pH = 7.03 (Figure 3.9). Next, the control system added 0.6 l 0.1 M $HNO_3$ resulting in bringing back the pH to the range 6.0 to 6.5. Some other mis-measurements of pH can be seen in Figure 3.9, but these did not cause pH adjustments.

It is obvious in Figure 3.9 that the pH of the nutrient solution after a acid dosage never reached the expected value of 6.0, but always lowered to an average value of 6.3. There are several aspects to be considered, viz.:
- error in calculation procedure: wrong interpolation in titration curve, wrong system volume,
- wrong concentration of $HNO_3$ solution,
- error in dosage pump, or
- error in titration curve.

At the beginning of the experiment the original solution was used to determine the titration curve. These data are then used in a computer program to interpolate between the measured and desired pH values. From this the desired amount of $HNO_3$ per liter nutrient solution can be obtained. This procedure was checked, and judged as correct. The amount of $HNO_3$ per liter nutrient solution to be added was 94.1 ml in case the pH has to be lowered from 6.5 to 6.0. Due to discrete dosage of the dosage pumps (5 ml per pulse), 95 ml was added each time. This is slightly more than necessary, so that this is not the cause for the observed pH change. However, the computer program used a preset system volume of 150 l. The exact system volume is unknown, but was in the range 168 to 176 l. This then causes the pH to drop only to approximately 6.1, thus not explaining the observed drop in pH. A few weeks after the end of the experiment the pH control system was checked. The concentration of the $HNO_3$ solution was measured and it was correct at 0.1 M. The pH of a new nutrient solution was manually raised and the control system was used to calculate the amounts to be dosed, based on a newly determined titration curve, and to carry out the dosage. The true amount dosed was measured by weighing the bottle with $HNO_3$ solution. The computed and weighed amounts were equal. However, during this testing it appeared that every now and then the pulse pump hampered, so that not all the pulses were carried out. It is unknown whether this also occurred during experiment 6705. It may well be that due to the long time between the end of experiment 6705 and the test-experiment some dirt deposited on the pump mechanism. Based on the original titration curve this means that each time approximately 47.1 ml $HNO_3$ was added, i.e. always the pump added half the amount desired, which is unlikely. Finally, the titration curve may be in error. Due to the change in composition of the nutrient solution, especially for the buffering element P, the actual composition differs from time to time and is not equal to the composition of the original solution. Therefore, the titration curves of the original solution before and just after filling the NFT system were determined. It was planned to determine also the titration curve of the nutrient solution after the test, but, unfortunately, this sample got lost. It can be seen that a slight dilution of the original nutrient solution of approximately 8 to 10%, causes a different titration curve (Figure 3.10). That is, the more diluted the solution the steeper the titration curve, thus the more acid is needed to achieve a certain pH drop. During the growth period the P concentration, as for all elements, was lower than the concentration in the original nutrient solution. It is especially the P concentration that determines the pH buffer capacity of the nutrient solution. Thus the lower the P concentration the steeper the titration curve, so that the amount of $HNO_3$ to be added was always underestimated. This is most likely the main cause of the observed small pH drop after an acid dosage.

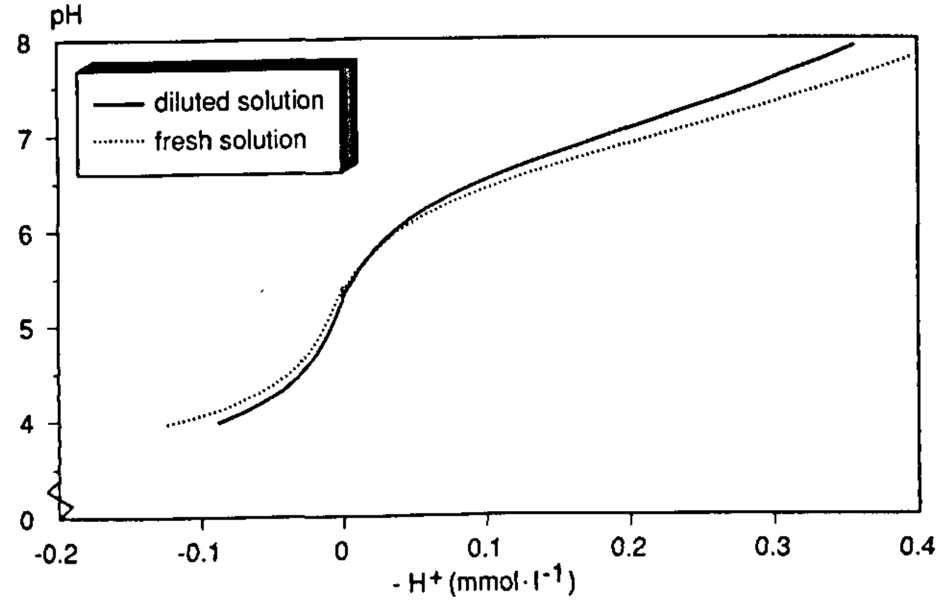



Figure 3.10 The pH titration curves of a nutrient solution and a 8 to 10% diluted nutrient solution.

## 3.12 EC and $NO_3$ course in time

The measured EC is depicted in Figure 3.11. The manual dosages resulted in sharp increases in EC. Uptake of nutrients by the crop then resulted in a slow decrease in EC in time. On average the EC remained constant between days 8 and 33; for all days the average EC was 0.84 $mS{\cdot}cm^{-1}$ (cv 8.9%). The extra dosage of $KH_2PO_4$ at day 37 caused in a large increase in EC. After day 44 the average EC increases in time, which is caused by a decrease in uptake by the crop, which was not accounted for in the dosage program. In general, the elaborative manual dosage procedure was able to keep the concentration of the nutrient solution at a constant level. This can also be seen in the $NO_3$ concentrations as a function of time measured daily (Figure 3.12). For completeness it is mentioned that these samples were taken at 08:00 h each day and that dosages, if necessary, were carried out at 16:00 h. The average $NO_3$ concentration was 4.5 $mmol{\cdot}l^{-1}$ (cv 6.5%). There was a trend of decreasing concentration in time between days 7 and 35, which is due to the increasing uptake rate. After day 35 the concentration increased due to decreasing uptake rate. Moreover, the dosage program used a constant system volume which was too low, thus the $NO_3$ level was always lower than its set point of 5.0 $mmol{\cdot}l^{-1}$. And, due to increase in root mat volume, the volume of solution increased step-wise in time, yielding lower concentrations.

## 3.13 Ion selective electrode behavior

The ion selective electrodes (ISE) were regularly cleaned and calibrated (Appendix 8). Cleaning of the electrodes was suggested by Heinen and Harmanny (1992), and was also necessary in this experiment, but they did not become too filthy between the successive calibrations. The calibration lines of the $NO_3$ ISE's were constant in time, but that of the K ISE fluctuated in time. Therefore, the behavior of the $NO_3$ ISE's may be judged as good, and some caution is needed for the K ISE. Measurements with the ISE's were started on day 18 (Figure 3.13). At all times the first $NO_3$ ISE yielded higher concentrations than the second one: the average concentrations were 4.20 (cv 7.1%) and 3.54 (cv 10.8%), respectively. The K ISE yielded sometimes too high K concentrations (Figure 3.13): the average K concentration was 4.39 (cv 26.2%). The temperature

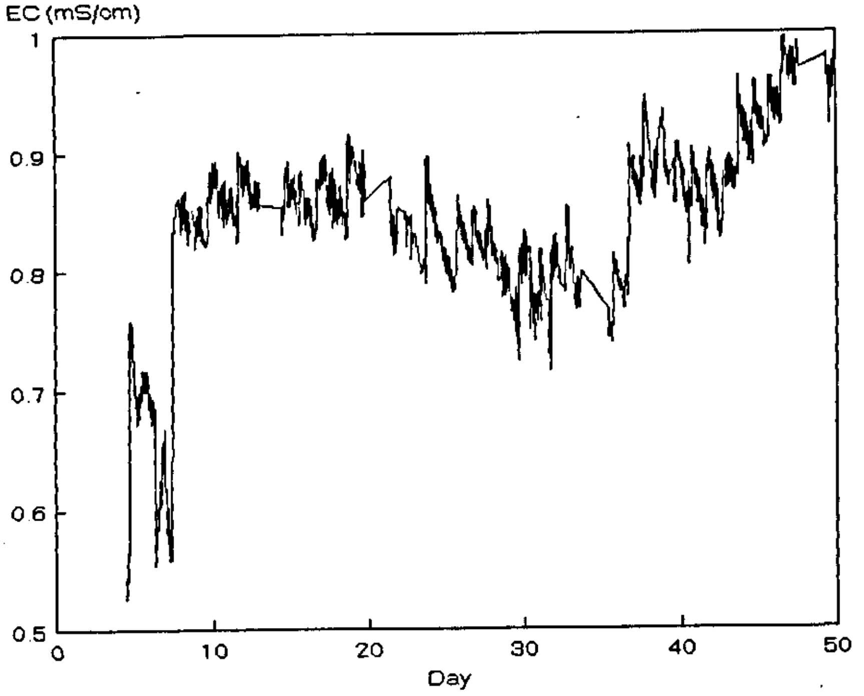



Figure 3.11 The EC of the nutrient solution in experiment 6705 as a function of time (solid line). Measurement interval: 15 min.

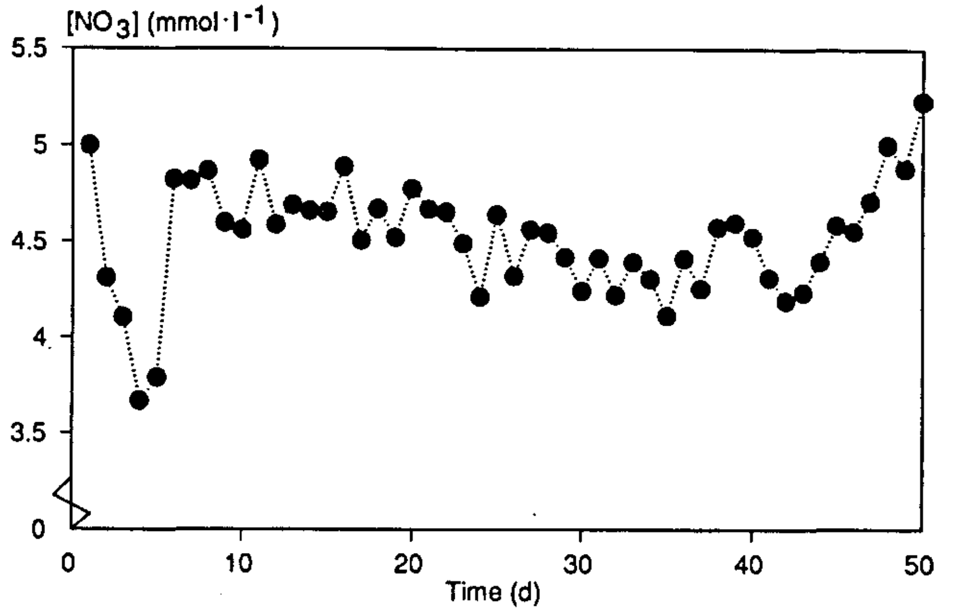
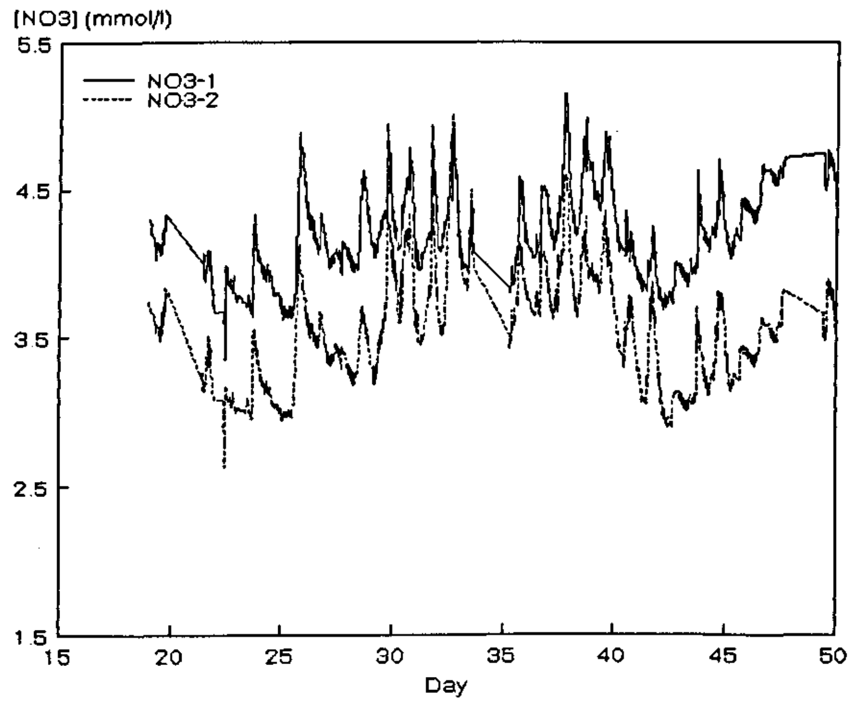



Figure 3.12 The $NO_3$ concentration of the samples used for dosage computations as a function of time.



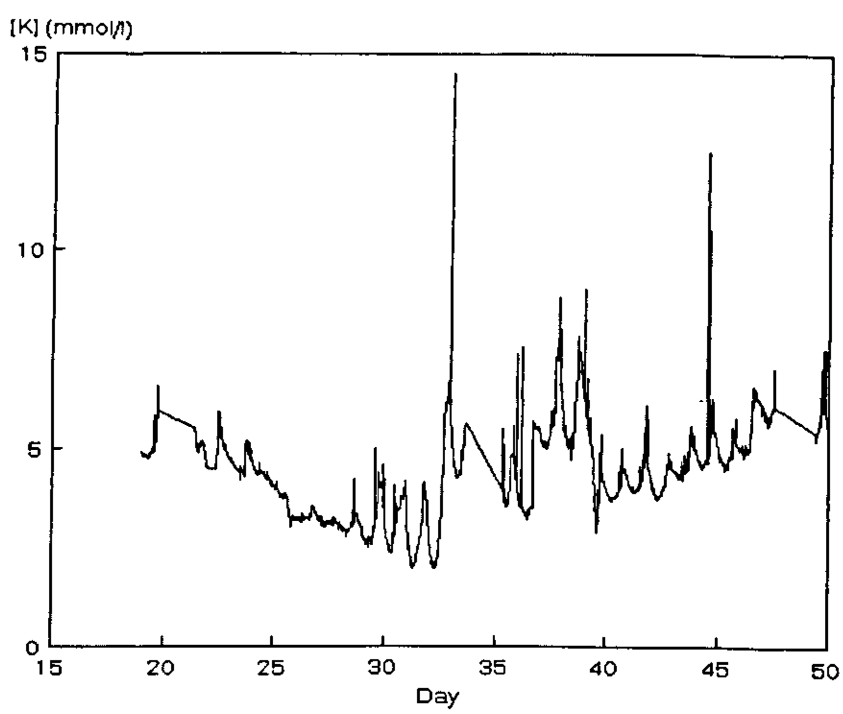




Figure 3.13 The $NO_3$ concentration measured by two ion selective electrodes (a) and the K concentration measured by an ion selective electrode (b) as a function of time. Measurement interval: 15 min.

in the measurement device was kept constant at 20 ± 1 °C. This temperature control worked well, except for days 33 to 39 (Figure 3.14): the average temperature was 19.8 °C (cv 6.4%). A constant temperature is needed for a good behavior of the ISE's (Heinen and Harmanny, 1992), but also for the pH and EC electrodes.

Especially for the $NO_3$ ISE's, the measured concentrations followed the same pattern as the EC measurements: sharp increase after a dosage, and slow decrease in time due to uptake. Thus with the regular cleaning and calibrations the $NO_3$ ISE's seem to function well, but this is too elaborative for practical use in commercial growth systems.

It is possible to determine the loss from nutrient solution using ISE measured concentrations. In that case the concentration just before harvest times is used in Eq. (8). The same values for $D$, $D^+$ and $S$ as in the regular $L$ computations were used. This was done for both $NO_3$ ISE's, the K ISE and also for the daily measured $NO_3$ concentrations (Table 3.8). On average loss based on the daily measured $NO_3$ concentration and based on the $NO_3$ ISE's yielded comparable loss data as the regular method. However, the loss based on the K ISE differed from the loss obtained through the regular method: sometimes larger and sometimes smaller. The cumulative loss of $NO_3$ in the last four weeks in the four cases was the same, as was also the case for K. Thus, under the given circumstances the weekly loss based on $NO_3$ ISE measurements seems possible, but this is not the case with the K ISE.

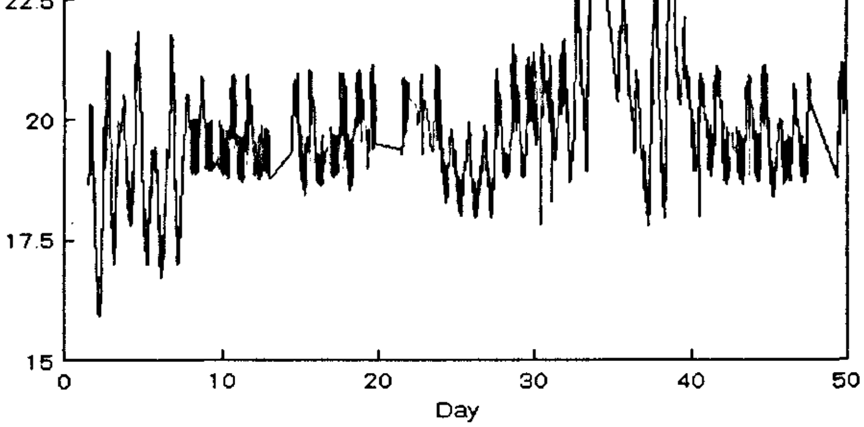



Figure 3.14 The temperature of the measurement cell with the ISE's, and pH and EC electrodes as a function of time. Measurement interval: 15 min.

Table 3.8. Computed loss according to Eq. (8) based on regular samples, daily $NO_3$ samples, two $NO_3$ and one K ion-selective electrodes (ISE) ($mmol{\cdot}week^{-1}$).

| Week | $NO_3$ regular | $NO_3$ daily | $NO_3$-1 ISE | $NO_3$-2 ISE | K regular | K ISE |
|---|---|---|---|---|---|---|
| 1 | 91.47 | | | | 76.58 | |
| 2 | 49.28 | 92.45 | | | 36.72 | |
| 3 | 236.40 | 250.85 | | | 166.84 | |
| 4 | 562.68 | 545.88 | 534.12 | 529.08 | 373.79 | 698.21 |
| 5 | 512.01 | 531.16 | 555.18 | 482.94 | 464.46 | 144.78 |
| 6 | 496.79 | 489.56 | 474.78 | 553.74 | 390.08 | 535.23 |
| 7 | 235.71 | 199.43 | 199.26 | 247.98 | 186.05 | 43.69 |

# 4. Conclusions

In 1987 a project entitled "Control of nutrient supply to plants in artificial horticultural substrates" was started at the DLO Institute for Soil Fertility Research (IB-DLO). The goal was to study uptake patterns or to steer uptake of crops grown on NFT with controlled composition of the nutrient solution. A NFT system was available and a measuring and control system was developed based on commercially available ion-selective electrodes. Unfortunately, the measuring and control system did not work properly, so that much time was spent to improve its functioning (Heinen, 1990a; 1992; Heinen and Harmanny, 1992). This did not lead to a reliable system. Thus, experiments were carried out with manual control of the composition of the nutrient solution. The results of the first experiment were discussed by Heinen et al. (1990; 1991), and the results of the second experiment were discussed and compared with those of the first experiment in this report. In both experiments only uptake patterns were studied, without trying to influence uptake.

NFT systems are good systems to study uptake patterns. Due to their small buffer capacity changes in nutrient concentration of the nutrient solution can be observed over short periods. Moreover, this small buffer capacity implies that steering of the uptake through changes in the composition of the nutrient solution is possible. However, the disadvantage of a low buffer capacity is the vulnerability to electrical failures and following leakages. Experience in this report indicates that such leakages cause extra work in determining loss data of nutrient from the nutrient solution, and in determining the transpiration.

With the current NFT system, with its measurement and control device, it was possible to control the pH of the nutrient solution, and to determine the transpiration using the volume of water added to control the water level in the supply tank. The pH was kept in a small range of 6.3 to 6.5. When a narrower range is desired it is better not to use the pH control system based on titration curves. A better control system is a so-called PID controller: in case the pH rises acid is added, if it lowers less or no acid is given, or when it keeps on rising more acid is given etc. As suggested by Heinen and Harmanny (1992), it seems possible to measure the $NO_3$ content using membrane ion-selective electrodes (ISE), in case they are cleaned and calibrated every week. This was not the case for the glass K ISE.

In both experiments uptake of the crop was determined in two ways: by plant analysis and analysis of the nutrient solution. Both mass balances ideally should yield the same uptake patterns. However, in both experiments the loss from the nutrient solution exceeded the uptake determined by the crop. In the second experiment some uncertain factors of the first experiment were eliminated. This resulted in a smaller difference between loss and uptake. However, it is reasonable to expect that loss will always be larger than uptake (e.g. Heinen et al., 1991; Willumsen, 1980; 1984) due to precipitation, immobilization by microorganisms, organic matter and root exudates, denitrification, and possible system leaks. Accumulation of root exudates and dead organic matter, i.e. dead roots, in various parts of the system must be considered as well. Nutrients may form complexes with this material and thus are lost from the nutrient solution. In case the mass balance of sums of anions and cations is used the loss of $H^+$ from the nutrient solution has to be incorporated in both the balances of uptake and loss. When less cations than anions are obtained, this can be attributed to the content of micronutrients, which will be present mainly as cations.

In case detailed information on plant uptake and transpiration is desired, the loss of water and nutrients due to sampling of the nutrient solution is an extra element to be considered. Especially, when sampling is regular and the system volume is small. Water uptake is split into two parts: increase in water content of the crop and transpiration. In this case it is assumed that water retention or release due to hydration or dehydration does not occur. This is only of importance for short-term, say on a minute basis, water uptake studies. Moreover, when leakages in the system occur, this will also cause extra losses, which are harder to account for. Leakage causes a larger loss of water and nutrients than is really taken up by the crop.

Due to the increase of root mass in the NFT gullies more and more nutrient solution will be held by the root mat. This causes a gradual decrease in water level of the supply tank. With an automatic water level control system, this will cause a dilution of the solution: both transpiration and uptake will be overestimated. In case some plants are harvested at regular time intervals this will cause an increase in water level of the supply tank, which results in an underestimation of transpiration during that day. This increase is due to the fact that part of the root mat is removed from the gullies, and thus water is released causing an increase in water level of the supply tank.

The goal of the experiment described in this report was to repeat an earlier experiment described by Heinen et al. (1990, 1991). In short, the following results were obtained. In both experiments growth and nutrient uptake were well described by a logistic model. S-shaped dry matter production and nutrient uptake was also observed for lettuce grown in soils (Slangen et al., 1987). Growth in experiments 6705 and 5132 were comparable. In both experiments relative cumulative uptake of N, P, K, S, Cl, B, and Zn, and to a lesser extent those of Ca and Mg followed the same time course as relative growth, i.e. the contents of these elements remained constant in time. This implies that constant uptake ratios for these nutrients can be expected. This was indeed the case, although not for all combinations. The loss from nutrient solution exceeded the increase of nutrients in the plants; the difference in experiment 6705, however, was smaller than in experiment 5132. This can be ascribed to the absence of peat in the system during the second experiment, and a more detailed data analysis. In experiment 6705 the relationships between growth and time, growth and radiation, and transpiration and radiation were best described by a logistic function, but not the relationship between growth and transpiration, for which a linear function was observed. No explanation for this aspect can be given. The goodness of fit parameter R2 for linear and logistic relationships for growth and radiation, and transpiration and radiation differed only slightly, and, therefore, it was decided to present only linear relationships between growth, transpiration and radiation. The average dry mass production per liter transpiration was 2.86 $g{\cdot}l^{-1}$ in 6705 and 3.1 $g{\cdot}l^{-1}$ in 5132. The transpiration per unit increase in radiation was 3.8 $l{\cdot}cm^2{\cdot}kJ^{-1}$ in 6705 and 5.8 $l{\cdot}cm^2{\cdot}kJ^{-1}$ in 5132. In 5132 only Cl and B showed uptake which could be related to uptake of one or more macronutrients, in 6705 this was true for B, Cu, Zn, Cl, and Na. In both experiments there were no constant uptake ratios for Fe, Mn and Mo with respect to macronutrients. For detailed uptake of Fe, Mn and/or Mo these elements should measured separately.

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# Appendices

Appendix 1: Fortran source code listing of program DOSAGE.FOR, and input file DOSAGE.RAT.

```
      PROGRAM DOSAGE

*************************************************************************
* Compute the amounts to be dosed of each of the stock solutions based *
* on input of NO3-need. De ratio factors for P/N, S/N, Cl/N, K/N,      *
* Ca/N, Mg/N are stored in datafile DOSAGE.RAT, and can be changed as  *
* an option.                                                            *
* The uptake ratios are based upon total NO3 uptake. When in the mean- *
* time other sources of NO3 have been used (e.g. HNO3 for pH regula-   *
* tion) this amount has to be given too.                                *
*                                                                       *
* Marius Heinen, May 1991.                                              *
*************************************************************************
      REAL RATIO(6),NO3(3),DOSE(6),STOCK(6),PUMP,VOL,ION(6),IONC(6),NO3C
      CHARACTER FNAME*10,DATUM*10
* concentrations of stock solutions (see subroutine CALDOS)
      DATA (STOCK(I),I=1,6)/0.1,0.247,0.595,0.149,0.25,0.857/
*
      CALL CLS

* Obtain date and create outputfile FNAME
      CALL DATE(DATUM,FNAME)

* Ask which option of the program to use:
* 1 - Calculate dosages
* 2 - Change parameters
* 3 - Stop
11    CALL OPTION(N)

* Stop
      IF(N.EQ.3) GOTO 10

* Change parameters
      IF(N.EQ.2) THEN
          CALL CHANGE
          GOTO 11
      ENDIF

* Read RATIO and NO3 using READIN
* Calculate dosages using CALDOS
      CALL READIN(RATIO,VOL,PUMP,NO3)
      CALL CALDOS(RATIO,NO3,STOCK,PUMP,VOL,DOSE,ION,IONC,NO3C)

* Write dosages to screen and outputfile FNAME using WRDOS
      CALL WRDOS(DATUM,FNAME,VOL,STOCK,DOSE,NO3,ION,IONC,NO3C)
      GOTO 11
10    CALL CLS

* End of program DOSAGE
      STOP
      END
*
```

```
      SUBROUTINE OPTION(N)
************************************************************************
* Ask user which OPTION of the program to use. 1: Calculate dosages;  *
* 2: Change parameters; 3 - Stop. Accept only entries 1, 2 or 3.       *
************************************************************************
      INTEGER*2 KEY,ASYNRD,EXTCOD
      CHARACTER IN*1

      CALL CLS
      WRITE(*,1)
      WRITE(*,2)
      WRITE(*,3)
      WRITE(*,4)

* Repeat until input equals 1, 2 or 3; store input as N
10    CONTINUE
          KEY = ASYNRD(EXTCOD)
          IF(KEY.GE.49.AND.KEY.LE.51) THEN
              IN = CHAR(KEY)
              READ(IN,'(I1)') N
              GOTO 99
          ENDIF
      GOTO 10

* Formats
1     FORMAT(4(/),10X,' 1 - Calculate dosages')
2     FORMAT(//,10X,' 2 - Change parameters')
3     FORMAT(//,10X,' 3 - Stop')
4     FORMAT(//,15X,' Enter your choice (1,2,3) : '\)

* End of subroutine OPTION
99    RETURN
      END
*
      SUBROUTINE CHANGE
************************************************************************
* Ask what is to be changed: 1 - uptake ratios R, or 2 - systemvolume  *
* (V) and dosagevolume (P). Accept new values. Show new values and let *
* user confirm them. If not redo the procedure.                        *
************************************************************************
      INTEGER*2 KEY,ASYNRD,EXTCOD
      REAL R(6),V,P
      CHARACTER IN*1

* Read old values first
      CALL READR(R,V,P)

* Ask what is to be changed:
* 1 - uptake ratios R
* 2 - systemvolume and/or dosagevolume
      CALL CLS
      WRITE(*,100)
      WRITE(*,101)
      WRITE(*,102)
```

```
* Repeat until input equals 1 or 2; store input as N
900   CONTINUE
          KEY = ASYNRD(EXTCOD)
          IF(KEY.GE.49.AND.KEY.LE.50) THEN
              IN = CHAR(KEY)
              READ(IN,'(I1)') N
              GOTO 901
          ENDIF
      GOTO 900

* Accept new values for array R entry by entry
901   IF(N.EQ.1) THEN
11        CALL CLS
          WRITE(*,1)
          READ(*,*) R(1)
          WRITE(*,2)
          READ(*,*) R(2)
          WRITE(*,3)
          READ(*,*) R(3)
          WRITE(*,4)
          READ(*,*) R(4)
          WRITE(*,5)
          READ(*,*) R(5)
          WRITE(*,6)
          READ(*,*) R(6)

* Show new values and ask user to confirm them, if not redo the procedure
          CALL CLS
          WRITE(*,7) (R(I), I=1,6)
          WRITE(*,8)
910       CONTINUE
              KEY = ASYNRD(EXTCOD)
              IF(KEY.EQ.78.OR.KEY.EQ.110) THEN
                  GOTO 11
              ELSE
                  IF(KEY.GT.0) GOTO 911
              ENDIF
          GOTO 910
911       CALL WRITR(R,V,P)
      ENDIF

* Accept new values for V and P
      IF(N.EQ.2) THEN
12        CALL CLS
          WRITE(*,200)
          READ(*,*) V
          WRITE(*,201)
          READ(*,*) P

* Show new values and ask user to confirm them, if not redo the procedure
          CALL CLS
          WRITE(*,202) V,P
          WRITE(*,8)
920       CONTINUE
              KEY = ASYNRD(EXTCOD)
              IF(KEY.EQ.78.OR.KEY.EQ.110) THEN
```

```
                GOTO 12
             ELSE
                IF(KEY.GT.0) GOTO 921
             ENDIF
          GOTO 920
921       CALL WRITR(R,V,P)
       ENDIF

* Formats
1      FORMAT(' Enter new value for P/N  : '\)
2      FORMAT(' Enter new value for S/N  : '\)
3      FORMAT(' Enter new value for Cl/N : '\)
4      FORMAT(' Enter new value for K/N  : '\)
5      FORMAT(' Enter new value for Ca/N : '\)
6      FORMAT(' Enter new value for Mg/N : '\)
7      FORMAT(' The new values for P/N, S/N, Cl/N, K/N, Ca/N, and Mg/N'
      &,' are respectively:',//,6F8.3)
8      FORMAT(//,' Are these values correct (Y/N)? : '\)
100    FORMAT(4(/),10X,' 1 - Change uptake ratio''s')
101    FORMAT(/,10X,' 2 - Change systemvolume and dosagevolume')
102    FORMAT(//,15X,' Enter your choice (1,2) : '\)
200    FORMAT(' Enter new value for systemvolume VOL (l)    : '\)
201    FORMAT(' Enter new value for dosagevolume PUMP (ml) : '\)
202    FORMAT(' The new values for systemvolume (VOL, l) and ',/,
      &' dosagevolume (PUMP, ml) are, respectively:',//2F10.3)

* End of procedure CHANGE
       RETURN
       END
*
       SUBROUTINE READIN(R,V,P,N)
*************************************************************************
* Read V, P and array R from file DOSAGE.RAT using subroutine READR.    *
* Accept real-N from screen.                                            *
*************************************************************************
       REAL R(6),N(3),V,P

* Read R using subroutine READR
       CALL READR(R,V,P)

* Accept N from screen
       CALL CLS
       WRITE(*,1)
       READ(*,*) N(1)
       WRITE(*,2)
       READ(*,*) N(2)
       N(3) = N(1) + N(2)

* Formats
1      FORMAT(' Enter amount of NO3 (mmol/l) to be applied based on',
      &' chemical analysis : '\)
2      FORMAT(' Enter amount of NO3 (mmol/l) already given as HNO3 ',
      &'                    : '\)
```

```
* End of subroutine READIN
      RETURN
      END
*

      SUBROUTINE READR(R,V,P)
***********************************************************************
* Read V, P and array R from file DOSAGE.RAT.                         *
* Use read modules of TTUTIL library by C. Rappoldt and D.W.G. van    *
* Kraalingen (Reference manual of the FORTRAN utility library TTUTIL  *
* with applications, DLO-Centre for Agrobiological Research and       *
* Wageningen Agricultural University Department of Theoretical        *
* Production Ecology, Wageningen, 1990, 122 pp.).                     *
***********************************************************************
      REAL R(6),V,P
      INTEGER IR

      CALL RDINIT(19,0,'DOSAGE.RAT')
      CALL RDSREA('VOL',V)
      CALL RDSREA('DOSVOL',P)
      CALL RDAREA('RATIOS',R,6,IR)

* End of subroutine READR
      CLOSE(UNIT=20)
      RETURN
      END
*
      SUBROUTINE WRITR(R,V,P)
***********************************************************************
* Write array R to file DOSAGE.RAT. Overwrite existing file.          *
***********************************************************************
      REAL R(6)

      OPEN(UNIT=20,FILE='DOSAGE.RAT',STATUS='OLD')
      WRITE(20,1) V
      WRITE(20,2) P
      WRITE(20,3) (R(J), J=1,6)

* Formats
1     FORMAT(' VOL    = ',F8.3,'         ! volume of system')
2     FORMAT(' DOSVOL = ',F8.3,'         ! minimum amount that can be',
     &' applied')
3     FORMAT(' RATIOS = ',F8.3,',        ! uptake ratio of P/N',/,
     &10X,F8.3,',        ! uptake ratio of S/N',/,
     &10X,F8.3,',        ! uptake ratio of Cl/N',/,
     &10X,F8.3,',        ! uptake ratio of K/N',/,
     &10X,F8.3,',        ! uptake ratio of Ca/N',/,
     &10X,F8.3,'         ! uptake ratio of Mg/N')

* End of subroutine WRITR
      CLOSE(UNIT=20)
      RETURN
      END
*
```

```
      SUBROUTINE CALDOS(RATIO,NO3,STOCK,PUMP,VOL,DOSE,ION,IONC,NO3C)
************************************************************************
* Stock solutions; concentrations are defined in DATA statement in     *
* main module.                                                         *
*                                                                      *
* CaCl2       STOCK(1)     0.100  mol/l  ;    P    ION(1)              *
* KH2PO4      STOCK(2)     0.247    "    ;    S    ION(2)              *
* Ca(NO3)2    STOCK(3)     0.595    "    ;    Cl   ION(3)              *
* Mg(NO3)2    STOCK(4)     0.149    "    ;    K    ION(4)              *
* K2SO4       STOCK(5)     0.250    "    ;    Ca   ION(5)              *
* KNO3        STOCK(6)     0.857    "    ;    Mg   ION(6)              *
*                                                                      *
* Dosage scheme:                                                       *
* {salt}: amount (ml) to be dosed to 1 liter solution.                 *
* [ion] : amount of ion to be supplied (mmol/l).                       *
* [salt]: concentration of salt mol/l.                                 *
*                                                                      *
*   {CaCl2}     = [Cl]/[CaCl2]                                         *
*   {KH2PO4}    = [P]/[KH2PO4]                                         *
*   {Ca(NO3)2}  = ([Ca] - [Cl]/2)/[Ca(NO3)2]                           *
*   {Mg(NO3)2}  = [Mg]/[Mg(NO3)2]                                      *
*   {K2SO4}     = [S]/[K2SO4]                                          *
*   KNEW        = [K] - [P] - 2*[S]                                    *
*   NNEW        = [N] - 2*([Ca] - [Mg])                                *
* if KNEW ≤ NNEW then                                                  *
*   {KNO3}      = [KNEW]/[KNO3]                                        *
* else                                                                 *
*   {KNO3}      = [NNEW]/[KNO3]                                        *
* endif                                                                *
*                                                                      *
* NO3    : decrease in no3-concentration, i.e. the amount to be dosed  *
*          (mmol/l)                                                    *
* ION    : decrease in ion-concentratio, related to no3 with ratio     *
*          (mmol/l)                                                    *
* STOCK  : salt-concentrations (MOL/L)                                 *
* DOSE   : amount (ML) to be dosed to system of volume (vol (L)), ex-  *
*          pressed as multiples of dosagevolume (pump (ML))            *
* IONC   : true amounts dosed (MMOL/L) due to discrete dosages         *
* KNEW, NNEW : dummies, in which the amounts to be dosed for N and K   *
*              are stored, corrected for the amounts already given     *
*              through other salts                                     *
*                                                                      *
************************************************************************
      REAL RATIO(6),NO3(3),DOSE(6),STOCK(6),ION(6),IONC(6),KNEW,NNEW
      REAL SALT(6),PUMP,VOL,NO3C

* Initialize ION and DOSE
      DO 10 I=1,6
          ION(I) = RATIO(I) * NO3(3)
          DOSE(I) = 0.0
10    CONTINUE
      VP = VOL/PUMP

*----- Salt CaCL2 to supply Cl
      IF(ION(3).GT.0.) THEN
          SALT(1) = 0.5 * ION(3)/STOCK(1)
```

```
          DOSE(1) = PUMP * NINT(SALT(1) * VP)
          IONC(3) = 2.0 * DOSE(1) * STOCK(1)/VOL
      ENDIF

*----- Salt KH2PO4 to supply PO4
      IF(ION(1).GT.0.) THEN
          SALT(2) = ION(1)/STOCK(2)
          DOSE(2) = PUMP * NINT(SALT(2) * VP)
          IONC(1) = DOSE(2) * STOCK(2)/VOL
      ENDIF

*----- Salt Ca(NO3)2 to supply Ca, corrected for the amount given
*----- through CaCl2
      IF((ION(5) - 0.5 * IONC(3)).GT.0.) THEN
          SALT(3) = (ION(5) - 0.5 * IONC(3))/STOCK(3)
          DOSE(3) = PUMP * NINT(SALT(3) * VP)
          IONC(5) = DOSE(3) * STOCK(3)/VOL + 0.5*IONC(3)
      ENDIF

*----- Salt Mg(NO3)2 to supply Mg
      IF(ION(6).GT.0.) THEN
          SALT(4) = ION(6)/STOCK(4)
          DOSE(4) = PUMP * NINT(SALT(4) * VP)
          IONC(6) = DOSE(4) * STOCK(4)/VOL
      ENDIF

*----- Salt K2SO4 to supply SO4
      IF(ION(2).GT.0.) THEN
          SALT(5) = ION(2)/STOCK(5)
          DOSE(5) = PUMP * NINT(SALT(5) * VP)
          IONC(2) = DOSE(5) * STOCK(5)/VOL
      ENDIF

*----- Salt KNO3 to supply the least demanding of the remaining two
*----- ions K and NO3, corrected for the amounts already given through
*----- the salts Ca(NO3)2, Mg(NO3)2, KH2PO4, K2SO4
      KNEW = ION(4) - IONC(1) - 2. * IONC(2)
      NNEW = NO3(1) - 2. * (IONC(5) + IONC(6)) + IONC(3)
      IF(KNEW.GT.0..AND.NNEW.GT.0.) THEN
          IF(KNEW.LE.NNEW) THEN
              SALT(6) = KNEW/STOCK(6)
              DOSE(6) = PUMP * NINT(SALT(6) * VP)
          ELSE
              SALT(6) = NNEW/STOCK(6)
              DOSE(6) = PUMP * NINT(SALT(6) * VP)
          ENDIF
      ENDIF
      A = DOSE(6) * STOCK(6)/VOL
      NO3C = A + 2. * (IONC(5) + IONC(6)) - IONC(3)
      IONC(4) = A + IONC(1) + 2. * IONC(2)

* End of subroutine CALDOS
      RETURN
      END
*
```

```
      SUBROUTINE WRDOS(DATUM,FNAME,VOL,STOCK,DOSE,NO3,ION,IONC,NO3C)
************************************************************************
* Write the amounts to be dosed (DOSE) to screen and to outputfile     *
* FNAME. Write tables of exact amounts per ion to be dosed (ION), and  *
* the amounts that can will be dosed due to discrete dosages(IONC).    *
************************************************************************
      REAL STOCK(6),DOSE(6),VOL,NO3(3),ION(6),IONC(6),NO3C
      CHARACTER FNAME*10,DATUM*10,TIME*8

* Get time in string TIME
      CALL TIJD(TIME)

* Write to screen
      CALL CLS
      WRITE(*,3) DATUM,TIME
      WRITE(*,1) VOL
      WRITE(*,2) (STOCK(J),DOSE(J), J=1,6)
      WRITE(*,9) FNAME

* Write to outputfile FNAME
      OPEN(UNIT=20,FILE=FNAME,STATUS='UNKNOWN')
      WRITE(20,3) DATUM,TIME
      WRITE(20,1) VOL
      WRITE(20,2) (STOCK(J),DOSE(J), J=1,6)
      WRITE(20,4) NO3(1)
      WRITE(20,14) NO3(2)
      WRITE(20,5)
      WRITE(20,6) (ION(I),IONC(I), I=1,6)
      WRITE(20,7) NO3(3),NO3C,NO3(2)
      CALL TOETS

* Formats
1     FORMAT(4X,' The following amounts of salts (ml) have to be added'
     &,' to the system',/,4X,' of ',F4.0, ' liter.',/)
2     FORMAT(4X,' CaCl2    (',F5.3,' mol/l)   : ',F10.2,'  ml',/,4X,
     &         ' KH2PO4   (',F5.3,' mol/l)   : ',F10.2,'  ml',/,4X,
     &         ' Ca(NO3)2 (',F5.3,' mol/l)   : ',F10.2,'  ml',/,4X,
     &         ' Mg(NO3)2 (',F5.3,' mol/l)   : ',F10.2,'  ml',/,4X,
     &         ' K2SO4    (',F5.3,' mol/l)   : ',F10.2,'  ml',/,4X,
     &         ' KNO3     (',F5.3,' mol/l)   : ',F10.2,'  ml')
3     FORMAT(4X,' Date : ',A10,10X,' Time : ',A8,/)
4     FORMAT(//,4X,' The amount of NO3 to be applied was    : ',F8.3)
14    FORMAT(4X,' The amount of NO3 applied as HNO3 was : ',F8.3)
5     FORMAT(/,4X,' The amounts of other ions to be applied and the',/,
     &4X,' true amounts applied due to discrete dosages:',/)
6     FORMAT(4X,' P  : ',2F10.4,/,4X,' S  : ',2F10.4,/,4X,' Cl : ',
     &2F10.4,/,4X,' K  : ',2F10.4,/,4X,' Ca : ',2F10.4,/,4X,
     &' Mg : ',2F10.4)
7     FORMAT(4X,' N  : ',2F10.4,' + ',F10.4)
9     FORMAT(//,' A complete overview of the calculations is written'
     &,' to outputfile ',A10,'.',8(/))

* End subroutine WRDOS
      CLOSE(UNIT=20)
      RETURN
      END
```

```
*
      SUBROUTINE DATE(DATUM,FNAME)
************************************************************************
* Obtain date using MS-FORTRAN procedure GETDAT. Convert this date to  *
* julian day number (since January 1 of the current year) in three     *
* digits using function JULDAY. Create FileNAME DOSAGE.OUT, where OUT  *
* equals the Julian day number. Create string DATUM as IDAY-IMON-IYR.  *
************************************************************************
      INTEGER*2 IY,IM,ID
      CHARACTER FNAME*10,OUT*3,DATUM*10

* Get date using MS-FORTRAN procedure GETDAT
      CALL GETDAT(IY,IM,ID)
      IYR = IY
      IMON = IM
      IDAY = ID

* Compute Julian day using function JULDAY
      JD = JULDAY(IMON,IDAY,IYR)

* Convert to day number since 31-12 of last year (IYR-1) by substracting
* JULDAY of 31-12-(IYR-1)
      JD = JD - JULDAY(12,31,IYR-1)

* Copy Julian day to character OUT using internal write. OUT consists
* of 3 characters with leading blanks turned to zeros
      IF(JD.LT.10) WRITE(OUT,11) JD
      IF(JD.GE.10.AND.JD.LT.100) WRITE(OUT,12) JD
      IF(JD.GE.100) WRITE(OUT,13) JD

* Create FileNAME as DOSAGE.OUT
      FNAME = 'DOSAGE.'//OUT

* Create string DATUM as IDAY-IMON-IYR using internal write
      IF(IDAY.LT.10.AND.IMON.LT.10) WRITE(DATUM,15) IDAY,IMON,IYR
      IF(IDAY.LT.10.AND.IMON.GE.10) WRITE(DATUM,16) IDAY,IMON,IYR
      IF(IDAY.GE.10.AND.IMON.LT.10) WRITE(DATUM,17) IDAY,IMON,IYR
      IF(IDAY.GE.10.AND.IMON.GE.10) WRITE(DATUM,18) IDAY,IMON,IYR

* Formats
11    FORMAT( '00',I1)
12    FORMAT( '0',I2)
13    FORMAT(I3)
15    FORMAT( '0',I1,'-0',I1,'-',I4)
16    FORMAT( '0',I1,'-',I2,'-',I4)
17    FORMAT(I2,'-0',I1,'-',I4)
18    FORMAT(I2,'-',I2,'-',I4)

* End of subroutine DATE
      RETURN
      END
*
```

```
      FUNCTION JULDAY(MM,ID,IYYY)
************************************************************************
* From Press et al., 1987, Numerical recipes, p. 10.                   *
************************************************************************
      PARAMETER (IGREG=15+31*(10+12*1582))

      IF (IYYY.EQ.0) PAUSE 'There is no Year Zero.'
      IF (IYYY.LT.0) IYYY=IYYY+1
      IF (MM.GT.2) THEN
        JY=IYYY
        JM=MM+1
      ELSE
        JY=IYYY-1
        JM=MM+13
      ENDIF
      JULDAY=INT(365.25*JY)+INT(30.6001*JM)+ID+1720995
      IF (ID+31*(MM+12*IYYY).GE.IGREG) THEN
        JA=INT(0.01*JY)
        JULDAY=JULDAY+2-JA+INT(0.25*JA)
      ENDIF

* End of function JULDAY
      RETURN
      END
*
      SUBROUTINE TIJD(TIME)
************************************************************************
* Get time using MS-FORTRAN subroutine GETTIM, and convert it to a     *
* string TIME.                                                         *
************************************************************************
      INTEGER*2 IHR,IMIN,ISEC,I100TH
      CHARACTER TIME*8

      CALL GETTIM(IHR,IMIN,ISEC,I100TH)
      IF(IHR.LT.10.AND.IMIN.LT.10.AND.ISEC.LT.10)
     &    WRITE(TIME,1) IHR,IMIN,ISEC
      IF(IHR.LT.10.AND.IMIN.LT.10.AND.ISEC.GE.10)
     &    WRITE(TIME,2) IHR,IMIN,ISEC
      IF(IHR.LT.10.AND.IMIN.GE.10.AND.ISEC.LT.10)
     &    WRITE(TIME,3) IHR,IMIN,ISEC
      IF(IHR.LT.10.AND.IMIN.GE.10.AND.ISEC.GE.10)
     &    WRITE(TIME,4) IHR,IMIN,ISEC
      IF(IHR.GE.10.AND.IMIN.LT.10.AND.ISEC.LT.10)
     &    WRITE(TIME,5) IHR,IMIN,ISEC
      IF(IHR.GE.10.AND.IMIN.LT.10.AND.ISEC.GE.10)
     &    WRITE(TIME,6) IHR,IMIN,ISEC
      IF(IHR.GE.10.AND.IMIN.GE.10.AND.ISEC.LT.10)
     &    WRITE(TIME,7) IHR,IMIN,ISEC
      IF(IHR.GE.10.AND.IMIN.GE.10.AND.ISEC.GE.10)
     &    WRITE(TIME,8) IHR,IMIN,ISEC

* Formats
1     FORMAT( '0',I1,':0',I1,':0',I1)
2     FORMAT( '0',I1,':0',I1,':',I2)
3     FORMAT( '0',I1,':',I2,':0',I1)
4     FORMAT( '0',I1,':',I2,':',I2)
```

```
5     FORMAT(I2,':0',I1,':0',I1)
6     FORMAT(I2,':0',I1,':',I2)
7     FORMAT(I2,':',I2,':0',I1)
8     FORMAT(I2,':',I2,':',I2)

* End of subroutine TIJD
      RETURN
      END
*
      SUBROUTINE CLS
      WRITE(*,*) CHAR(27),'[2J'
      RETURN
      END
*
      SUBROUTINE TOETS
      WRITE(*,*)
      PAUSE 'Press <ENTER> to continue.'
      RETURN
      END
```

Input file DOSAGE.RAT

```
 VOL    =  150.000      ! volume of system
 DOSVOL =     .100      ! minimum amount that can be applied
 RATIOS =     .000,     ! uptake ratio of P/N
              .013,     ! uptake ratio of S/N
              .040,     ! uptake ratio of Cl/N
              .757,     ! uptake ratio of K/N
              .053,     ! uptake ratio of Ca/N
              .026      ! uptake ratio of Mg/N
```

Appendix 2: Fortran source code listing of program RATIO.FOR, and input file RATIO.DAT.

```
      PROGRAM RATIO
*
* compute uptake ratios of S/N, P/N, K/N, Ca/N, Mg/N, Cl/N
*
* the uptake per day is computed as the loss from nutrient solution
* per day corrected for the amounts dosed during the time interval
* considered (cf Heinen et al, 1991, Uptake of nutrients by lettuce on NFT
* with controlled composition of the nutrient solution, Netherlands Journal
* of Agricultural Science 39: 197-212)
*
*           C(t-dt) - C(t) + D
*     UPT = ------------------ * VOL
*                   dt
*
* where : UPT    : uptake rate (mmol/d)                    UPTi
*         C      : concentratio (mmol/l)                   Ci
*         VOL    : system voluem = 150 l                   VOL
*         t      : time (d)
*         dt     : time interval between sampling (d)      DELT
*         D      : amount supplied during dt (mmol/l)      Di
*
* the concentrations Ci, the amounts supplied Di and the time intervals
* DELT are read from inputfile RATIO.DAT
* for this purpose routines of the TTUTIL library are used (C. Rappoldt
* and D.W.G. van Kraalingen, 1990, Reference manual of the FORTRAN utility
* library TTUTIL with applications, DLO-Centre for Agrobiological Research
* and Wageningen Agricultural University Department of Theoretical
* Production Ecology, Wageningen, 122 pp).
*
* then the uptake ratios are calculated as
*
*                  UPT ion
*         UPTRAT = -------
*                  UPT N
*
* the uptake ratios UPTRAT are written to outputfile RATIO.OUT
*
* Marius Heinen, Institute for Soil Fertility Research, Haren, June 1991
*
      INTEGER NPAIR,NTIMES,ITIMES
      PARAMETER (NPAIR=7,NTIMES=13)
      REAL CN(NTIMES),CS(NTIMES),CP(NTIMES),CK(NTIMES),CCA(NTIMES),
     &     CMG(NTIMES),CCL(NTIMES),CNA(NTIMES)
      REAL DN(NTIMES-1),DP(NTIMES-1),DK(NTIMES-1),DS(NTIMES-1),
     &     DCA(NTIMES-1),DMG(NTIMES-1),DCL(NTIMES-1),DNA(NTIMES-1)
      REAL UPTRAT(NPAIR,NTIMES),DELT(NTIMES-1)
      REAL UPTN(NTIMES-1),UPTP(NTIMES-1),UPTK(NTIMES-1),UPTS(NTIMES-1),
     &     UPTCA(NTIMES-1),UPTMG(NTIMES-1),UPTCL(NTIMES-1),
     &     UPTNA(NTIMES-1)
      REAL DATA(NTIMES-1),AVER(NPAIR),STDEV(NPAIR)
      CHARACTER FORM*13
      DATA VOL/150.0/
```

```
*     input section ; analyse input file (TTUTIL)
      CALL RDINIT (40, 20, 'RATIO.DAT')
*     get values from file (TTUTIL)
      CALL RDAREA ('CN'    , CN    , NTIMES, ITIMES)
      CALL RDAREA ('CS'    , CS    , NTIMES, I)
      CALL RDAREA ('CP'    , CP    , NTIMES, I)
      CALL RDAREA ('CK'    , CK    , NTIMES, I)
      CALL RDAREA ('CCA'   , CCA   , NTIMES, I)
      CALL RDAREA ('CMG'   , CMG   , NTIMES, I)
      CALL RDAREA ('CCL'   , CCL   , NTIMES, I)
      CALL RDAREA ('CNA'   , CNA   , NTIMES, I)
      CALL RDAREA ('DN'    , DN    , NTIMES-1, I)
      CALL RDAREA ('DP'    , DP    , NTIMES-1, I)
      CALL RDAREA ('DK'    , DK    , NTIMES-1, I)
      CALL RDAREA ('DS'    , DS    , NTIMES-1, I)
      CALL RDAREA ('DCA'   , DCA   , NTIMES-1, I)
      CALL RDAREA ('DMG'   , DMG   , NTIMES-1, I)
      CALL RDAREA ('DCL'   , DCL   , NTIMES-1, I)
      CALL RDAREA ('DNA'   , DNA   , NTIMES-1, I)
      CALL RDAREA ('DELT'  , DELT  , NTIMES-1, I)
*     delete temporary file
      CLOSE (40, STATUS='DELETE')
*     end of input section

      OPEN(UNIT=20,FILE='RATIO.OUT',STATUS='UNKNOWN')
      WRITE (FORM,'(A,I2,A)') '(1X',NPAIR,'F8.3,1X)'
      WRITE (20,1)
      WRITE (20,2)
      WRITE (20,3)

      DO 10 I=2,ITIMES
          UPTN(I-1) = (CN(I-1) - CN(I) + DN(I-1)) * VOL / DELT(I-1)
          UPTP(I-1) = (CP(I-1) - CP(I) + DP(I-1)) * VOL / DELT(I-1)
          UPTK(I-1) = (CK(I-1) - CK(I) + DK(I-1)) * VOL / DELT(I-1)
          UPTS(I-1) = (CS(I-1) - CS(I) + DS(I-1)) * VOL / DELT(I-1)
          UPTCA(I-1) = (CCA(I-1) - CCA(I) + DCA(I-1)) * VOL / DELT(I-1)
          UPTMG(I-1) = (CMG(I-1) - CMG(I) + DMG(I-1)) * VOL / DELT(I-1)
          UPTCL(I-1) = (CCL(I-1) - CCL(I) + DCL(I-1)) * VOL / DELT(I-1)
          UPTNA(I-1) = (CNA(I-1) - CNA(I) + DNA(I-1)) * VOL / DELT(I-1)
10    CONTINUE

      DO 20 I=1,ITIMES-1
          UPTRAT(1,I) = UPTS(I) / UPTN(I)
          UPTRAT(2,I) = UPTP(I) / UPTN(I)
          UPTRAT(3,I) = UPTK(I) / UPTN(I)
          UPTRAT(4,I) = UPTCA(I) / UPTN(I)
          UPTRAT(5,I) = UPTMG(I) / UPTN(I)
          UPTRAT(6,I) = UPTCL(I) / UPTN(I)
          UPTRAT(7,I) = UPTNA(I) / UPTN(I)
          WRITE(20,FORM) (UPTRAT(J,I), J=1,NPAIR)
20    CONTINUE

      DO 30 I=1,NPAIR
          DO 31 J=1,ITIMES-1
              DATA(J) = UPTRAT(I,J)
31        CONTINUE
```

```
        CALL MOMENT(DATA,ITIMES-1,AVE,SDEV)
        AVER(I) = AVE
        STDEV(I) = SDEV
30    CONTINUE
      WRITE(20,*)
      WRITE(20,FORM) (AVER(I), I=1,NPAIR)
      WRITE(20,FORM) (STDEV(I), I=1,NPAIR)

      WRITE(20,4)
      WRITE(20,'(A6,7F10.3,/,6X,7F10.3)') ' N  : ',
     &                                    (UPTN(I)/VOL,I=1,ITIMES-1)
      WRITE(20,'(A6,7F10.3,/,6X,7F10.3)') ' P  : ',
     &                                    (UPTP(I)/VOL,I=1,ITIMES-1)
      WRITE(20,'(A6,7F10.3,/,6X,7F10.3)') ' K  : ',
     &                                    (UPTK(I)/VOL,I=1,ITIMES-1)
      WRITE(20,'(A6,7F10.3,/,6X,7F10.3)') ' Ca : ',
     &                                    (UPTCA(I)/VOL,I=1,ITIMES-1)
      WRITE(20,'(A6,7F10.3,/,6X,7F10.3)') ' Mg : ',
     &                                    (UPTMG(I)/VOL,I=1,ITIMES-1)
      WRITE(20,'(A6,7F10.3,/,6X,7F10.3)') ' S  : ',
     &                                    (UPTS(I)/VOL,I=1,ITIMES-1)
      WRITE(20,'(A6,7F10.3,/,6X,7F10.3)') ' Cl : ',
     &                                    (UPTCL(I)/VOL,I=1,ITIMES-1)
      WRITE(20,'(A6,7F10.3,/,6X,7F10.3)') ' Na : ',
     &                                    (UPTNA(I)/VOL,I=1,ITIMES-1)

1     FORMAT('     S/N      P/N      K/N      Ca/N     Mg/N     Cl/N     Na/N')
2     FORMAT('   (0.013) (0.084) (0.686) (0.053) (0.026) (0.040) (0.0)')
3     FORMAT(58('-'))
4     FORMAT(///,' Uptake rates (mmol/l/d)',/)

      STOP
      END
*
      SUBROUTINE MOMENT(DATA,N,AVE,SDEV)
      DIMENSION DATA(N)

      IF(N.LE.1)PAUSE 'N must be at least 2'
      S=0.
      DO 11 J=1,N
        S=S+DATA(J)
11    CONTINUE
      AVE=S/N
      ADEV=0.
      VAR=0.
      DO 12 J=1,N
        S=DATA(J)-AVE
        ADEV=ADEV+ABS(S)
        P=S*S
        VAR=VAR+P
12    CONTINUE
      ADEV=ADEV/N
      VAR=VAR/(N-1)
      SDEV=SQRT(VAR)
```

```
      RETURN
      END
```

Input file RATIO.DAT

```
*
* CN, CS, CP, CK, CCa, CMg, CCl, CNa : gemeten concentraties als tijdserie
* (mmol/l)
* achtereenvolgens monsters: VB 1A, 2A, 3A, 6A, 10A, 13A, 17A, 20A, 24A,
* 27A, 31A
*
CN  = 4.497, 3.704, 4.747, 4.875, 4.618, 4.611, 4.661, 4.582, 4.383, 4.226,
      4.425, 4.568, 4.183
CS  = 0.   , 0.   , 0.   , 0.   , 0.   , 0.   , 0.   , 0.   , 0.   , 0.   ,
      0.   , 0.   , 0.
CP  = 0.369, 0.319, 0.330, 0.347, 0.350, 0.357, 0.342, 0.324, 0.275, 0.262,
      0.252, 0.878, 0.937
CK  = 2.229, 1.932, 2.654, 2.803, 2.803, 2.951, 3.015, 2.696, 2.314, 1.958,
      1.577, 2.420, 2.378
CCa = 1.006, 0.900, 1.018, 1.011, 0.999, 0.942, 0.983, 0.993, 1.038, 1.150,
      1.362, 1.337, 1.275
CMg = 0.342, 0.315, 0.394, 0.397, 0.387, 0.372, 0.365, 0.367, 0.362, 0.360,
      0.414, 0.429, 0.419
CCl = 0.068, 0.059, 0.118, 0.133, 0.141, 0.141, 0.150, 0.139, 0.121, 0.148,
      0.162, 0.207, 0.220
CNa = 0.184, 0.161, 0.165, 0.165, 0.148, 0.148, 0.148, 0.142, 0.139, 0.136,
      0.168, 0.155, 0.155
*
* DN, DS, DP, DK, DCa, DMg, DCl, DNa : gedoseerde hoeveelheid over
* afgelopen tijdsinterval (mmol/l)
*
DN  = 0., 1.2021, 0.2984, 0.2842, 0.7311, 0.9295, 1.2143, 1.2986, 1.5207,
          1.9705, 2.2623, 1.2900
DS  = 0., 0.0168, 0.0057, 0.0053, 0.0122, 0.0141, 0.0136, 0.0178, 0.0198,
          ww264, 0.0324, 0.0238
DP  = 0., 0.1092, 0.0361, 0.0344, 0.0781, 0.0909, 0.0873, 0.1147, 0.1277,
          0.1704, 0.9632, 0.2629
DK  = 0., 0.8919, 0.2948, 0.2810, 0.6371, 0.7414, 0.7128, 0.9364, 0.7346,
          1.3687, 2.2236, 1.3833
DCa = 0., 0.1688, 0.0229, 0.0217, 0.0491, 0.1072, 0.1449, 0.2276, 0.2541,
          0.3385, 0.2322, 0.0975
DMg = 0., 0.0837, 0.0112, 0.0106, 0.0241, 0.0281, 0.0389, 0.0559, 0.0624,
          0.0831, 0.0778, 0.0473
DCl = 0., 0.0520, 0.0172, 0.0164, 0.0372, 0.0432, 0.0416, 0.0545, 0.0608,
          0.0811, 0.0993, 0.0728
DNa = 0., 0.    , 0.    , 0.    , 0.    , 0.    , 0.    , 0.    , 0.    ,
          0.    , 0.    , 0.
*
* tijdsintervallen tussen monsternames van bovengenoemde monsters
*
DELT = 3.,4.,3.,4.,3.,4.,3.,4.,3.,4.,3.,4.
```

Appendix 3: Data on nutrient solution analysis.

The measured concentrations C of all macro- and micro-nutrients and Cl, Na and H at different weeks, the amounts supplied to the system through daily manual Dosage, the extra dosage, Dosage+, after adding fresh nutrient solution to the system after leakage due to electrical faults, the removal of nutrients due to regular sampling, S, and the computed (Cumulative) Loss according to Eq. (5) in the text, with D equal to the sum of Dosage and Dosage+. Dimensions are given in the tables. The loss data were used as input C13 in Table B of Appendix 4.

N

| Day | Week | C(t-1) (mmol/l) | C(t) (mmol/l) | Dosage (mmol/l) | Dosage + (mmol/l) | S (mmol/w) | Loss (mmol/w) | C loss (mmol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 4.354 | - | | | - | |
| 8 | 1 | 4.354 | 4.675 | 1.0733 | | 34.918 | 91.469 | 91.469 |
| 15 | 2 | 4.675 | 4.718 | 0.5202 | | 30.889 | 49.277 | 140.746 |
| 22 | 3 | 4.718 | 4.668 | 1.5377 | | 30.328 | 236.402 | 377.148 |
| 29 | 4 | 4.668 | 4.468 | 3.2285 | 0.0987 | 29.889 | 562.678 | 939.826 |
| 36 | 5 | 4.468 | 4.575 | 3.1547 | 0.1676 | 28.171 | 512.005 | 1451.830 |
| 43 | 6 | 4.575 | 4.354 | 2.9112 | | 29.417 | 496.786 | 1948.616 |
| 50 | 7 | 4.354 | 5.137 | 2.2512 | | 10.953 | 235.713 | 2184.329 |

P

| Day | Week | C(t-1) (mmol/l) | C(t) (mmol/l) | Dosage (mmol/l) | Dosage + (mmol/l) | S (mmol/w) | Loss (mmol/w) | C loss (mmol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 0.282 | - | | | - | |
| 8 | 1 | 0.282 | 0.327 | 0.0975 | | 2.536 | 6.284 | 6.284 |
| 15 | 2 | 0.327 | 0.348 | 0.0629 | | 2.177 | 4.870 | 11.154 |
| 22 | 3 | 0.348 | 0.340 | 0.1509 | | 2.234 | 24.460 | 35.614 |
| 29 | 4 | 0.340 | 0.261 | 0.2115 | 0.0018 | 2.042 | 47.067 | 82.681 |
| 36 | 5 | 0.261 | 0.248 | 0.2662 | 0.0168 | 1.685 | 48.036 | 130.718 |
| 43 | 6 | 0.248 | 0.944 | 1.0947 | | 4.168 | 62.819 | 193.537 |
| 50 | 7 | 0.944 | 0.805 | 0.0000 | | 2.326 | 21.026 | 214.563 |

K

| Day | Week | C(t-1) (mmol/l) | C(t) (mmol/l) | Dosage (mmol/l) | Dosage + (mmol/l) | S (mmol/w) | Loss (mmol/w) | C loss (mmol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 2.399 | - | | | - | |
| 8 | 1 | 2.399 | 2.633 | 0.7963 | | 17.895 | 76.578 | 76.578 |
| 15 | 2 | 2.633 | 2.824 | 0.5141 | | 17.559 | 36.723 | 113.301 |
| 22 | 3 | 2.824 | 2.951 | 1.2308 | | 18.599 | 166.840 | 280.141 |
| 29 | 4 | 2.951 | 2.314 | 1.7279 | -0.034 | 17.813 | 373.786 | 653.927 |
| 36 | 5 | 2.314 | 1.550 | 1.8779 | 0.2015 | 13.242 | 464.457 | 1118.384 |
| 43 | 6 | 1.550 | 2.399 | 3.2510 | | 13.456 | 390.077 | 1508.461 |
| 50 | 7 | 2.399 | 3.170 | 1.9153 | | 6.189 | 186.048 | 1694.509 |

Ca

| Day | Week | C(t-1) (mmol/l) | C(t) (mmol/l) | Dosage (mmol/l) | Dosage + (mmol/l) | S (mmol/w) | Loss (mmol/w) | C loss (mmol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1.000 | 0.996 | - | | | - | |
| 8 | 1 | 0.996 | 1.013 | 0.0614 | | 8.087 | -0.623 | -0.623 |
| 15 | 2 | 1.013 | 0.988 | 0.0398 | | 6.539 | 4.351 | 3.728 |
| 22 | 3 | 0.988 | 0.983 | 0.1396 | | 6.246 | 18.039 | 21.767 |
| 29 | 4 | 0.983 | 1.027 | 0.3524 | 0.0515 | 6.328 | 54.137 | 75.904 |
| 36 | 5 | 1.027 | 1.362 | 0.5291 | -0.0014 | 7.205 | 25.170 | 101.074 |
| 43 | 6 | 1.362 | 1.277 | 0.2944 | | 8.655 | 55.080 | 156.154 |
| 50 | 7 | 1.277 | 1.238 | 0.1336 | | 3.186 | 25.806 | 181.960 |

Mg

| Day | Week | C(t-1) (mmol/l) | C(t) (mmol/l) | Dosage (mmol/l) | Dosage + (mmol/l) | S (mmol/w) | Loss (mmol/w) | C loss (mmol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 0.335 | - | | | - | |
| 8 | 1 | 0.335 | 0.375 | 0.0302 | | 2.756 | -4.406 | -4.406 |
| 15 | 2 | 0.375 | 0.375 | 0.0195 | | 2.472 | 0.798 | -3.608 |
| 22 | 3 | 0.375 | 0.362 | 0.0466 | | 2.385 | 7.629 | 4.021 |
| 29 | 4 | 0.362 | 0.345 | 0.0944 | 0.0102 | 2.292 | 18.133 | 22.154 |
| 36 | 5 | 0.345 | 0.417 | 0.1299 | 0.005 | 2.347 | 8.222 | 30.376 |
| 43 | 6 | 0.417 | 0.402 | 0.1117 | | 2.684 | 18.601 | 48.977 |
| 50 | 7 | 0.402 | 0.407 | 0.0654 | | 1.022 | 9.118 | 58.095 |

S

| Day | Week | C(t-1) (mmol/l) | C(t) (mmol/l) | Dosage (mmol/l) | Dosage + (mmol/l) | S (mmol/w) | Loss (mmol/w) | C loss (mmol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 0.168 | - | | | - | |
| 8 | 1 | 0.168 | 0.186 | 0.0150 | | 1.4 | -1.904 | -1.904 |
| 15 | 2 | 0.186 | 0.189 | 0.0098 | | 1.221 | -0.075 | -1.979 |
| 22 | 3 | 0.189 | 0.167 | 0.0235 | | 1.179 | 6.462 | 4.483 |
| 29 | 4 | 0.167 | 0.113 | 0.0329 | 0.0031 | 0.98 | 14.133 | 18.616 |
| 36 | 5 | 0.113 | 0.097 | 0.0412 | 0.0156 | 0.667 | 11.572 | 30.188 |
| 43 | 6 | 0.097 | 0.053 | 0.0502 | | 0.522 | 15.300 | 45.488 |
| 50 | 7 | 0.053 | 0.050 | 0.0328 | | 0.133 | 5.876 | 51.364 |

Cl

| Day | Week | C(t-1) (mmol/l) | C(t) (mmol/l) | Dosage (mmol/l) | Dosage + (mmol/l) | S (mmol/w) | Loss (mmol/w) | C loss (mmol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 0.088 | - | | | - | |
| 8 | 1 | 0.088 | 0.129 | 0.0464 | | 0.65 | 0.262 | 0.262 |
| 15 | 2 | 0.129 | 0.149 | 0.0300 | | 0.859 | 0.821 | 1.083 |
| 22 | 3 | 0.149 | 0.154 | 0.0718 | | 0.964 | 10.256 | 11.339 |
| 29 | 4 | 0.154 | 0.131 | 0.1007 | -0.0129 | 0.918 | 17.699 | 29.038 |
| 36 | 5 | 0.131 | 0.168 | 0.1267 | -0.0109 | 0.91 | 12.328 | 41.366 |
| 43 | 6 | 0.168 | 0.213 | 0.1537 | | 1.23 | 17.025 | 58.391 |
| 50 | 7 | 0.213 | 0.251 | 0.1008 | | 0.554 | 9.997 | 68.388 |

Na

| Day | Week | C(t-1) (mmol/l) | C(t) (mmol/l) | Dosage (mmol/l) | Dosage + (mmol/l) | S (mmol/w) | Loss (mmol/w) | C loss (mmol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 0.191 | - | | | - | |
| 8 | 1 | 0.191 | 0.168 | 0.0000 | | 1.52 | 2.344 | 2.344 |
| 15 | 2 | 0.168 | 0.161 | 0.0000 | | 1.069 | 0.107 | 2.451 |
| 22 | 3 | 0.161 | 0.148 | 0.0000 | | 0.988 | 1.196 | 3.647 |
| 29 | 4 | 0.148 | 0.136 | 0.0000 | -0.0274 | 0.946 | -3.533 | 0.114 |
| 36 | 5 | 0.136 | 0.168 | 0.0357 | -0.0212 | 0.89 | -3.828 | -3.714 |
| 43 | 6 | 0.168 | 0.161 | 0.0000 | | 1.02 | 0.156 | -3.558 |
| 50 | 7 | 0.161 | 0.153 | 0.0000 | | 0.394 | 0.950 | -2.608 |

Fe

| Day | Week | C(t-1) (umol/l) | C(t) (umol/l) | Dosage (umol/l) | Dosage + (umol/l) | S (umol/w) | Loss (umol/w) | C loss (umol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 111.465 | - | | | - | |
| 8 | 1 | 111.465 | 94.651 | 0.0000 | | | 2824.718 | 2824.718 |
| 15 | 2 | 94.651 | 83.747 | 0.0000 | | | 1832.005 | 4656.723 |
| 22 | 3 | 83.747 | 43.691 | 0.0000 | | | 6729.386 | 11386.108 |
| 29 | 4 | 43.691 | 13.788 | 0.0000 | -8.2746 | | 3633.593 | 15019.701 |
| 36 | 5 | 13.788 | 10.242 | 85.1318 | -0.3773 | | 16514.384 | 31534.085 |
| 43 | 6 | 10.242 | 1.540 | 0.0000 | | | 1461.994 | 32996.079 |
| 50 | 7 | 1.540 | 0.072 | 0.0000 | | | 246.674 | 33242.753 |

Mn

| Day | Week | C(t-1) (umol/l) | C(t) (umol/l) | Dosage (umol/l) | Dosage + (umol/l) | S (umol/w) | Loss (umol/w) | C loss (umol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 5.069 | - | | | - | |
| 8 | 1 | 5.069 | 4.551 | 0.0000 | | | 87.153 | 87.153 |
| 15 | 2 | 4.551 | 3.549 | 0.0000 | | | 168.190 | 255.342 |
| 22 | 3 | 3.549 | 0.419 | 0.0000 | | | 525.975 | 781.317 |
| 29 | 4 | 0.419 | 0.255 | 0.0000 | -0.033 | | 21.978 | 803.295 |
| 36 | 5 | 0.255 | 0.510 | 3.5608 | 0.1473 | | 580.149 | 1383.444 |
| 43 | 6 | 0.510 | 0.036 | 0.0000 | | | 79.508 | 1462.952 |
| 50 | 7 | 0.036 | 0.018 | 0.0000 | | | 3.058 | 1466.010 |

B

| Day | Week | C(t-1) (umol/l) | C(t) (umol/l) | Dosage (umol/l) | Dosage + (umol/l) | S (umol/w) | Loss (umol/w) | C loss (umol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 23.310 | - | | | - | |
| 8 | 1 | 23.310 | 19.425 | 0.0000 | | | 652.669 | 652.669 |
| 15 | 2 | 19.425 | 18.685 | 0.0000 | | | 124.318 | 776.986 |
| 22 | 3 | 18.685 | 16.002 | 0.0000 | | | 450.652 | 1227.639 |
| 29 | 4 | 16.002 | 11.192 | 0.0000 | -3.0635 | | 293.398 | 1521.036 |
| 36 | 5 | 11.192 | 26.270 | 17.2725 | -1.4451 | | 126.033 | 1647.070 |
| 43 | 6 | 26.270 | 20.812 | 0.0000 | | | 916.844 | 2563.914 |
| 50 | 7 | 20.812 | 19.425 | 0.0000 | | | 233.096 | 2797.009 |

Cu

| Day | Week | C(t-1) (umol/l) | C(t) (umol/l) | Dosage (umol/l) | Dosage + (umol/l) | S (umol/w) | Loss (umol/w) | C loss (umol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 1.857 | - | | | - | |
| 8 | 1 | 1.857 | 2.345 | 0.0000 | | | -81.956 | -81.956 |
| 15 | 2 | 2.345 | 2.518 | 0.0000 | | | -29.081 | -111.038 |
| 22 | 3 | 2.518 | 32.087 | 0.0000 | | | -4967.614 | -5078.652 |
| 29 | 4 | 32.087 | 59.343 | 0.0000 | -6.1823 | | -5617.609 | -10696.260 |
| 36 | 5 | 59.343 | 77.928 | 0.3082 | -11.1774 | | -4948.291 | -15644.551 |
| 43 | 6 | 77.928 | 82.460 | 0.0000 | | | -761.401 | -16405.953 |
| 50 | 7 | 82.460 | 88.949 | 0.0000 | | | -1090.108 | -17496.060 |

Zn

| Day | Week | C(t-1) (umol/l) | C(t) (umol/l) | Dosage (umol/l) | Dosage + (umol/l) | S (umol/w) | Loss (umol/w) | C loss (umol/w) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 3.610 | - | | | - | |
| 8 | 1 | 3.610 | 4.849 | 0.0000 | | | -208.137 | -208.137 |
| 15 | 2 | 4.849 | 6.103 | 0.0000 | | | -210.707 | -418.844 |
| 22 | 3 | 6.103 | 13.154 | 0.0000 | | | -1184.582 | -1603.426 |
| 29 | 4 | 13.154 | 22.362 | 0.0000 | -2.3805 | | -1946.819 | -3550.245 |
| 36 | 5 | 22.362 | 25.665 | 1.0629 | -2.9458 | | -871.355 | -4421.600 |
| 43 | 6 | 25.665 | 21.413 | 0.0000 | | | 714.347 | -3707.253 |
| 50 | 7 | 21.413 | 21.372 | 0.0000 | | | 6.852 | -3700.401 |

H

| Day | Week | C(t-1) (mmol/l) | C(t) (mmol/l) | Dosage (mmol/l) | Loss (mmol/w) | Cum loss (mmol) | |
|---|---|---|---|---|---|---|---|
| 1 | 0 | - | 0.010 | - | - | 0 | 3/6 |
| 8 | 1 | 0.010 | 0.001 | 0.0000 | 1.566 | 1.566 | 10/6 |
| 15 | 2 | 0.001 | 0.000 | 0.0000 | 0.152 | 1.718 | 17/6 |
| 22 | 3 | 0.000 | 0.000 | 0.2054 | 34.515 | 36.233 | 24/6 |
| 29 | 4 | 0.000 | 0.000 | 0.9881 | 165.984 | 202.217 | 1/7 |
| 36 | 5 | 0.000 | 0.000 | 0.4315 | 72.511 | 274.728 | 8/7 |
| 43 | 6 | 0.000 | 0.000 | 0.2262 | 37.998 | 312.726 | 15/7 |
| 50 | 7 | 0.000 | 0.000 | 0.4911 | 82.494 | 395.220 | 22/7 |

Appendix 4: Data on plant analysis.

Plant analysis consisted of weight and nutrient analysis. From these data several related parameters can be computed. The data on weight analysis are listed in 20 columns, in Table A numbered as K1 through K20, respectively. The data on nutrient analysis are listed in 17 columns per nutrient, in Table B numbered as C1 through C17. Some computation codes in Table B refer to column codes of Table A. No computation code means input data. *E* in the third column, entitled 'Meaning', of Table B stands for Element, i.e. macro- or micro-nutrient. In Table B uptake and loss rates are given in dimension per week. But as can be seen from the data, halfway the experiment the harvest times were at weeks 2 and 4, then the uptake or loss at t = 4 weeks is given per two weeks.

Table A

| Column | Computation | Meaning | Dimension |
|---|---|---|---|
| K1 | | time | week |
| K2 | | number of plants harvested | |
| K3 | | number of plants that have grown during (t-1) and t | |
| K4 | | fresh shoot weight of all harvested plants | g |
| K5 | K4/K2 | fresh shoot weight per plant | g |
| K6 | | standard deviation of fresh shoot weight | g |
| K7 | | dry shoot weight of all harvested plants | g |
| K8 | K7/K2 | dry shoot weight per plant | g |
| K9 | K8*K3 | dry shoot weight of all plants present just before harvest at time t | g |
| K10 | 100*K8/K5 | dry matter content of shoot | % |
| K11 | | fresh root weight of all harvested plants | g |
| K12 | K11/K2 | fresh root weight per plant | g |
| K13 | | standard deviation of fresh root weight | g |
| K14 | | dry root weight of all harvested plants | g |
| K15 | K14/K2 | dry root weight per plant | g |
| K16 | K15*K3 | dry root weight of all plants present just before harvest at time t | g |
| K17 | 100*K15/K12 | dry matter content of root | % |
| K18 | K8/K15 | shoot/root ratio | |
| K19 | 100*(K8+K15) /(K5+K12) | dry matter content of plant | % |
| K20 | K8+K15 | dry weight of plant | g |

Table B

| Column | Computation | Meaning | Dimension |
|---|---|---|---|
| C1 | | time | week |
| C2 | | amount of *E* in 1 g dry shoot | $mmol \cdot g^{-1}$ or $\mu mol \cdot g^{-1}$ |
| C3 | | amount of *E* in 1 g dry root | $mmol \cdot g^{-1}$ or $\mu mol \cdot g^{-1}$ |
| C4 | C2*K9 | total amount of *E* in all shoots present just before harvest at t | mmol or $\mu$mol |
| C5 | C3*K16 | total amount of *E* in all roots present just before harvest at t | mmol or $\mu$mol |
| C6 | C4+C5 | total amount of *E* in all plants present just before harvest at t | mmol or $\mu$mol |
| C7 | K3*(C8(t)-C8(t-1)) | total uptake of *E* by the plants per week | $mmol \cdot week^{-1}$ or $\mu mol \cdot week^{-1}$ |
| C8 | C6/K3 | *E* content per plant | mmol or $\mu$mol |
| C9 | C8(t)-C8(t-1) | total amount of *E* uptake per plant per week | mmol or $\mu$mol |
| C10 | C10(t-1)+C9 | idem, cumulative | mmol or $\mu$mol |
| C11 | C4(t)/K3(t) - C4(t-1)/K3(t-1) | total amount of *E* uptake per shoot per week | mmol or $\mu$mol |
| C12 | C12(t-1)+C11 | idem, cumulative | mmol or $\mu$mol |
| C13 | | weekly loss of *E* from nutrient solution | $mmol \cdot week^{-1}$ or $\mu mol \cdot week^{-1}$ |
| C14 | C13/K3 | idem, per plant | $mmol \cdot week^{-1}$ or $\mu mol \cdot week^{-1}$ |
| C15 | C15(t-1)+C14 | idem, cumulative | $mmol \cdot week^{-1}$ or $\mu mol \cdot week^{-1}$ |
| C16 | C16(t-1)+C13 | cumulative uptake of *E* from system | mmol or $\mu$mol |
| C17 | C17(t-1)+C13 | cumulative loss of *E* from system | mmol or $\mu$mol |

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| Week | # plant harvest | # plant system | shoot fresh harvest (g) | shoot fresh plant (g) | idem cv plant (%) | shoot dry harvest (g) | shoot dry plant (g) | shoot dry syst. (g) | shoot dry matter (%) | root fresh harvest (g) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 100 | 144 | 9.92 | 0.099 | 27.1 | 0.69 | 0.007 | 0.994 | 6.96 | 3.25 |
| 1 | 48 | 144 | 20.83 | 0.434 | 37.5 | 1.51 | 0.031 | 4.530 | 7.25 | 7.55 |
| 2 | 24 | 96 | 46.86 | 1.953 | 51.7 | 3.03 | 0.126 | 12.120 | 6.47 | 13.62 |
| 4 | 24 | 72 | 1071.05 | 44.627 | 36.4 | 52.87 | 2.203 | 158.610 | 4.94 | 173.95 |
| 5 | 24 | 48 | 2884.41 | 120.184 | 29.5 | 160.40 | 6.683 | 320.800 | 5.56 | 457.24 |
| 6 | 12 | 24 | 2647.68 | 220.640 | 36.7 | 145.29 | 12.108 | 290.580 | 5.49 | 357.28 |
| 7 | 12 | 12 | 3990.91 | 332.576 | 41.0 | 219.60 | 18.300 | 219.600 | 5.50 | 476.74 |

| root fresh plant (g) | idem cv plant (%) | root dry harvest (g) | root dry plant (g) | root dry system (g) | root dry matter (%) | shoot/ root (-) | plant dry matter (%) | plant dry plant (g) |
|---|---|---|---|---|---|---|---|---|
| 0.033 | 42.3 | 0.46 | 0.005 | 0.662 | 14.15 | 1.50 | 8.73 | 0.012 |
| 0.157 | 41.6 | 0.45 | 0.009 | 1.350 | 5.96 | 3.36 | 6.91 | 0.041 |
| 0.568 | 41.3 | 0.79 | 0.033 | 3.160 | 5.80 | 3.84 | 6.32 | 0.159 |
| 7.248 | 30.5 | 10.32 | 0.430 | 30.960 | 5.93 | 5.12 | 5.08 | 2.633 |
| 19.052 | 25.4 | 31.30 | 1.304 | 62.600 | 6.85 | 5.12 | 5.74 | 7.988 |
| 29.773 | 37.3 | 22.35 | 1.863 | 44.700 | 6.26 | 6.50 | 5.58 | 13.970 |
| 39.728 | 39.8 | 29.60 | 2.467 | 29.600 | 6.21 | 7.42 | 5.58 | 20.767 |

Nutrient plant data experiment 6705 project 402

| Week | N shoot (mmol/g) | N root (mmol/g) | N shoot (mmol) | N root (mmol) | N plant (mmol) | N uptake (mmol/w) | N content (mmol/pl) | N up/week (mmol/pl) | cum N up/week (mmol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 3.214 | 2.171 | 3.194 | 1.438 | 4.632 | | 0.032 | | |
| 1 | 3.929 | 4.114 | 17.796 | 5.554 | 23.351 | 18.719 | 0.162 | 0.130 | 0.130 |
| 2 | 4.121 | 4.043 | 49.952 | 12.775 | 62.727 | 47.160 | 0.653 | 0.491 | 0.621 |
| 4 | 3.821 | 3.379 | 606.117 | 104.601 | 710.717 | 663.672 | 9.871 | 9.218 | 9.839 |
| 5 | 2.829 | 2.957 | 907.406 | 185.117 | 1092.523 | 618.711 | 22.761 | 12.890 | 22.729 |
| 6 | 2.743 | 3.093 | 797.019 | 138.251 | 935.270 | 389.009 | 38.970 | 16.209 | 38.937 |
| 7 | 2.564 | 2.971 | 563.117 | 87.954 | 651.071 | 183.436 | 54.256 | 15.286 | 54.224 |

| N up/week (mmol/sh) | cum N up/week (mmol/sh) | N loss (mmol/w) | N loss/week (mmol/pl) | N closs/w (mmol/pl) | N cum. upt. (mmol) | N cum. loss (mmol) |
|---|---|---|---|---|---|---|
| 0.101 | 0.101 | 91.469 | 0.635 | 0.635 | 18.719 | 91.469 |
| 0.397 | 0.498 | 49.277 | 0.513 | 1.149 | 65.879 | 140.746 |
| 7.898 | 8.396 | 799.080 | 11.098 | 12.247 | 729.551 | 939.826 |
| 10.486 | 18.882 | 512.005 | 10.667 | 22.914 | 1348.262 | 1451.831 |
| 14.305 | 33.187 | 496.786 | 20.699 | 43.613 | 1737.271 | 1948.617 |
| 13.717 | 46.904 | 235.713 | 19.643 | 63.256 | 1920.707 | 2184.330 |

| Week | P shoot (mmol/g) | P root (mmol/g) | P shoot (mmol) | P root (mmol) | P plant (mmol) | P uptake (mmol/w) | P content (mmol/pl) | P up/week (mmol/pl) | cum P up/week (mmol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.206 | 0.159 | 0.205 | 0.105 | 0.310 | | 0.002 | | |
| 1 | 0.270 | 0.353 | 1.222 | 0.477 | 1.699 | 1.389 | 0.012 | 0.010 | 0.010 |
| 2 | 0.295 | 0.383 | 3.578 | 1.211 | 4.789 | 3.657 | 0.050 | 0.038 | 0.048 |
| 4 | 0.291 | 0.389 | 46.153 | 12.041 | 58.195 | 54.603 | 0.808 | 0.758 | 0.806 |
| 5 | 0.243 | 0.298 | 77.866 | 18.660 | 96.526 | 57.730 | 2.011 | 1.203 | 2.009 |
| 6 | 0.251 | 0.375 | 73.006 | 16.751 | 89.757 | 41.493 | 3.740 | 1.729 | 3.738 |
| 7 | 0.240 | 0.379 | 52.679 | 11.218 | 63.897 | 19.019 | 5.325 | 1.585 | 5.323 |

| P up/week (mmol/sh) | cum P up/week (mmol/sh) | P loss (mmol/w) | P loss/week (mmol/pl) | P closs/w (mmol/pl) | P cum. upt. (mmol) | P cum. loss (mmol) |
|---|---|---|---|---|---|---|
| 0.007 | 0.007 | 6.284 | 0.044 | 0.044 | 1.389 | 6.284 |
| 0.029 | 0.036 | 4.870 | 0.051 | 0.094 | 5.046 | 11.154 |
| 0.604 | 0.640 | 71.527 | 0.993 | 1.088 | 59.648 | 82.681 |
| 0.981 | 1.621 | 48.036 | 1.001 | 2.089 | 117.378 | 130.717 |
| 1.420 | 3.040 | 62.819 | 2.617 | 4.706 | 158.872 | 193.536 |
| 1.348 | 4.389 | 21.026 | 1.752 | 6.458 | 177.891 | 214.562 |

| Week | K shoot (mmol/g) | K root (mmol/g) | K shoot (mmol) | K root (mmol) | K plant (mmol) | K uptake (mmol/w) | K content (mmol/pl) | K up/week (mmol/pl) | cum K up/week (mmol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | 2.008 | | 9.098 | 0.000 | 9.098 | 9.098 | 0.063 | 0.063 | 0.063 |
| 2 | 2.395 | 2.448 | 29.026 | 7.736 | 36.762 | 30.696 | 0.383 | 0.320 | 0.383 |
| 4 | 2.174 | 2.151 | 344.834 | 66.587 | 411.421 | 383.849 | 5.714 | 5.331 | 5.714 |
| 5 | 2.346 | 1.771 | 752.620 | 110.846 | 863.466 | 589.185 | 17.989 | 12.275 | 17.989 |
| 6 | 2.306 | 1.981 | 670.000 | 88.546 | 758.546 | 326.813 | 31.606 | 13.617 | 31.606 |
| 7 | 2.151 | 1.938 | 472.303 | 57.377 | 529.681 | 150.408 | 44.140 | 12.534 | 44.140 |

| K up/week (mmol/sh) | cum K up/week (mmol/sh) | K loss (mmol/w) | K loss/week (mmol/pl) | K closs/w (mmol/pl) | K cum. upt. (mmol) | K cum. loss (mmol) |
|---|---|---|---|---|---|---|
| 0.063 | 0.063 | 76.578 | 0.532 | 0.532 | 9.098 | 76.578 |
| 0.239 | 0.302 | 36.723 | 0.383 | 0.914 | 39.795 | 113.301 |
| 4.487 | 4.789 | 540.626 | 7.509 | 8.423 | 423.644 | 653.927 |
| 10.890 | 15.680 | 464.457 | 9.676 | 18.099 | 1012.829 | 1118.384 |
| 12.237 | 27.917 | 390.077 | 16.253 | 34.352 | 1339.642 | 1508.461 |
| 11.442 | 39.359 | 186.048 | 15.504 | 49.856 | 1490.050 | 1694.509 |

| Week | Ca shoot (mmol/g) | Ca root (mmol/g) | Ca shoot (mmol) | Ca root (mmol) | Ca plant (mmol) | Ca uptake (mmol/w) | Ca content (mmol/pl) | Ca up/week (mmol/pl) | cum Ca up/week (mmol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | 0.285 | | 3.458 | 0.000 | 3.458 | 3.458 | 0.036 | 0.036 | 0.036 |
| 4 | 0.232 | 0.125 | 36.768 | 3.864 | 40.632 | 38.039 | 0.564 | 0.528 | 0.564 |
| 5 | 0.210 | 0.128 | 67.501 | 8.037 | 75.538 | 48.450 | 1.574 | 1.009 | 1.574 |
| 6 | 0.218 | 0.152 | 63.215 | 6.775 | 69.990 | 32.221 | 2.916 | 1.343 | 2.916 |
| 7 | 0.234 | 0.164 | 51.297 | 4.856 | 56.153 | 21.158 | 4.679 | 1.763 | 4.679 |

| Ca up/week (mmol/sh) | cum Ca up/week (mmol/sh) | Ca loss (mmol/w) | Ca loss/week (mmol/pl) | Ca closs/w (mmol/pl) | Ca cum. upt. (mmol) | Ca cum. loss (mmol) |
|---|---|---|---|---|---|---|
| 0.000 | 0.000 | -0.623 | -0.004 | -0.004 | 0.000 | -0.623 |
| 0.036 | 0.036 | 4.351 | 0.045 | 0.041 | 3.458 | 3.728 |
| 0.475 | 0.511 | 72.176 | 1.002 | 1.043 | 41.497 | 75.904 |
| 0.896 | 1.406 | 25.170 | 0.524 | 1.568 | 89.946 | 101.074 |
| 1.228 | 2.634 | 55.080 | 2.295 | 3.863 | 122.167 | 156.154 |
| 1.641 | 4.275 | 25.806 | 2.151 | 6.013 | 143.326 | 181.960 |

| Week | Mg shoot (mmol/g) | Mg root (mmol/g) | Mg shoot (mmol) | Mg root (mmol) | Mg plant (mmol) | Mg uptake (mmol/w) | Mg content (mmol/pl) | Mg up/week (mmol/pl) | cum Mg up/week (mmol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | 0.131 | | 1.594 | 0.000 | 1.594 | 1.594 | 0.017 | 0.017 | 0.017 |
| 4 | 0.089 | 0.072 | 14.165 | 2.227 | 16.392 | 15.197 | 0.228 | 0.211 | 0.228 |
| 5 | 0.072 | 0.074 | 23.079 | 4.659 | 27.738 | 16.810 | 0.578 | 0.350 | 0.578 |
| 6 | 0.072 | 0.092 | 20.905 | 4.103 | 25.008 | 11.139 | 1.042 | 0.464 | 1.042 |
| 7 | 0.079 | 0.092 | 17.433 | 2.717 | 20.150 | 7.646 | 1.679 | 0.637 | 1.679 |

| Mg up/week (mmol/sh) | cum Mg up/week (mmol/sh) | Mg loss (mmol/w) | Mg loss/week (mmol/pl) | Mg closs/w (mmol/pl) | Mg cum. upt. (mmol) | Mg cum. loss (mmol) |
|---|---|---|---|---|---|---|
| 0.000 | 0.000 | -4.406 | -0.031 | -0.031 | 0.000 | -4.406 |
| 0.017 | 0.017 | 0.798 | 0.008 | -0.022 | 1.594 | -3.608 |
| 0.180 | 0.197 | 25.762 | 0.358 | 0.336 | 16.791 | 22.154 |
| 0.284 | 0.481 | 8.222 | 0.171 | 0.507 | 33.601 | 30.376 |
| 0.390 | 0.871 | 18.601 | 0.775 | 1.282 | 44.740 | 48.977 |
| 0.582 | 1.453 | 9.118 | 0.760 | 2.042 | 52.385 | 58.095 |

| Week | S shoot (mmol/g) | S root (mmol/g) | S shoot (mmol) | S root (mmol) | S plant (mmol) | S uptake (mmol/w) | S content (mmol/pl) | S up/week (mmol/pl) | cum S up/week (mmol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4 | 0.083 | 0.197 | 13.209 | 6.091 | 19.301 | 19.301 | 0.268 | 0.268 | 0.268 |
| 5 | 0.073 | 0.118 | 23.377 | 7.364 | 30.741 | 17.874 | 0.640 | 0.372 | 0.640 |
| 6 | 0.074 | 0.173 | 21.477 | 7.725 | 29.202 | 13.831 | 1.217 | 0.576 | 1.217 |
| 7 | 0.072 | 0.186 | 15.774 | 5.516 | 21.290 | 6.689 | 1.774 | 0.557 | 1.774 |

| S up/week (mmol/sh) | cum S up/week (mmol/sh) | S loss (mmol/w) | S loss/week (mmol/pl) | S closs/w (mmol/pl) | S cum. upt. (mmol) | S cum. loss (mmol) |
|---|---|---|---|---|---|---|
| 0.000 | 0.000 | -1.904 | -0.013 | -0.013 | 0.000 | -1.904 |
| 0.000 | 0.000 | -0.075 | -0.001 | -0.014 | 0.000 | -1.979 |
| 0.183 | 0.183 | 20.595 | 0.286 | 0.272 | 19.301 | 18.616 |
| 0.304 | 0.487 | 11.572 | 0.241 | 0.513 | 37.175 | 30.188 |
| 0.408 | 0.895 | 15.300 | 0.638 | 1.151 | 51.006 | 45.488 |
| 0.420 | 1.314 | 5.876 | 0.490 | 1.640 | 57.695 | 51.364 |

| Week | Cl shoot (mmol/g) | Cl root (mmol/g) | Cl shoot (mmol) | Cl root (mmol) | Cl plant (mmol) | Cl uptake (mmol/w) | Cl content (mmol/pl) | Cl up/week (mmol/pl) | cum Cl up/week (mmol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | 0.245 | | 2.974 | 0.000 | 2.974 | 2.974 | 0.031 | 0.031 | 0.031 |
| 4 | 0.149 | 0.059 | 23.711 | 1.834 | 25.545 | 23.314 | 0.355 | 0.324 | 0.355 |
| 5 | 0.113 | 0.031 | 36.194 | 1.942 | 38.137 | 21.107 | 0.795 | 0.440 | 0.795 |
| 6 | 0.113 | 0.039 | 32.785 | 1.765 | 34.550 | 15.482 | 1.440 | 0.645 | 1.440 |
| 7 | 0.113 | 0.042 | 24.776 | 1.252 | 26.029 | 8.754 | 2.169 | 0.729 | 2.169 |

| Cl up/week (mmol/sh) | cum Cl up/week (mmol/sh) | Cl loss (mmol/w) | Cl loss/week (mmol/pl) | Cl closs/w (mmol/pl) | Cl cum. upt. (mmol) | Cl cum. loss (mmol) |
|---|---|---|---|---|---|---|
| 0.000 | 0.000 | 0.262 | 0.002 | 0.002 | 0.000 | 0.262 |
| 0.031 | 0.031 | 0.821 | 0.009 | 0.010 | 2.974 | 1.083 |
| 0.298 | 0.329 | 27.957 | 0.388 | 0.399 | 26.289 | 29.040 |
| 0.425 | 0.754 | 12.328 | 0.257 | 0.655 | 47.395 | 41.368 |
| 0.612 | 1.366 | 17.025 | 0.709 | 1.365 | 62.877 | 58.393 |
| 0.699 | 2.065 | 9.997 | 0.833 | 2.198 | 71.631 | 68.390 |

| Week | Na shoot (mmol/g) | Na root (mmol/g) | Na shoot (mmol) | Na root (mmol) | Na plant (mmol) | Na uptake (mmol/w) | Na content (mmol/pl) | Na up/week (mmol/pl) | cum Na up/week (mmol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | 0.136 | | 0.614 | 0.000 | 0.614 | 0.614 | 0.004 | 0.004 | 0.004 |
| 2 | 0.097 | 0.116 | 1.173 | 0.367 | 1.540 | 1.131 | 0.016 | 0.012 | 0.016 |
| 4 | 0.023 | 0.032 | 3.583 | 0.999 | 4.582 | 3.426 | 0.064 | 0.048 | 0.064 |
| 5 | 0.029 | 0.023 | 9.317 | 1.414 | 10.731 | 7.676 | 0.224 | 0.160 | 0.224 |
| 6 | 0.023 | 0.019 | 6.564 | 0.865 | 7.429 | 2.064 | 0.310 | 0.086 | 0.310 |
| 7 | 0.016 | 0.016 | 3.543 | 0.478 | 4.021 | 0.306 | 0.335 | 0.026 | 0.335 |

| Na up/week (mmol/sh) | cum Na up/week (mmol/sh) | Na loss (mmol/w) | Na loss/week (mmol/pl) | Na closs/w (mmol/pl) | Na cum. upt. (mmol) | Na cum. loss (mmol) |
|---|---|---|---|---|---|---|
| 0.004 | 0.004 | 2.344 | 0.016 | 0.016 | 0.614 | 2.344 |
| 0.008 | 0.012 | 0.107 | 0.001 | 0.017 | 1.745 | 2.451 |
| 0.038 | 0.050 | 3.761 | 0.052 | 0.070 | 5.171 | 6.212 |
| 0.144 | 0.194 | 1.532 | 0.032 | 0.102 | 12.848 | 7.744 |
| 0.079 | 0.273 | 0.156 | 0.007 | 0.108 | 14.911 | 7.900 |
| 0.022 | 0.295 | 0.950 | 0.079 | 0.187 | 15.217 | 8.850 |

| Week | Fe shoot (umol/g) | Fe root (umol/g) | Fe shoot (umol) | Fe root (umol) | Fe plant (umol) | Fe uptake (umol/w) | Fe content (umol/pl) | Fe up/week (umol/pl) | cum Fe up/week (umol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4 | 2.507 | 47.755 | 397.611 | 1478.509 | 1876.121 | 1876.121 | 26.057 | 26.057 | 26.057 |
| 5 | 1.486 | 35.185 | 476.774 | 2202.607 | 2679.381 | 1428.634 | 55.820 | 29.763 | 55.820 |
| 6 | 1.074 | 28.542 | 312.189 | 1275.839 | 1588.028 | 248.337 | 66.168 | 10.347 | 66.168 |
| 7 | 1.164 | 22.150 | 255.591 | 655.634 | 911.225 | 117.211 | 75.935 | 9.768 | 75.935 |

| Fe up/week (umol/sh) | cum Fe up/week (umol/sh) | Fe loss (umol/w) | Fe loss/week (umol/pl) | Fe closs/w (umol/pl) | Fe cum. upt. (umol) | Fe cum. loss (umol) |
|---|---|---|---|---|---|---|
| 0.000 | 0.000 | 2824.718 | 19.616 | 19.616 | 0.000 | 2824.718 |
| 0.000 | 0.000 | 1832.005 | 19.083 | 38.699 | 0.000 | 4656.723 |
| 5.522 | 5.522 | 10362.979 | 143.930 | 182.630 | 1876.121 | 15019.702 |
| 4.410 | 9.933 | 16514.384 | 344.050 | 526.679 | 3304.755 | 31534.086 |
| 3.075 | 13.008 | 1461.994 | 60.916 | 587.596 | 3553.092 | 32996.080 |
| 8.291 | 21.299 | 246.674 | 20.556 | 608.152 | 3670.304 | 33242.754 |

| Week | Mn shoot (umol/g) | Mn root (umol/g) | Mn shoot (umol) | Mn root (umol) | Mn plant (umol) | Mn uptake (umol/w) | Mn content (umol/pl) | Mn up/week (umol/pl) | cum Mn up/week (umol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4 | 2.912 | 1.474 | 461.932 | 45.647 | 507.579 | 507.579 | 7.050 | 7.050 | 7.050 |
| 5 | 2.002 | 2.075 | 642.324 | 129.899 | 772.223 | 433.837 | 16.088 | 9.038 | 16.088 |
| 6 | 1.565 | 0.837 | 454.874 | 37.428 | 492.302 | 106.190 | 20.513 | 4.425 | 20.513 |
| 7 | 0.947 | 0.582 | 207.856 | 17.241 | 225.097 | -21.054 | 18.758 | -1.754 | 18.758 |

| Mn up/week (umol/sh) | cum Mn up/week (umol/sh) | Mn loss (umol/w) | Mn loss/week (umol/pl) | Mn closs/w (umol/pl) | Mn cum. upt. (umol) | Mn cum. loss (umol) |
|---|---|---|---|---|---|---|
| 0.000 | 0.000 | 87.153 | 0.605 | 0.605 | 0.000 | 87.153 |
| 0.000 | 0.000 | 168.190 | 1.752 | 2.357 | 0.000 | 255.343 |
| 6.416 | 6.416 | 547.953 | 7.610 | 9.968 | 507.579 | 803.296 |
| 6.966 | 13.382 | 580.149 | 12.086 | 22.054 | 941.416 | 1383.445 |
| 5.571 | 18.953 | 79.508 | 3.313 | 25.367 | 1047.606 | 1462.953 |
| -1.632 | 17.321 | 3.058 | 0.255 | 25.622 | 1026.553 | 1466.011 |

| Week | B shoot (umol/g) | B root (umol/g) | B shoot (umol) | B root (umol) | B plant (umol) | B uptake (umol/w) | B content (umol/pl) | B up/week (umol/pl) | cum B up/week (umol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4 | 2.146 | | 340.371 | 0.000 | 340.371 | 340.371 | 4.727 | 4.727 | 4.727 |
| 5 | 2.349 | 2.016 | 753.706 | 126.231 | 879.937 | 653.023 | 18.332 | 13.605 | 18.332 |
| 6 | 2.507 | 2.275 | 728.399 | 101.713 | 830.112 | 390.143 | 34.588 | 16.256 | 34.588 |
| 7 | 2.738 | 2.257 | 601.254 | 66.806 | 668.060 | 253.004 | 55.672 | 21.084 | 55.672 |

| B up/week (umol/sh) | cum B up/week (umol/sh) | B loss (umol/w) | B loss/week (umol/pl) | B closs/w (umol/pl) | B cum. upt. (umol) | B cum. loss (umol) |
|---|---|---|---|---|---|---|
| 0.000 | 0.000 | 652.669 | 4.532 | 4.532 | 0.000 | 652.669 |
| 0.000 | 0.000 | 124.318 | 1.295 | 5.827 | 0.000 | 776.987 |
| 4.727 | 4.727 | 744.050 | 10.334 | 16.161 | 340.371 | 1521.037 |
| 10.975 | 15.702 | 126.033 | 2.626 | 18.787 | 993.394 | 1647.070 |
| 14.648 | 30.350 | 916.844 | 38.202 | 56.989 | 1383.537 | 2563.914 |
| 19.755 | 50.105 | 233.096 | 19.425 | 76.414 | 1636.542 | 2797.010 |

| Week | Cu shoot (umol/g) | Cu root (umol/g) | Cu shoot (umol) | Cu root (umol) | Cu plant (umol) | Cu uptake (umol/w) | Cu content (umol/pl) | Cu up/week (umol/pl) | cum Cu up/week (umol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4 | 0.250 | 7.255 | 39.686 | 224.602 | 264.288 | 264.288 | 3.671 | 3.671 | 3.671 |
| 5 | 0.263 | 9.286 | 84.307 | 581.315 | 665.622 | 489.430 | 13.867 | 10.196 | 13.867 |
| 6 | 0.277 | 13.082 | 80.480 | 584.759 | 665.240 | 332.429 | 27.718 | 13.851 | 27.718 |
| 7 | 0.260 | 19.671 | 57.020 | 582.255 | 639.275 | 306.656 | 53.273 | 25.555 | 53.273 |

| Cu up/week (umol/sh) | cum Cu up/week (umol/sh) | Cu loss (umol/w) | Cu loss/week (umol/pl) | Cu closs/w (umol/pl) | Cu cum. upt. (umol) | Cu cum. loss (umol) |
|---|---|---|---|---|---|---|
| 0.000 | 0.000 | -81.956 | -0.569 | -0.569 | 0.000 | -81.956 |
| 0.000 | 0.000 | -29.081 | -0.303 | -0.872 | 0.000 | -111.037 |
| 0.551 | 0.551 | -10585.223 | -147.017 | -147.889 | 264.288 | -10696.260 |
| 1.205 | 1.756 | -4948.291 | -103.089 | -250.978 | 753.718 | -15644.551 |
| 1.597 | 3.353 | -761.401 | -31.725 | -282.703 | 1086.147 | -16405.952 |
| 1.398 | 4.752 | -1090.108 | -90.842 | -373.546 | 1392.802 | -17496.060 |

| Week | Zn shoot (umol/g) | Zn root (umol/g) | Zn shoot (umol) | Zn root (umol) | Zn plant (umol) | Zn uptake (umol/w) | Zn content (umol/pl) | Zn up/week (umol/pl) | cum Zn up/week (umol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4 | 3.977 | 35.668 | 630.753 | 1104.294 | 1735.046 | 1735.046 | 24.098 | 24.098 | 24.098 |
| 5 | 5.873 | 35.837 | 1884.173 | 2243.374 | 4127.547 | 2970.849 | 85.991 | 61.893 | 85.991 |
| 6 | 6.592 | 57.250 | 1915.570 | 2559.072 | 4474.642 | 2410.868 | 186.443 | 100.453 | 186.443 |
| 7 | 6.332 | 59.544 | 1390.554 | 1762.508 | 3153.062 | 915.741 | 262.755 | 76.312 | 262.755 |

| Zn up/week (umol/sh) | cum Zn up/week (umol/sh) | Zn loss (umol/w) | Zn loss/week (umol/pl) | Zn closs/w (umol/pl) | Zn cum. upt. (umol) | Zn cum. loss (umol) |
|---|---|---|---|---|---|---|
| 0.000 | 0.000 | -208.137 | -1.445 | -1.445 | 0.000 | -208.137 |
| 0.000 | 0.000 | -210.707 | -2.195 | -3.640 | 0.000 | -418.844 |
| 8.760 | 8.760 | -3131.401 | -43.492 | -47.132 | 1735.046 | -3550.245 |
| 30.493 | 39.254 | -871.355 | -18.153 | -65.285 | 4705.895 | -4421.600 |
| 40.562 | 79.815 | 714.347 | 29.764 | -35.521 | 7116.764 | -3707.253 |
| 36.064 | 115.879 | 6.852 | 0.571 | -34.950 | 8032.505 | -3700.401 |

| Week | Mo shoot (umol/g) | Mo root (umol/g) | Mo shoot (umol) | Mo root (umol) | Mo plant (umol) | Mo uptake (umol/w) | Mo content (umol/pl) | Mo up/week (umol/pl) | cum Mo up/week (umol/pl) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | 0.000 | 0.000 | 0.000 | | 0.000 | | |
| 1 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4 | 0.029 | | 4.646 | 0.000 | 4.646 | 4.646 | 0.065 | 0.065 | 0.065 |
| 5 | 0.034 | 0.182 | 10.767 | 11.386 | 22.153 | 19.056 | 0.462 | 0.397 | 0.462 |
| 6 | 0.041 | | 11.933 | 0.000 | 11.933 | 0.857 | 0.497 | 0.036 | 0.497 |
| 7 | 0.036 | 0.364 | 8.011 | 10.764 | 18.776 | 12.809 | 1.565 | 1.067 | 1.565 |

| Mo up/week (umol/sh) | cum Mo up/week (umol/sh) | Mo loss (umol/w) | Mo loss/week (umol/pl) | Mo closs/w (umol/pl) | Mo cum. upt. (umol) | Mo cum. loss (umol) |
|---|---|---|---|---|---|---|
| 0.000 | 0.000 | | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.000 | 0.000 | | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.065 | 0.065 | | 0.000 | 0.000 | 4.646 | 0.000 |
| 0.160 | 0.224 | | 0.000 | 0.000 | 23.701 | 0.000 |
| 0.273 | 0.497 | | 0.000 | 0.000 | 24.558 | 0.000 |
| 0.170 | 0.668 | | 0.000 | 0.000 | 37.367 | 0.000 |

For H: first column is input; second column is first column divided by K3 (Table A); third column represents cumulative data of second column; fourth column represents cumulative data of first column

| H loss (mmol/w) | H loss/week (mmol/pl) | H closs/w (mmol/pl) | H cum. loss (mmol) |
|---|---|---|---|
| 1.398 | 0.010 | 0.010 | 1.398 |
| 0.135 | 0.001 | 0.011 | 1.533 |
| 200.500 | 2.785 | 2.796 | 202.033 |
| 72.509 | 1.511 | 4.306 | 274.542 |
| 37.998 | 1.583 | 5.890 | 312.540 |
| 82.494 | 6.875 | 12.764 | 395.034 |

Appendix 5: Values of fitted parameters $y_i$, $y_f$ and k of Eq. (3) for dry matter of lettuce and cumulative uptake by lettuce for all macro- and micronutrients as a function of time.

Additionally the time of inflection, $t^*$, and percentage of variance accounted for, PVA, and $R^2$ are given.

| | dry_matter | K | P |
|---|---|---|---|
| $y_i$ | 0.041 | 0.056 | 0.010 |
| $y_f$ | 26.48 | 51.65 | 6.65 |
| k | 0.1578 | 0.1748 | 0.1599 |
| $t^*$ | 40.96 | 39.08 | 40.35 |
| PVA | 99.8 | 99.8 | 100.0 |
| $R^2$ | 99.91 | 99.93 | 99.99 |

| | B | Mg | S |
|---|---|---|---|
| $y_i$ | 0.075 | 0.006 | 0.004 |
| $y_f$ | 76.01 | 2.65 | 2.34 |
| k | 0.1616 | 0.1347 | 0.1518 |
| $t^*$ | 42.85 | 45.01 | 41.44 |
| PVA | 99.4 | 99.8 | 100.0 |
| $R^2$ | 99.87 | 99.95 | 100.0 |

| | Ca | Mn | Zn |
|---|---|---|---|
| $y_i$ | 0.012 | 0.002 | 0.088 |
| $y_f$ | 6.93 | 19.75 | 300.03 |
| k | 0.1446 | 0.3142 | 0.2056 |
| $t^*$ | 44.00 | 29.94 | 39.54 |
| PVA | 99.8 | 98.4 | 100.0 |
| $R^2$ | 99.95 | 99.77 | 100.0 |

| | Cl | Mo |
|---|---|---|
| $y_i$ | 0.009 | 0.005 |
| $y_f$ | 3.12 | 67.51 |
| k | 0.1370 | 0.1190 |
| $t^*$ | 43.00 | 80.71 |
| PVA | 99.9 | 91.8 |
| $R^2$ | 99.98 | 97.79 |

| | Cu | N |
|---|---|---|
| $y_i$ | 0.100 | 0.172 |
| $y_f$ | 111.53 | 67.49 |
| k | 0.1412 | 0.1503 |
| $t^*$ | 49.66 | 39.74 |
| PVA | 99.6 | 99.9 |
| $R^2$ | 99.90 | 99.97 |

| | Fe | Na |
|---|---|---|
| $y_i$ | 0.092 | 0.000 |
| $y_f$ | 75.33 | 0.33 |
| k | 0.2181 | 0.2953 |
| $t^*$ | 30.73 | 32.73 |
| PVA | 99.1 | 99.7 |
| $R^2$ | 99.87 | 99.90 |

Appendix 6: Values of fitted parameters $y_i$, $y_f$ and k of Eq. (3) for N, K and P relative cumulative uptake as a function of cumulative daily radiation.

Additionally the time of inflection, $t^*$, and percentage of variance accounted for, PVA, and $R^2$ are given.

| | N |
|---|---|
| $y_i$ | 0.498 |
| $y_f$ | 72.88 |
| k | 0.0844 |
| $t^*$ | 58.97 |
| PVA | 99.7 |
| $R^2$ | 99.89 |

| | K |
|---|---|
| $y_i$ | 0.207 |
| $y_f$ | 55.39 |
| k | 0.0970 |
| $t^*$ | 57.56 |
| PVA | 99.9 |
| $R^2$ | 99.97 |

| | P |
|---|---|
| $y_i$ | 0.034 |
| $y_f$ | 7.27 |
| k | 0.0892 |
| $t^*$ | 60.18 |
| PVA | 99.8 |
| $R^2$ | 99.93 |

Appendix 7: Uptake or content ratios between macro- (mmol) and micro-nutrients (μmol), with less than 20% difference between maximum and minimum observed ratios (in relation to their mean) during the last four weeks.

If the difference was less than 10% the ratio is underlined. Four cases are considered: case #1: weekly cumulative uptake by whole system; case #2: weekly cumulative loss from solution by whole system; case #3: weekly cumulative uptake by one plant week or content of one plant at the end of every week; case #4: content of one head at the end of every week.

| | K | P | Ca | Mg | S | Fe | Mn | B | Cu | Zn | Mo | Cl | Na |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N | | 0.087 | | 0.025 | 0.028 | | | | | | | 0.036 | |
| K | 1 | 0.128 | 0.093 | 0.036 | | | | | | | | | |
| P | | 1 | 0.751 | 0.288 | 0.321 | | | | | | | 0.418 | |
| Ca | | | 1 | 0.385 | 0.434 | | | | | | | | |
| Mg | | | | 1 | 1.125 | | | | | | | 1.467 | |
| S | | | | | 1 | | | | | | | 1.297 | |
| Fe | | | | | | 1 | 0.283 | | | | | | |
| Mn | | | | | | | 1 | | | | | | |
| B | | | | | | | | 1 | 0.805 | 4.941 | | | |
| Cu | | case #1 | | | | | | | 1 | 6.166 | | | |
| Zn | | | | | | | | | | 1 | | | |
| Mo | | | | | | | | | | | 1 | | |
| Cl | | | | | | | | | | | | 1 | |
| N | 0.754 | 0.094 | 0.078 | | 0.022 | | | | | | | 0.030 | |
| K | 1 | 0.125 | | | 0.029 | | | | | | | 0.040 | |
| P | | 1 | 0.837 | 0.256 | 0.233 | | | | | | | 0.322 | |
| Ca | | | 1 | 0.306 | 0.279 | | | | | | | 0.385 | |
| Mg | | | | 1 | 0.912 | | | | | | | 1.261 | |
| S | | | | | 1 | | | | | | | 1.386 | |
| Fe | | | | | | 1 | | | | | | | |
| Mn | | | | | | | 1 | | | | | | |
| B | | | | | | | | 1 | | | | | |
| Cu | | case #2 | | | | | | | 1 | | | | |
| Zn | | | | | | | | | | 1 | | | |
| Mo | | | | | | | | | | | 1 | | |
| Cl | | | | | | | | | | | | 1 | |
| N | | 0.090 | | | 0.030 | | | | | | | 0.037 | |
| K | 1 | | 0.097 | | | | | | | | | | |
| P | | 1 | | 0.297 | 0.326 | | | | | | | 0.413 | |
| Ca | | | 1 | 0.381 | | | | | | | | | |
| Mg | | | | 1 | 1.116 | | | | | | | 1.424 | |
| S | | | | | 1 | | | | | | | 1.254 | |
| Fe | | | | | | 1 | | | | | | | |
| Mn | | | | | | | 1 | | | | | | |
| B | | | | | | | | 1 | | 5.041 | | | |
| Cu | | case #3 | | | | | | | 1 | | | | |
| Zn | | | | | | | | | | 1 | | | |
| Mo | | | | | | | | | | | 1 | | |
| Cl | | | | | | | | | | | | 1 | |
| N | | | | | | | | | | | | 0.042 | |
| K | 1 | | 0.099 | | | | | | 0.116 | | | | |
| P | | 1 | 0.886 | 0.309 | 0.293 | | | | | | | 0.482 | |
| Ca | | | 1 | 0.358 | 0.333 | | | | 1.176 | | | | |
| Mg | | | | 1 | 0.966 | | | | | | | 1.546 | |
| S | | | | | 1 | 1.662 | | | | | | 1.662 | |
| Fe | | | | | | 1 | | | | | | | |
| Mn | | | | | | | 1 | | | | | | |
| B | | | | | | | | 1 | | | | | |
| Cu | | case #4 | | | | | | | 1 | | | | |
| Zn | | | | | | | | | | 1 | | | |
| Mo | | | | | | | | | | | 1 | | |
| Cl | | | | | | | | | | | | 1 | |

Appendix 8: Results of calibration of pH electrode and ion selective electrodes used in experiment 6705.

Calibration line pH electrode

$$E = A \cdot (pH) + B$$

where $E$ is the measured potential (V), and $A$ and $B$ are the slope and intercept of the calibration line, respectively.

Calibration results of pH electrode: day, $A$, and $B$.

| Day | $A$ | $B$ |
|---|---|---|
| 1 | 60.333 | 444.933 |
| 4 | 60.700 | 441.900 |
| 16 | 62.333 | 452.333 |
| 19 | 59.633 | 436.233 |
| 26 | 60.333 | 438.033 |
| 33 | 61.133 | 441.733 |
| 40 | 61.900 | 445.500 |
| 51 | 60.300 | 434.600 |

Calibration line ion selective electrodes

$$E = A \cdot \log(c) + B$$

where $E$ is the measured potential (V), and $A$ and $B$ are the slope and intercept of the calibration line, respectively.

[Table on next page]

Calibration results of ion selective electrodes: electrode (ISE), day, *A*, and *B*.

| ISE | Day | *A* | *B* |
|---|---|---|---|
| NO3-1 | 4 | -60.238 | 151.4 |
| | 16 | -59.241 | 161.0 |
| | 19 | -57.469 | 160.0 |
| | 26 | -57.802 | 159.3 |
| | 33 | -58.023 | 159.4 |
| | 40 | -58.134 | 157.3 |
| | 51 | -57.137 | 154.0 |
| NO3-2 | 4 | -59.352 | 162.3 |
| | 16 | -59.463 | 156.7 |
| | 19 | -57.912 | 151.0 |
| | 26 | -57.580 | 153.8 |
| | 33 | -58.466 | 152.1 |
| | 40 | -58.134 | 151.5 |
| | 51 | -58.134 | 149.7 |
| K | 4 | 53.151 | -59.3 |
| | 16 | 54.812 | -56.5 |
| | 19 | 49.829 | -55.7 |
| | 26 | 51.822 | -57.3 |
| | 33 | 54.037 | -66.0 |
| | 40 | 51.047 | -65.5 |
| | 51 | 50.604 | -63.6 |