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INTRODUCTION

In horticulture a wide variety of soilless culture systems is in use (Steiner, 1972, 1976; Bunt, 1976; Schubert, 1977; Resh, 1978; Winsor *et al.*, 1979). The systems differ widely with regard to the degree of mixing of the nutrient solution. The two extremes are 1) systems in which nutrient solutions circulate rapidly such that the resulting composition hardly varies from place to place: *perfect mixing*, and 2) systems in which nutrient solutions move slowly without hardly any mixing: *perfect displacement*. Nutrient film and gulley systems tend to the first extreme, while rockwool systems tend to the second. In this paper I formulate balances of water, nutrients, and impurities for both extreme types. Some simple implications of the theory will also be pointed out.

PERFECT MIXING

<u>The time course of the composition</u>- Let M_i be the number of moles of constituent i in the nutrient solution at any moment. The time rate of change of M_i is given by

$$\frac{dM_i}{dt} = \sum_{k=1}^{K} A_{ik} - \sum_{l=1}^{L} B_{il} , \qquad (1)$$

where A_{ik} is the rate of supply of constituent i from source k and B_{il} is the rate of loss of constituent i to sink l. The set of constituents i includes the water, the nutrients (both major and minor), dissolved gases (e.g. O_2, CO_2), and any inorganic and organic substances present in the solution. Often attention is focussed upon subsets of the complete set of constituents: e.g. the water and the major nutrients. The set of sources includes dilute solutions serving primarily as supplies of water, more concentrated solutions serving primarily as supplies of nutrients, solutes from dissolution of precipitates (e.g. from $CaCO_3$, $MgSO_4$), or system components (e.g. Zn, Cu) and any products of metabolic processes in the plants and in any other organisms present. Water may be supplied by well water, deionized water, desalinized water, etc. In connection with precipitation, the need to correct imbalances, and pH control, usually more than one source of nutrients is used. The set of losses includes uptake of water and solutes by the plants and any other organisms, evaporation of water, drainage of water, and precipitation of salts.

The total number of moles M, the total rate of supply A_k from source k, and the total rate of loss B_l to sink l are defined, respectively, by summation of M_i, A_{ik}, and B_{ik} over all constituents

$$M \equiv \sum_{i=1}^{N} M_i, \tag{2}$$

$$A_k \equiv \sum_{i=1}^{N} A_{ik}, \tag{3}$$

$$B_l \equiv \sum_{i=1}^{N} B_{il}. \tag{4}$$

The corresponding mole fractions m_i in the nutrient solution, a_{ik} in the supply from source k, and b_{il} in the loss to sink l are defined by

$$m_i \equiv M_i/M, \tag{5}$$

$$a_{ik} \equiv A_{ik}/A_k, \tag{6}$$

$$b_{il} \equiv B_{il}/B_l. \tag{7}$$

These mole fractions describe the compositions of the nutrient solution, of the supply from source k, and of the loss to sink l, respectively. The mole fractions are subject to the constraints

$$\sum_{i=1}^{N} m_i = 1, \tag{8}$$

$$\sum_{i=1}^{N} a_{ik} = 1, \tag{9}$$

$$\sum_{i=1}^{N} b_{il} = 1. \tag{10}$$

Of course, the nutrient solution can be described by listing either the number of moles M_i of each of the N constituents, or by giving the total number of moles M and the mole fractions of N-1 of the N constituents. For dilute solutions it suffices to list the total volume and the concentrations of the solutes.

Using the definitions (2) - (7), equation (1) can be rewritten as

$$\frac{d\, m_i\, M}{dt} = \sum_{k=1}^{K} a_{ik}\, A_k - \sum_{l=1}^{L} b_{il}\, B_l. \tag{11}$$

Expanding the derivative on the left hand side of (11) and solving for $d\, m_i/dt$ gives

$$\frac{d\, m_i}{dt} = M^{-1}\{ \sum_{k=1}^{K} a_{ik}\, A_k - \sum_{l=1}^{L} b_{il}\, B_l - m_i \frac{d\, M}{dt} \}. \tag{12}$$

Summation of equation (1) or (11) over all constituents gives

$$\frac{d\, M}{dt} = \sum_{k=1}^{K} A_k - \sum_{l=1}^{L} B_l. \tag{13}$$

Substitution of dM/dt as given by (13) into (12) gives:

$$\frac{d\, m_i}{dt} = M^{-1} \{ \sum_{k=1}^{K} (a_{ik} - m_i)\, A_k - \sum_{l=1}^{L} (b_{il} - m_i)\, B_l \}. \tag{14}$$

Equations (12) and (14) are two versions of the set of N differential equations describing the time course of the composition. In equation (14) the differences $(a_{ik} - m_i)$ and $b_{il} - m_i)$ are measures of the discrepancies between, on the one hand, the compositions of the supplies from the sources k and the losses to the sinks l and, on the other hand, the composition of the nutrient solution. Each term on the right hand side of (14) is the product of a rate and a discrepancy. Any particular term vanishes whenever the rate and/or the discrepancy is zero.

Steiner (1961, 1966, 1973) found that the composition of the uptake is within wide limits independent of the composition of the nutrient solution, but does depend upon the growth phase.
Temperature and light intensity appear to exert their influence mainly through their effect upon the growth phase. It is fortunate plants have such a large selective capacity. The present theory allows one to calculate the time course of the composition of the nutrient solution.

Equation (12) is a linear, ordinary differential equation with variable coefficients. Its solution is:

$$m_i = \exp\{-\ln(M/M_o)\} \left[\int_{t_o}^{t} Q \exp\{\ln(M/M_o)\} dt + m_{io}\right], \qquad (15)$$

where M_o and m_{io} are, respectively, the total number of moles and the mole fraction at the initial time t_o, and Q is defined as

$$Q \equiv M^{-1} \{\sum_{k=1}^{K} a_{ik} A_k - \sum_{l=1}^{L} b_{il} B_l\} \qquad (16)$$

$$= M^{-1} \{\sum_{k=1}^{K} A_{ik} - \sum_{l=1}^{L} B_{il}\}.$$

Equation (15) gives an explicit expression for the time course of m_i in terms of the time courses of the supplies and losses.

Some special cases- Given the fact that nutrient solutions are quite dilute, keeping the volume of the nutrient supply constant is nearly equivalent to keeping the total number of moles M constant:

$$d\,M/dt = 0, \text{ and } M = M_o. \qquad (17)$$

Then the terms with d M/dt in equations (12) and (13) vanish and equation (15) reduces to

$$m_i = m_{io} + \int_{t_o}^{t} Q\, dt. \qquad (18)$$

Note that deviations from m_{io} are proportional to the total number of moles in the system. If, moreover, there is supply from only one source (K = 1) and loss to only one sink (L = 1), then

$$A_1 = B_1 = E, \qquad (19)$$

where E is approximately equal to the rate of evapotranspiration, and

$$m_i = m_{io} + M^{-1} \int_{t_o}^{t} (a_{i1} - b_{i1})\, E\, d\, t. \qquad (20)$$

Equations (20) and (21) give a simple expression from which the time course of the composition of the nutrient solution can be calculated.

There are three important special cases with vanishing discrepancies (cf. equation (14)).

1. Supply from a source whose composition is the same as the composition of the nutrient solution

$$a_{ik} = m_i. \quad (21)$$

2. Loss as drainage water

$$b_{il} = m_i. \quad (22)$$

3. Balanced uptake of water and nutrients, i.e., the composition of the uptake is equal to the composition of the nutrient solution

$$a_{ip} = m_i. \quad (23)$$

This is the ideal situation, particularly in systems with infrequent replenishment and no drainage, e.g., setups used for "office-scaping".

Finally, supply or loss of pure water also simplifies some terms in the equations:
1. Supply of deionized water from source k

$$a_{wk} = 1, \quad \underset{i \neq w}{a_{ik}} = 0. \quad (24)$$

2. Loss of water by direct evaporation to sink l

$$b_{wl} = 1, \quad \underset{i \neq w}{b_{il}} = 0. \quad (25)$$

PERFECT DISPLACEMENT

In many soilless culture systems, particularly those based on a porous substrate, the nutrient solution is not perfectly mixed. For example, infiltration of dyed water into wet rockwool resulted in displacement with a sharp interface between the dyed water and the water originally present (Van Noordwijk and Raats, 1980). Moreover, just like with soil-based drip irrigation culture, the flow pattern will generally be multidimensional. The limited volume of the substrate or the flowing nutrient solution is usually the main factor determining the volume occupied by the roots. In soil-based drip irrigation culture the volume occupied by the roots often also remains confined to a small zone with favorable aeration and supplies of water and nutrients. The interaction between flow of water and a solute has been studied in most detail for one-dimensional flows in which water is taken up, but the solute is completely excluded (Raats, 1975; Jury *et al.*, 1978). The main difference between soilless culture and soil-based culture is the limited adsorption capacity of most artificial substrates for ions like potassium and orthophosphate.

In the following, I sketch a simple one-dimensional model involving steady supply, uptake, and drainage. This model is applicable to slowly circulating nutrient film culture and, with simple modifications, to individual streamtubes of multidimensional flows in artificial substrates.

The steady balance of mass for the water or for a solute can be written as

$$\frac{d\,F_i}{d\,x} = \lambda_i \quad \Lambda_i, \tag{26}$$

where x is the spatial coordinate, F_i is the mass flux per unit area per unit time, Λ_i is the rate of uptake per unit time over the entire range from x = 0 to x = L, and λ_i is the uptake distribution function over the same range. By definition

$$\int_o^L \lambda_i \; d\,x = 1 \, . \tag{27}$$

Integration of equation (26) gives

$$F_i = F_{io} - \Lambda_i \int_o^x \lambda_i \; d\,x, \tag{28}$$

where F_{io} is the rate of supply at x = 0. Dividing both sides of equation (28) by F_{io} gives

$$F_i/F_{io} = 1 - (\Lambda_i/F_{io}) \int_o^x \lambda_i \; d\,x. \tag{29}$$

Evaluating equation (29) at x = L and using equation (27) gives

$$F_{iL}/F_{io} = 1 - \Lambda_i/F_{io}. \tag{30}$$

The ratios F_{iL}/F_{io} and Λ_i/F_{io} are, respectively, the leaching and uptake fractions for the constituent i. Let the subscript w denote the water and the subscript s the solute, then for purely convective transport

$$F_s = F_w \, c, \tag{31}$$

or, using equation (29)

$$\frac{c}{c_o} = \frac{F_s/F_{so}}{F_w/F_{wo}} = \frac{1 - (\Lambda_s/F_{so}) \int_o^x \lambda_s \, d\,x}{1 - (\Lambda_w/F_{wo}) \int_o^x \lambda_w \, d\,x} \, . \tag{32}$$

Evaluating equation (32) at x = L and using equation (27) gives

$$\frac{c_L}{c_o} = \frac{F_{sL}/F_{so}}{F_{wL}/F_{wo}} = \frac{1 - \Lambda_s/F_{so}}{1 - \Lambda_w/F_{wo}} \quad . \tag{33}$$

According to equation (32) the distribution of the salt is determined by the fractions Λ_s/F_{so} and Λ_w/F_{wo}, and the uptake distribution functions λ_s and λ_w. According to equation (33) the ratio c_L/c_o is equal to the ratio of the leaching fractions of the solute and of the water. If the solute is completely excluded then $\Lambda_s = 0$ and equations (32) and (33) reduce to

$$\frac{c}{c_o} = \frac{F_{wo}}{F_w} = \{1 - (\Lambda_w/F_{wo}) \int_o^x \lambda_w \, d\,x\}^{-1} \tag{34}$$

and

$$\frac{c_L}{c_o} = \frac{F_{wo}}{F_w} = \{ 1 - \Lambda_w/F_{wo}\}^{-1}. \tag{35}$$

Equation (35) is the well known relationship between the concentrations of irrigation and drainage waters and the leaching fraction (U.S. Salinity Labaratory, 1954; Raats, 1975).

As an example, consider a nutrient film or gulley in which the uptake distribution functions of water and solutes are equal to each other and uniform, i.e.

$$\lambda_w = \lambda_s = L^{-1}. \tag{36}$$

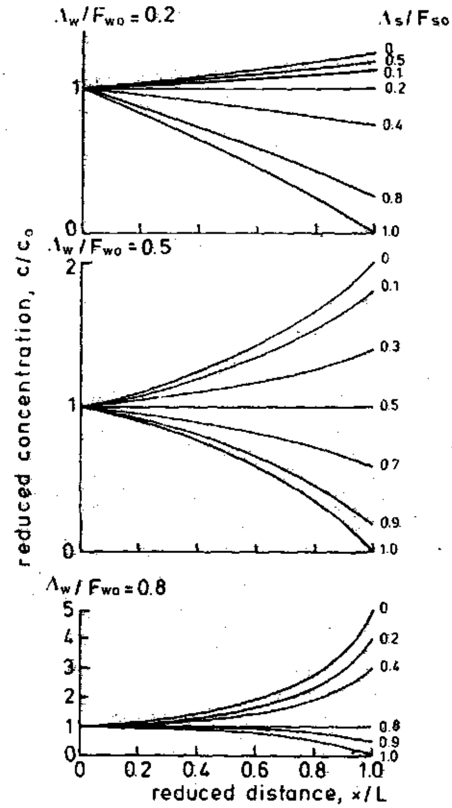
Note that this choice is compatible with the normality condition expressed in equation (27). Substituting (36) into (32) gives

$$\frac{c}{c_o} = \frac{F_s/F_{so}}{F_w/F_{wo}} = \frac{1 - (\Lambda_s/F_{so})\ x/L}{1 - (\Lambda_w/F_{wo})\ x/L} \quad . \tag{37}$$

Figure 1 shows the resulting concentration profiles for three values of the uptake fraction for the water, Λ_w/F_{wo}, and a range of values of the uptake fraction for the solute, Λ_s/F_{so}. Note that

1. $c/c_o > 1$ if $\Lambda_s/F_{so} < \Lambda_w/F_{wo}$,
2. " $=1$ " " $=$ " ,
3. " <1 " " $>$ " .

Fig. 1. Distribution of concentration on a nutrient film or gulley



CONCLUDING REMARKS

The theory formulated in this paper allows one to estimate under what circumstances and how soon any discrepancies between supply and demand of water and nutrients go beyond permissible levels. Eventually it may provide a common basis for the automation of a wide variety of soilless culture systems.

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ABSTRACT

In horticulture a wide variety of soilless culture systems is in use. The systems fall in two categories: 1) systems in which nutrient solutions circulate rapidly such that the resulting composition hardly varies from place to place, and 2) systems in which nutrient solutions move slowly such that the composition clearly varies from place to place. In this paper balances of water and nutrients are formulated for both types of systems. Some simple implications of the theory are pointed out.